FUNDAMENTALS OF WEED SCIENCE

[THIRD EDITION]

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Fundamentals of Weed Science

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PREFACE

More than 30 years ago, the Monsanto Company distributed a picture that hangs in my study. It showed four books[1] with several weed seedlings emerging from each. It was a good picture that portrayed the beginnings of books relevant to weed science. Two (Ahlgren et al. and King) were textbooks, and two (Muenscher and Fernald) were plant identification books. They were the beginning of a now greatly expanded literature on weed science.

Many, but not all, textbooks written for undergraduate weed science courses lack an ecological-management perspective on the rapidly developing science of weeds and their control. This book does not ignore the history of weed science and the development of chemical weed control, but it strives to include herbicides as one management technique among many rather than the primary method of choice to solve most weed problems.

Science, of all kinds, is not in favor these days. Scientists, including weed scientists, eagerly accepted the credit when in 1945, after World War II, many advances in societal development were widely regarded as contributions of science. The public regarded these advances, which included herbicides and other pesticides, as desirable and benign. Now science is held responsible for many problems that have grown out of its linkage with technology. Herbicides are no longer regarded as benign but rather as threats to humans and the environment and are seen by many as undesirable scientific creations. The public's attitude toward science and scientists has become a mingling of awe

[1]The books pictured were Ahlgren, G.H., G.C. Klingman, and D.E. Wolf. 1951. *Principles of Weed Control*. J. Wiley & Sons, New York, 368 pp.; Fernald, M.L. 1970. *Gray's Manual of Botany*. 8th ed. American Book Co. New York, 926 pp.; King, L.J. 1966. *Weeds of the World: Biology and Control*. Interscience Pub., Inc. New York, 526 pp.; and Muenscher, W.C. 1935. *Weeds*. The Macmillan Co. New York, 577 pp.

and fear. The practice of science is constrained because while it claims to be an end in itself, it is publicly supported and tolerated because of its utility and its practical value, and it is feared because of its well-known undesirable consequences. Weed science is not atypical, and because of its close identification with chemical herbicides, it may be regarded with more apprehension than some other areas of agricultural science. The public's lack of understanding or its misunderstanding of what weed scientists do will not lessen the need for what is done, and it increases the responsibility of weed scientists and educators to be clear about the problem of weeds and proposed solutions. The responsibility is not so much to educate the public about "what we do" as it is to engage in a conversation (a dialogue, not a monologue) with the public. It is an engagement in public scholarship, whereby original, peer-reviewed intellectual work is fully integrated with the social learning of the public (Jordan et al., 2002).[2]

This book includes herbicides[3] and their use as an important aspect of modern weed management, but it strives to place them in an ecological framework. Any book that purports to discuss the present state of the practice (and art) of weed management would be of little consequence and limited value to students and others who wish to know about weed management, as it is now practiced, if it omitted discussion of herbicides. Many weed scientists believe agriculture is a continuing struggle with weeds. That is, they believe that without good weed control, good, profitable agriculture is impossible and herbicides are an essential component of success. Each agricultural discipline sees itself as central to agriculture's success and continued progress, and weed scientists are no exception. While not denying the importance of weed management to successful agriculture, its role in the larger ecological context is emphasized. The role of culture, economics, and politics in weed management are mentioned but are not strong themes.

This, the third edition, is not a complete revision of the original text, but it has been changed in several significant ways while maintaining an overall ecological framework. Some references in the first edition have been omitted, but 494 new references have been added, 294 of which are work published after 1999, and 89 of them are from the ecological literature. The literature review for this edition was completed in early 2006.

The chapters are arranged in a logical progression. Chapter 1 addresses the question "Why should we study weeds?" The book guides discussions of why weeds are important. The second chapter pursues the discussion of the

[2]Jordan, N., J. Gunsolus, R. Becker, and S. White. 2002. Public scholarship—linking weed science with public work. *Weed Sci*. 50:547–554.

[3]Common names of herbicides will be used throughout the text except in some tables where they may be paired with one or more trade names.

definition of weed that began in Chapter 1, and it presents the characteristics and harmful aspects of weeds. It concludes with a discussion of what weeds cost. Chapter 3 classifies weeds in several ways, and Chapter 4, unique among weed science texts, discusses the fact that not all plants that are weedy in some environments are all bad. Many plants have uses that are known to and studied by ethnobotanists. Weed reproduction and dispersal and the very important topics of seed germination and dormancy are presented in Chapter 5. Chapter 6 is important because it presents the fundamental ecological base of weed science, including plant competition and the interactions of weeds and other pests. Chapter 7, an extended discussion of the role and importance of invasive plant species, is new in this edition and also unique among weed science textbooks. It is followed by a discussion of allelopathy in Chapter 8—a subject included as a minor point in many weed science texts. Having established the ecological base of weed science, the significance of weed-crop competition is presented in Chapter 9.

Chapter 10 begins with a consideration of weed management. For many this is the essence of weed science, the fundamental topic: How are weeds controlled? Weed problems are created, and those who wish to control them need to ask *why* the weed is there as well as how to manage or control it (Zimdahl, R.L., 1999. My View Weed Sci. 47:1). Key concepts of prevention, control, and management are presented in Chapter 10, followed by presentation of mechanical, nonmechanical, and cultural control techniques, as well as the new topic (in this edition) of herbicide-resistant crops. Chapter 11 continues discussion of control but by biological means. Chapter 12 introduces important concepts related to chemical control of weeds, and Chapter 13, one of the longest and most difficult, classifies herbicides based on how they do what they do—their mode of action and their chemical family. Chapters 14 and 15 are central to understanding of the interactions of herbicides and plants and herbicides and soil. Herbicide application is covered briefly in Chapter 14. Herbicide formulation is presented in Chapter 16.

Chapter 17 returns to the ecological theme, but this time with information on the interaction between herbicides and the environment, including effects on water, humans, and global change. A central, and intentionally unanswered, question is how one balances and judges the potential harmful and beneficial aspects of herbicide use. The chapter concludes with a discussion of herbicide safety. Chapter 18 presents the legislative decisions that were required to address some of the questions raised in Chapter 17.

Chapter 19 brings things together by discussing weed management systems, many of which are largely conceptual and not yet prescriptive. They evolve and improve with time. New sections on the influence of molecular biology on weed management and weed management decision aids have been added. Finally, Chapter 20 presents a view of the future of weed science. It is meant to provoke thought and discussion. It is not an infallible prediction of what will be.

There is a strong, growing trend in weed science away from exclusive study of annual control techniques toward understanding weeds and the systems in which they occur. Control is important, but understanding endures. Herbicides and weed control are important parts of the text, but it is hoped that understanding the principles of management and the biology and ecology of the weeds to be managed will be seen as the dominant themes. That is the primary objective of the book: to introduce the concepts fundamental to weed science and provide adequate citations so interested readers can pursue specific interests and learn more.

The study of weeds, weed management, and herbicides is a challenging, demanding task that requires diverse abilities. Weed science involves far more than answering the difficult question of what chemical will selectively kill weeds in a given crop. Weed science includes work on selection of methods to control weeds in a broad range of crops, on noncrop lands, in forests, and in water. Weed scientists justifiably claim repute as plant physiologists, ecologists, botanists, agronomists, organic and physical chemists, molecular biologists, and biochemists. However, lest the reader be intimidated by that list of disciplines, I hasten to add that this text will emphasize general principles—the fundamentals—of weed science and not attempt to include all applicable knowledge. It is tempting, and would not be much more difficult, to incorporate extensive, sophisticated knowledge developed by weed scientists. While this knowledge is impressive and valuable, it is beyond the scope of an introductory text.

It is hoped that the book conveys some of the challenges of the world of weeds and their management and the importance of weed problems to agriculture, society, and to meeting the demand to feed a growing world population. The aim has been to include most aspects of weed science without exhaustively exploring each. The book is designed for undergraduate weed science courses. It is hoped that the text is not too simple for sophisticated readers and that omissions of depth of coverage do not sacrifice accuracy and necessary detail. Readers should note that in nearly all cases I have used units of measure from the original reference rather than changing all to one measurement system.

Several colleagues provided helpful suggestions on this and earlier editions of the *Fundamentals of Weed Science*. I thank all of them, even though some comments were difficult to hear. The first edition had some inaccuracies, and those have been corrected. I thank the following colleagues for suggestions and critical review of portions of the manuscript included in this and earlier editions: Dr. Kenneth A. Barbarick, Dr. K. George Beck, Dr. Cynthia S. Brown, Dr. Sandra K. McDonald, Dr. Philip Westra, Dr. Scott J. Nissen, and Mr. Steven

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Robert L. Zimdahl
Fort Collins, Colorado
2006

This book is dedicated to the memory
of
Ann Osborn Zimdahl
and to
the loving presence
of
Pamela Jeanne Zimdahl

How little we know of what there is to know.
I wish that I were going to live a long time . . .
I'd like to be an old man and to really know
I wonder if you keep on learning or if there is
only a certain amount each man can understand.
I thought I knew about so many things that I
know nothing of. I wish there was more time.

For Whom the Bell Tolls by Ernest Hemingway

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CHAPTER 1

Introduction

See them tumbling down,
Pledging their love to the ground
Lonely but free I'll be found
Drifting along with the tumbling tumbleweeds.

Cares of the past are behind
Nowhere to go but I'll find
Just where the trail will wind
Drifting along with the tumbling tumbleweeds.

I know when night has gone
That a new world's born at dawn.

I'll keep rolling along
Deep in my heart is a song
Here on the range I belong
Drifting along with the tumbling tumbleweeds.

"Tumbling Tumbleweeds" Composed in 1932 by Bob Nolan and recorded by the Sons of the Pioneers

Everybody knows what weeds are. Songs and poems have even been written about them, but weeds have never received the recognition and respect they deserve. The fact that many people earn a living and serve society by controlling and managing weeds is often greeted with amusement, if not outright hysterical laughter. Even scientific colleagues who work in other esoteric disciplines find it hard to believe that another group of scientists could be concerned exclusively with what is perceived as a mundane and ordinary part of the environment.

Weeds have been with us since the advent of settled agriculture some 10,000 years ago. It has been suggested that the most common characteristic of the ancestors of our presently dominant crop plants is their "weediness"—their ability to proliferate and thrive in disturbed habitats, most notably around human dwellings (Cox, 2006). Bailey (1906, p. 199), to whom agricultural science owes so much, spoke of the Sisyphean battle against Russian thistle in the western United States:

> What I have thus far stated is only a well-known truth in organic evolution—that the distribution of an animal or plant upon the earth, and to a great extent the attributes of the organism itself, are the result of a struggle with other organisms. A plant which becomes a weed is only a victor in a battle with farm crops; and if the farmer is in command of the vanquished army, it speaks ill for his generalship when he is routed by a pigweed or a Russian thistle.

I am never surprised when a student who enrolls in a course about weeds questions why the course is recommended, or even required, and what it is about. Students who enroll in chemistry or English have a reasonably good idea of what they will learn in the class and how it fits into their curriculum. But this is not the case for weed science students. Of course, students who live on farms and ranches already know a lot about weeds and the problems they cause, but they do not always comprehend the complexities of weed management or the generalship required. Therefore, in this course, it is important that the subject be established and connected to students' prior knowledge of agricultural, biological, and general sciences. From the beginning, a textbook, the teacher, and the student should strive to establish relationships among weed science, agriculture, and society. This book introduces the fundamental concepts of weed science and explores how they have changed over the years.

The story of agriculture is a story of struggle. It is the story of struggles—those that have ensued "in consequence of the sudden overturning of established conditions, and the substitution therefor of a very imperfect and one-sided system of land occupancy" (Bailey, 1906, p. 200). This is what we know as modern agriculture. Agricultural history, although a fascinating subject, is too large a topic to address adequately in this book, so only small bits are included. Those who are interested in studying agricultural history are referred to Goodwin and Johnstone (1940) and Rasmussen (1975). The history of weed control was reviewed by Timmons (1970, republished in 2005) and Appleby (2005).

Formidable obstacles have been placed between humans and a continuing food supply. These include physical constraints such as a lack of good highways and transportation, economic constraints such as a lack of credit and operational funds, environmental constraints such as too much or too little water or too short a growing season, and biological constraints such as problems with fertility, varieties, soil pH, or salinity. One of the most formidable environmental constraints has been what are known as pests. Surveys by the Food and Agriculture Organization of the United Nations (1963, 1975) showed that in the 1960s and 1970s more than one-third of the potential annual world food harvest was destroyed by pests. The $75 billion lost was equivalent to the value of the entire world's grain crop (about $65 billion) and the world's potato[1] crop (about $10 billion). This means that insects, plant diseases, nematodes, and weeds deprived humans of food worth more than the entire world crop of wheat, rye, barley, oats, corn, millet, rice, and potatoes. These losses were only up to harvest and do not include damage during storage—another huge quantity. Current, less-complete estimates show that losses due to pests of all kinds have increased since the first FAO estimates were made.

History is filled with examples of human conflicts with pests, from biblical to modern times. Examples include locusts (*Melanoplus* spp.), which still plague the world, to late blight [*Phytophthora infestans* (Mont.) D. By.], which caused the Irish potato famine of the 1840s. The continuing worldwide presence of Colorado potato beetles (*Leptinotarsa decemlineata* Say) and the 1970s epidemic of Southern corn leaf blight (*Helminthosporium maydis* Nisik and Miyake) illustrate that the battle goes on. In fact, the battle has become even more intense as agriculture has changed, with the introduction of chemical pesticides and as an increasing population creates demand for ever greater demand for high-quality food.

One must respect the prescience of writer Jonathan Swift (1667–1745; see Williams, 1937), who said the following:

> Hobbes clearly proves that every creature
> Lives in a state of war with nature,
> . . .
> So, Nat'ralists observe, a Flea
> Hath smaller Fleas that on him prey;
> And these have smaller Fleas to bite 'em:
> And so proceed *ad infinitum*.

De Morgan (1850), who probably had read, but did not cite, Swift's poem, expressed the ubiquity of pests several years later:

> Great fleas have little fleas upon
> their backs to bite 'em,
> And little fleas have lesser fleas,
> and so ad infinitum,
> And the great fleas themselves, in
> turn, have greater fleas to go on;
> While these again have greater still,
> and greater still, and so on.

[1]Common and scientific names of all crops and weeds are listed in Appendixes 1 and 2.

The subject of this book is weeds, visible but unspectacular pests, whose presence may be formidable but whose effects are not. Weeds have always been with us and are mentioned in some of our oldest literature:

> Cursed is the ground for thy sake;
> in sorrow shalt thou eat of it all the days of thy life;
> thorns and thistles shall it bring forth to thee;
> and thou shalt eat the herb of the field.
>
> *Genesis 3:17–18*

> Ye shall know them by their fruits. Do men gather grapes
> of thorns, or figs of thistles?
>
> *Matthew 7:16*

> And thorns shall come up in her palaces, nettles and
> brambles in the fortresses thereof. . . .
>
> *Isaiah 34:13*

Jesus also spoke of weeds in his parables (Matthew 13:18–23). The biblical "thistles, thorns, and brambles" are common weeds and have been identified as such by biblical scholars (Moldenke and Moldenke. 1952). Weeds were and are still considered serious threats in the continuing battle to produce enough food for the world's inhabitants. The "tares" in the following parable (Matthew 13:24–30) are the common weed poison ryegrass, a continuing problem in cereal culture:

> The kingdom of heaven is likened unto a man which sowed good seed in his field: But while he slept, his enemy came and sowed tares among the wheat, and went his way. But when the blade was sprung up, and brought forth fruit, then appeared the tares also.

The Greek word *tares* is translated as "darnel"—a weed that grows among wheat. It is a grass that resembles wheat or rye but has smaller, poisonous seeds. The weed called tares in Europe today is a different species.

No agricultural enterprise or part of our environment is immune to the detrimental effects of weeds. They have interfered with human endeavors for all of history. In much of the world (including my garden), weeds are controlled by hand or with a hoe. The figure of a person holding a hoe may be as close as we can come to a universal symbol for "farmer," even though most farmers in developed countries no longer weed with hoes. For many, both the hoe and the weeding done with it symbolize the practice of agriculture. Controlling weeds is probably the farmer's most arduous task, as expressed by Edwin Markham in his poem "The Man with the Hoe":

Bowed by the weight of centuries he leans
Upon his hoe and gazes on the ground,
The emptiness of ages in his face,
And on his back the burden of the world.
Who made him dead to rapture and despair,
A thing that grieves not and that never hopes,
Stolid and stunned, a brother to the ox?
Who loosened and let down this brutal jaw?
Whose was the hand that slanted back this brow?
Whose breath blew out the light within this brain?
. . .
O masters, lords and rulers in all lands,
How will the future reckon with this man?
How answer his brute question in that hour
When whirlwinds of rebellion shake all shores?

Four major advances in agriculture have significantly increased food production:

1. The introduction of *mineral fertilizer*. Early work on plant nutrition and soil fertility proceeded directly from the pioneering studies of Justus von Liebig (1942), who questioned prevailing theories about plant nutrition.
2. *Agricultural mechanization*, which began in the United States with Eli Whitney's invention, the cotton gin, in 1793, McCormick's reaper in 1834, and Deere's moldboard plow in 1837.
3. *Genetic research* in plant and animal production. The Austrian monk Gregor Mendel, who pursued his studies in quiet and seclusion, had no dreams of pragmatic application or economic gain. His discoveries, most notably in the development of plant hybrids, have had a huge, generally positive, effect on our ability to produce food. The nearly simultaneous and independent rediscovery of Mendel's work by De Vries in Holland, Correns in Gemany, and Tschermak in Austria in 1900, while examining the literature to confirm their own discoveries, produced enormous benefits for agriculture.
4. The use of *pesticides* and *plant growth regulators*. These moved beyond mechanization to the chemicalization of agriculture and led to the development and growth of weed science. Weed science did not develop exclusively because of herbicide development, nor is its continued development dependent on herbicides, although they are an important part of knowledge of weeds and their management.

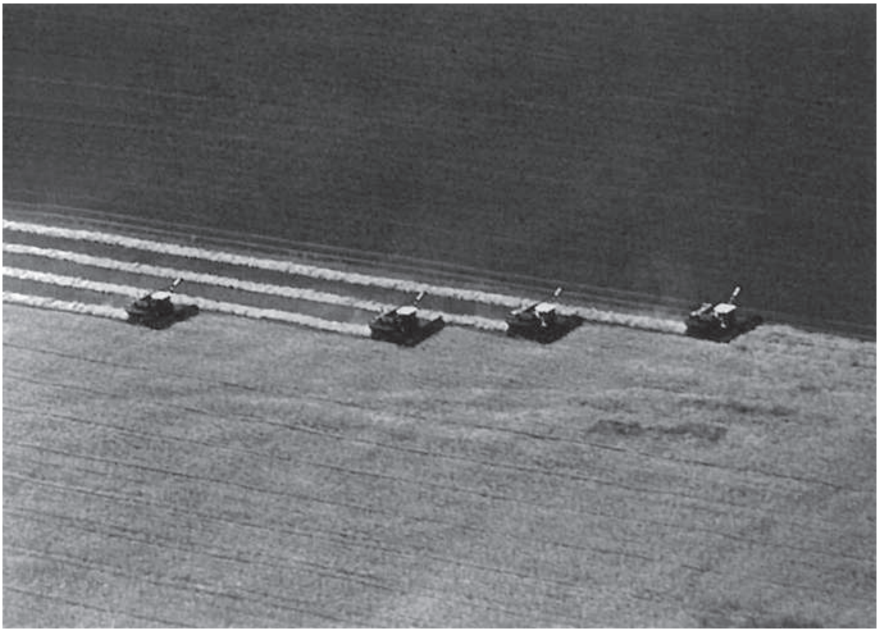
Weed science is vegetation management—the employment of many techniques to manage plant populations in an area. This includes dandelions in turf, poisonous plants on rangeland, and johnsongrass in soybean crops. Weed

The introduction of mineral fertilizer increased food production.

science might be considered a branch of applied ecology that attempts to modify the environment against natural evolutionary trends. Natural evolutionary or selection pressure tends toward the lower side of the curve (see Figure 1.1; Shaw et al., 1960) toward what ecologists call climax vegetation, the specific composition of which will vary with latitude, altitude, and environment. A climax plant community does not, and probably cannot, provide the kind or abundance of food 6.5+ billion humans want or need. Therefore, we attempt to modify nature to grow high-value crops for food and fiber.

In the beginning, there were no weeds. If one impartially examines the composition of natural plant communities or the morphology of weed flowers, one can find beauty and great aesthetic appeal. The flowers of wild onion, poison hemlock, dandelion, chicory, sunflower, and several of the morning glories are very attractive and worthy of artistic praise for symmetry and color. But what right do we have to call plants with beautiful flowers "weeds"? Who has the right to say a certain type of plant should be destroyed? By what authority do we so easily assign the derogatory term *weed* to a plant and accuse it of interfering with agriculture, increasing costs of crop production, reducing yields, and maybe even detracting from our quality of life?

Nature does not regard weeds as a separate category. One widely accepted definition is a plant that grows where it is not wanted (Buchholtz, 1967). Students should be aware of the anthropocentric dimension of this definition. Desire is a human trait, and therefore a particular plant is labeled a weed only in terms of human attitude. Ecologists speak of "weedy plants," but often their



Mechanization has increased agricultural productivity.

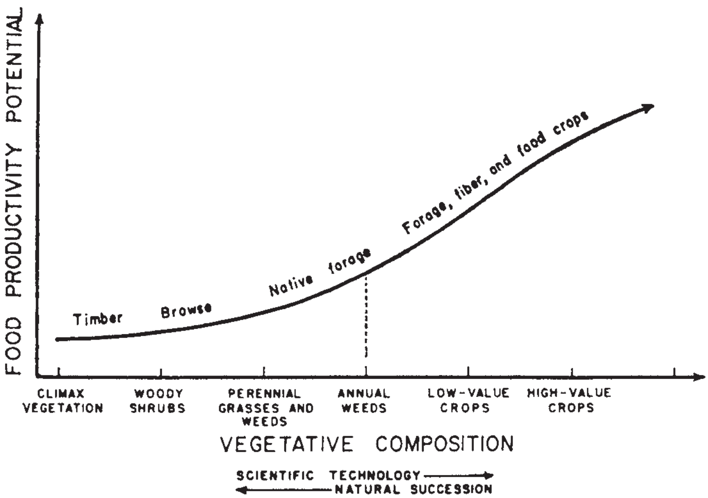
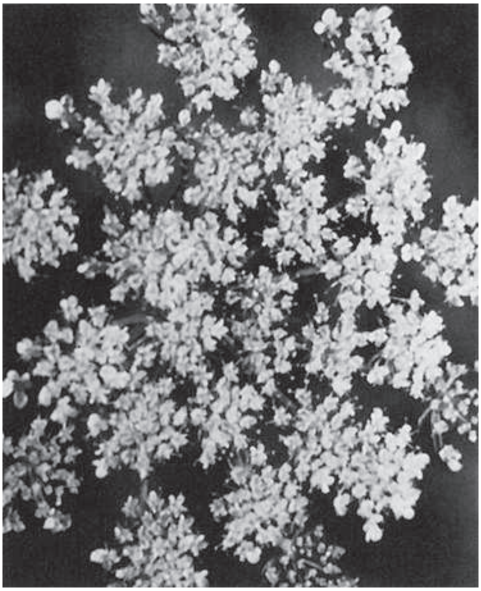


FIGURE 1.1. The food productivity potential of vegetation (Shaw et al., 1960).



The flowers of many weeds are beautiful and have great aesthetic appeal. This is the flower of wild carrot or Queen Anne's Lace.

use of the term is influenced by preconceptions of the role of vegetation on a particular site. People decide that a plant that grows in a certain location is not desirable and is therefore a weed. Weeds are regarded as the lowest of the kingdom of flowering plants not because they are innately harmful but because they are harmful to *us*.

Homeowners have been the ones to declare that dandelions and crabgrass are unacceptable in their lawns. Does grass really care what other plants it must share the soil with? Hayfever sufferers blame ragweed or sagebrush in the western United States for their misery. And only those who get an itchy rash from poison ivy insist that it should be eradicated. Farmers claim, with economic justification, that they want their crops to grow in a weed-free environment because it will maximize their yield and profits. So it is people who decide what plants are weeds and when, where, and how they will be controlled.

This book discusses many aspects of weeds, their biology, and their controls, but it differs from other weed science texts in significant ways. Most current weed science textbooks devote at least 50% of their content to herbicides and their use; in some, it is as much as 75%. One notable exception is Aldrich and Kremer's book (1997), which does not include any major section

The dandelion is considered a weed by many.

on herbicides. Because of the undeniable success of chemical weed management, however, this author believes that it deserves a place in any complete weed science textbook. Omitting that topic will produce students who are only partially prepared for modern weed management. This book discusses herbicides and their use but only as part, albeit an important part, of the fundamentals of weed science. This book also claims that killing weeds with herbicides is the modern way, as opposed to first understanding their biology and ecology. Weed control has been a major concern almost since the beginning of farming. The Weed Science Society of America has recently identified 17 important early publications on weeds (from 1895 to 1965), 12 of which dealt with their destruction, control, or eradication. As you read this book, you will see that although these important topics are included, the primary emphasis is on understanding everything about weeds.

One can establish a relationship between pesticide use and agricultural yield. Perhaps a better way to put it is that one can find a relationship between good pest management (regardless of how it is accomplished) and agricultural yield. One should not always equate good weed control with herbicide use. Good weed control depends on cultural knowledge—what a good farmer or plant grower knows. Cultural knowledge is different from the scientific knowledge that leads to herbicide development and successful use. Both kinds of knowledge—scientific to tell us what can be done and cultural to tell us what should be done—are essential to good weed management.

One can also postulate a relationship among the way weeds and other pests are controlled, the practice of pest management, and a nation's food supply. Figure 1.2 shows the world's tropical and subtropical areas, their major crops, and the percent of the world's total crop grown in each area. The region's ability to control weeds is shown in Figure 1.3, with data for the world and four major areas. Each segment in Figure 1.3 is divided into good, moderate or acceptable, low, and very poor weed management. The world's tropical and subtropical regions (Figure 1.2) are home to a majority of the world's population and produce most of some of the world's most important crops. But although pest management science has made remarkable progress since Figure 1.2 was prepared in 1971, these areas identified still suffer from underdevelopment of weed science and other agricultural technology (Figure 1.3). In a UN/FAO survey (Labrada, 1996) of 70 countries in Asia, Africa, and Latin America, which had 43.7% of the world's arable land and 65.8% of the world's people, an almost total lack of weed control technology and knowledge were found.

The founder of Latin prose, Cato the Elder, reminds us in his work on agriculture that "it is thus with farming: If you do one thing late, you will be late in all your work." We are late in implementing advanced weed manage-

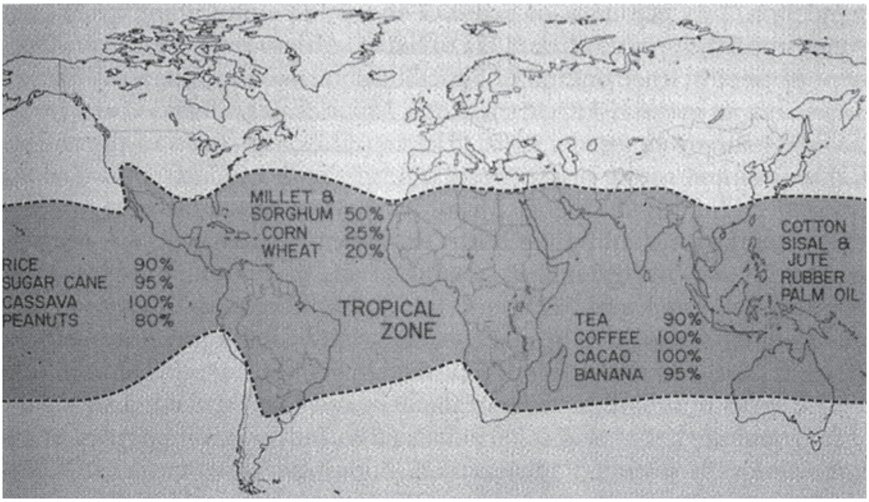


FIGURE 1.2. Crop production in the world's tropics (Holm, 1971).

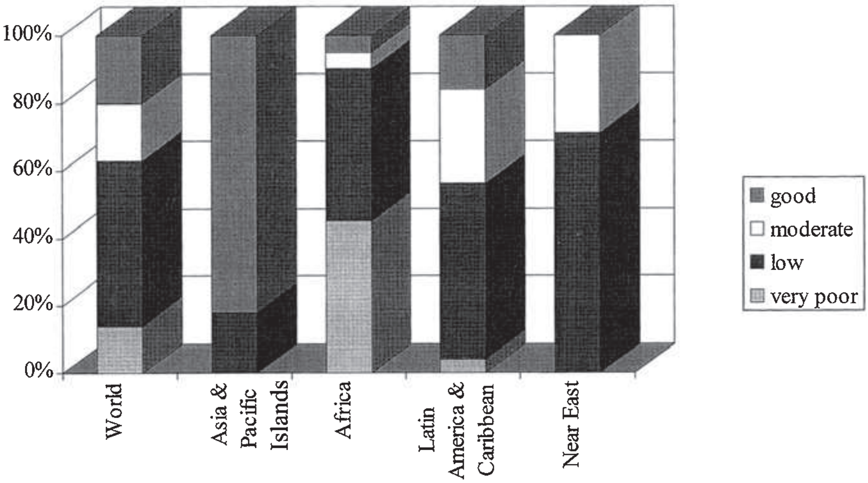


FIGURE 1.3. The level of weed control practices in the world and four regions (Labrada, 1996).

ment techniques in much of the world, and agriculture cannot progress to its full potential without them.

The agricultural productivity of the developed world is not an accident. US agriculture and that of other advanced nations grew out of a propitious combination of scientific advancement, industrial growth, and abundant resources of soil, climate, and water. One should not regard it as just good luck that we Americans can pay our food bills and still have money left over while many folks in the world are starving.

In much of the world, weeds are controlled by hand or with crude hoes. The sizes of a farmer's holding and yield per unit area are limited by several things and paramount among them is the rapidity with which a family can weed its crops. More human labor may be expended to weed crops than on any other single human enterprise, and often much of that labor is expended by women. Weed control in the Western world and in some other areas is performed by sophisticated machines and by substituting chemical energy for mechanical and human energy. There is a relationship between the way farmers control weeds and the ability of a nation to feed its people. Weed science is part of that relationship. Good weed management is one of the essential ingredients to increasing food production.

The early flights of the *Apollo* spacecrafts and subsequent space flights gave those back on Earth a view of the whole planet, floating in the great, black sea of space. Many had imagined but had never seen such a view before. Space exploration opened exciting new vistas and opportunities for someday living on other planets, but, for now, we are confined to Earth. About 1965, world food production began to lose the race with an expanding population, just as T.R. Malthus (1798) predicted it would. Each year, the apocalypse that Malthus predicted is prevented, but it remains a daily specter for many in the world. The world's population now exceeds 6.5 billion people, and it will continue to grow, albeit at a slower rate. More than 85% of the world's people live in poor, developing countries, and about 95% of the population growth will occur in those countries. As world population expands, food production is barely keeping pace and often slipping behind. About 10% of the world's 33 billion acres of land are arable, and while the area devoted to productive agriculture can be expanded, the cost will be great. One must also recognize that the world may lack the social and political will to handle the complex problems that may arise from expansion onto previously untilled land. Such expansion is certainly part of the solution to the world food dilemma, but an equally important one is to use appropriate, available technology and to develop new technology. If all the world's people are going to enjoy higher standards of living and be able to watch their children mature without fear of debilitating disease, malnutrition, or starvation, we must use intelligently all present agricultural technology and continue to develop better, safer technology. Shared technology and knowledge will permit our neighbors in this world to farm in ways that realize full agricultural and human potentials.

Weed science is not a panacea for the world's agricultural problems. The problems are too complex for any simple solution, and students should be suspicious of those who propose simple solutions to complex problems. In fact, the goals should be not to solve but to diminish, not to cure but to alleviate, and to at least anticipate the "brute question" and have some answers when "whirlwinds of rebellion strike all shores." The work of the weed scientist is fundamental to solving problems of production agriculture in our world. Weeds have achieved respect among farmers who deal with them every year in every crop. Weeds and weed scientists have achieved respect and credibility in academia and the business community. The world's weed scientists are and will continue to be in the forefront of efforts to feed the world's people.

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CHAPTER 2

Weeds—The Beginning

FUNDAMENTAL CONCEPTS

- The most basic concept of weed science is embodied in the term *weed*.
- Weeds are defined in many ways, but most definitions emphasize behavior that affects humans.
- All weeds share some characteristics.
- Weeds express their undesirability in at least nine distinct ways.
- Although it is difficult to estimate total weed cost, in the United States, losses due to weeds exceed $8 billion per year.

OBJECTIVES

- To understand the definitions of weeds.
- To identify the common characteristics of weeds.
- To understand how weeds cause damage
- To appreciate the enormous cost of weeds and how costs are estimated.

. . . and nothing teems
But hateful docks, rough thistles, kecksies, burs,
Losing both beauty and utility.
And as our vineyards, fallows, meads, and hedges
Defective in their natures, grow to wildness;
Even so our houses, and ourselves, and children,
Have lost, or do not learn, for want of time,
The sciences that should become our country.
King Henry V, Act 5, Scene 2. Play by William Shakespeare

I will go root away the noisome weeds,
which without profit suck the soil's fertility from wholesome flowers.
Richard II, Act 3, Scene 3. Play by William Shakespeare

There are laws in the village against weeds
The law says a weed is wrong and shall be killed
The weeds say life is a white and lovely thing
And the weeds come on and on in irrepressible regiments.
"Weeds" Poem by Carl Sandburg

I. DEFINITION OF THE WORD *WEED*

To be fully conversant with a subject, one must understand its basic concepts, and the most basic concept of weed science is embodied in the word *weed* itself. Each weed scientist has a clear understanding of the term, but there is no universal definition that is accepted by all scientists. In 1967 the Weed Science Society of America defined a weed as "a plant growing where it is not desired" (Buchholtz, 1967). In 1989 the Society's definition was changed to define a weed as "any plant that is objectionable or interferes with the activities or welfare of man" (Humburg, 1989, p. 267; Vencill, 2002, p. 462). The European Weed Research Society defined a weed as "any plant or vegetation, excluding fungi, interfering with the objectives or requirements of people" (EWRS, 1986). Although the definitions are clear, they are not accepted by all scientists. These definitions leave their interpretations with people, so they must be the ones to determine when a particular plant is growing where it is not wanted or where it interferes with their activities or welfare.

The *Oxford English Dictionary* (Little et al., 1973) defines a weed as a "herbaceous plant not valued for use or beauty, growing wild and rank, and regarded as cumbering the ground or hindering the growth of superior vegetation." The human role is again clear because it is we who determine use or beauty and which plants are to be regarded as superior. It is important that weed scientists and vegetation managers remember the importance of definitions as determinants of their views of plants and attitudes toward them.

How one defines something largely determines his or her attitude toward the thing defined, and, for the weed scientist and vegetation manager, determines which plants are weeds and therefore must be controlled. Weeds, like other plants, lack consciousness and cannot enter the court of public opinion to claim rights. Humans can assign rights to plants and serve as their counsel to determine or advocate their rights or lack thereof in our environment. Our attitude toward weedy plants need not always be shaped by another's definition because people seldom agree on definitions.

Once in a golden hour,
I cast to earth a seed.
Upon there came a flower,
The people said a weed.

Read my little fable:
He that runs may read
Most can raise the flowers now,
For all have got the seed.

And some are pretty enough,
And some are poor indeed:
And now again the people
Call it but a weed.

"The Flower" Poem by Alfred
Lord Tennyson

Not all people agree about what a weed is or what plants are weeds. Harlan and de Wet (1965) assembled several definitions to show the diversity of definitions of the same or similar plants. The array of definitions emphasizes the care weed scientists and vegetation managers must take in equating how something is defined with a right or privilege to control.

Definitions from plant scientists

W.S. Blatchley	1912	"A plant out of place or growing where it is not wanted."
A.E. Georgia	1916	"A plant that is growing where it is desired that something else shall grow."
W.W. Robbins et al.	1942	"These obnoxious plants are known as weeds."
W.C. Muenscher	1946	"Those plants with harmful or objectionable habits or characteristics which grow where they are not wanted, usually in places where it is desired that something else should grow."
J.L. Harper	1960	"Higher plants which are a nuisance."
E.J. Salisbury	1961	"A plant growing where we do not want it."
G.C. Klingman	1961	"A plant growing where it is not desired; or a plant out of place."

Definitions by enthusiastic amateurs

R.W. Emerson	1912	"A plant whose virtues have not yet been discovered."
F.C. King	1951	"Weeds have always been condemned without a fair trial."

Ecological definitions

A.H. Bunting	1960	"Weeds are pioneers of secondary succession, of which the weedy arable field is a special case."

W.S. Blatchley	1912	"A plant which contests with man for the possession of the soil."
T. Pritchard	1960	"Opportunistic species that follow human disturbance of the habitat."
E.J. Salisbury	1961	"The cosmopolitan character of many weeds is perhaps a tribute both to the ubiquity of man's modification of environmental conditions and his efficiency as an agent of dispersal."

Godinho (1984) compared the definitions of the French words *d'aventice* and *le mauvaise herbe* with the English *weed* and the German *unkraut*. No single definition was found for *weed* and *unkraut* because both words have two distinct meanings:

1. In the ecological context, *weed, unkraut*, and *d'aventice* mean a plant that grows spontaneously in an environment that has been modified by man.
2. In the weed science context, *weed, unkraut*, and *malherbe* (Italian) or *le mauvaise herbe* mean an unwanted plant.

In some languages weeds are just bad (*mal*) plants. In Spanish, it is *mala hierba* or *malezas*, and in Italian, *malherbe*. One must agree with Godinho (1984), Fryer and Makepeace (1977), Anderson, (1977), and Crafts and Robbins (1967) that neither the word *weed* nor the plants to which the word is assigned are easy to define.

Aldo Leopold (1943, as cited in Falder and Callicott, 1991) made the point well in an article written in 1943 that was critical of the 1926 bulletin *Weeds of Iowa*. Many of the native plants of Iowa are included in the bulletin, and Leopold noted that these plants, in addition to their inherent beauty, have value as wildlife food, for nitrogen fixation, or as makers of stable plant communities. He admits that many of the plants people consider weeds are common in pastures, but soil depletion, overgrazing, and needless disturbance of advanced successional stages often make control necessary. Leopold (1943) argues that the definition of *weed* is part of the problem because not all plants that some call weeds "should be blacklisted for general persecution." Leopold's view is supported by McMichael (2000), who noted, with supporting evidence, that "in many rural cultures, noncrop plants (often termed weeds) represent food, fodder, and medicine.

About 3,000 of the 350,000+ recognized plant species have been or are cultivated, and one cannot assume that the rest are weeds. Specific, unknown, and noncultivated plants must also be considered.

The ulterior etymology of the word *weed* is unknown, but an exposition of what is known was provided by King (1966). He traced the word to a Germanic romance language and Asian roots, but he concluded that *weed* is an "example of language as an accident of usage." He was unable to find a common word in any ancient language for the collective term *weed*.

It is logical to assume that even if one cannot define *weed*, it should still be possible to identify the origin of individual species and determine certain characteristics of weeds. They come from both native and naturalized flora. Some plants succeeded as weeds because they were able to evolve forms adapted to disturbed environments more readily than other species. Baker's (1965, 1991) definition emphasizes success in disturbed environments, a point he reiterated in the later paper:

> A plant is a "weed" if, in any specified geographical area, its populations grow entirely or predominantly in situations markedly disturbed by man (without, of course, being deliberately cultivated plants). Thus, for me, weeds include plants which are called *agrestals* by some writers of floras (they enter agricultural land) as well as those which are *ruderals* (and occur in waste places as well as along roadsides). It does not seem to me necessary to draw a line between these categories and accept only the agrestals as weeds (although this is advocated by some agriculturally oriented biologists) because in many cases the same species occupy both kinds of habitat. Ruderals and agrestals are faced with many similar ecological factors, and the taxa which show these distributions are, in my usage, "weedy."

If one considers weeds in the Darwinian sense of a struggle for existence, they represent one of the most successful groups of plants that have evolved simultaneously with human disruption of areas of indigenous vegetation and habitats and creation of disturbed habitats (King, 1966).

Aldrich (1984) and Aldrich and Kremer (1997, p. 8) offered a definition that does not deny the validity of others but introduces a desirable ecological base. A weed is "a plant that originated in a natural environment and, in response to imposed or natural environments, evolved, and continues to do so, as an interfering associate with our crops and activities." This definition provides "both an origin and continuing change perspective" (Aldrich, 1984). Aldrich wants us to recognize weeds as part of a "dynamic, not static, ecosystem." His definition departs from those that regard weeds as enemies to be controlled. Its ecological base defines weeds as plants with particular, perhaps unique, adaptations that enable them to survive and prosper in disturbed environments. Navas (1991) also included biological and ecological aspects of plants and effects on man in his definition. A weed was defined as "a plant that forms populations that are able to enter habitats cultivated, markedly disturbed or occupied by man, and potentially depress or displace the resident plant populations which are deliberately cultivated or are of ecological and/or aesthetic interest."

Although all do not agree on precisely what a weed is, most know they are not desirable. Those who want to control weeds must consider their definition. When the term *weed* is borrowed from agriculture and applied to plants in natural communities, a verification of negative effect on the natural community should be a minimal expectation. Simple yield affects are not acceptable, but the effects of the presumed weed in a natural community can be estimated in terms of a management goal such as establishment of presettlement conditions, preserving rare species, maximizing species diversity, or maintaining patch dynamics (Luken and Thieret, 1996). Many recognize the human role in creating the negative, often deserved, image. Weeds are detrimental and often must be controlled but only with adequate justification for the site and conditions.

II. CHARACTERISTICS OF WEEDS

Crop agriculture is based on a very few plants that thrive in a disturbed habitat (a cropped field) and produce an abundance of seed. Weeds also thrive in disturbed habitats and produce an abundance of seed that is not useful to humans (Manning, 2004, p. 55). Why is it that some plants that thrive in disturbed habitats are weeds? What is it that makes some plants capable of growing where they are not desired? Why are they difficult to control? What are their modes of interference and survival? The most consistent trait of weedy species is not related to their morphology or taxonomic relationships. It is, as Baker (1965) noted, their ability to grow well in habitats disturbed by human activity. They are plants that are growing where someone does not want them, and often that is in areas that have been disturbed or altered intentionally. Weeds grow especially well in gardens, cropped fields, golf courses, and similar places. Their ability to grow in habitats that have been disturbed by man makes them a kind of ecological Red Cross: They rush right into disturbed places to restore the land.

Two nonindigenous species, kudzu and purple loosestrife, illustrate the ability of weeds to spread to new areas and habitats. (See Chapter 7 for a discussion of the role of these plants as invasive species.) Both were introduced to the United States, and both now grow all over the country (see Figure 2.1; U.S. Congress, 1993).

Not all weeds possess every single characteristic that is considered undesirable, but in addition to growing in disturbed habitats, all have at least some of the following characteristics (see Baker, 1965):

1. Weeds have rapid seedling growth and the ability to reproduce when young. Redroot pigweed can flower and produce seed when less than 8 inches tall. Crops cannot do either.
2. Quick maturation or only a short time in the vegetative stage. Canada thistle can produce mature seed two weeks after flowering. Russian thistle seeds can germinate very quickly between 28° and 110°F in late spring (Young, 1991). It would spread more, but the seed must germinate in loose soil because the coiled root unwinds as it pushes into soil and is unable to do so in hard soil.

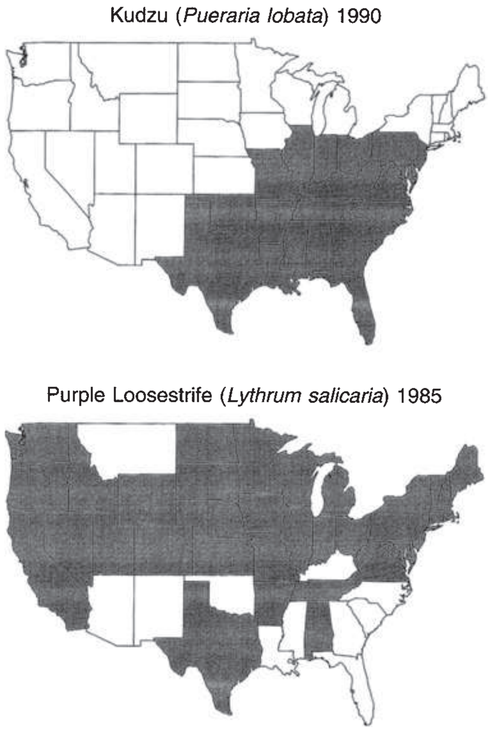

FIGURE 2.1. US distribution of kudzu and purple loosestrife (U.S. Congress, 1993; Thompson et al., 1987; also see Anonymous, 1990).

3. Dual modes of reproduction. Most weeds are angiosperms and reproduce by seed. Many also reproduce vegetatively (e.g., Canada thistle, field bindweed, leafy spurge, quackgrass).
4. Environmental plasticity. Many weeds are capable of tolerating and growing under a wide range of climatic and edaphic conditions.
5. Weeds are often self-compatible, but self-pollination is not obligatory.
6. If a weed is cross-pollinated, pollination is accomplished by nonspecialized flower visitors or by wind.
7. Weeds resist detrimental environmental factors. Most crop seeds rot if they do not germinate shortly after planting. Weed seeds resist decay for long periods in soil and remain dormant.
8. Weed seeds exhibit several kinds of dormancy or dispersal in time to escape the rigors of the environment and germinate when conditions are most favorable for survival. Many weeds have no special environmental requirements for germination.

9. Weeds often produce seed that is the same size and shape as crop seed, making physical separation difficult and facilitating spread by man.
10. Some annual weeds produce more than one seed crop per year, and seed is produced as long as growing conditions permit.
11. Each generation is capable of producing large numbers of seed per plant, and some seed is produced over a wide range of environmental conditions.
12. Many weeds have specially adapted long- and short-range seed dispersal mechanisms.
13. Roots of some weeds are able to penetrate and emerge from deep in the soil. While most roots are in the top foot of soil, Canada thistle roots routinely penetrate 3 to 6 feet and field bindweed roots have been recorded over 10 feet deep. Roots and rhizomes are capable of growing many feet per year.
14. Roots and other vegetative organs of perennials are vigorous with large food reserves, enabling them to withstand environmental stress and intensive cultivation.
15. Perennials have brittleness in lower stem nodes or in rhizomes and roots, and, if severed, vegetative organs will quickly regenerate a whole plant.
16. Many weeds have adaptations that repel grazing, such as spines, taste, or odor.
17. Weeds have great competitive ability for nutrients, light, and water and can compete by special means (e.g., rosette formation, climbing, allelopathy).
18. Weeds are ubiquitous. They exist everywhere that we practice agriculture.
19. Weeds resist control, including resistance to herbicides.

In spite of the anthropomorphic aspects of the definitions of weed and the multiple traits that weeds share, weed scientists have a clear idea of which plants are weeds. It seems that weeds are everywhere in almost every place, and many books have been written about weeds:

Common weed seedlings of the Central High Plains (Nissen and Kazarian, 2000)

Major Weeds of the Philippines (Moody et al., 1984)

Major Weeds of Thailand (Noda et al., 1985)

Striga *Identification and Control Handbook* (Ramaiah et al., 1983)

The Arable Weeds of Europe—with their Seedlings and Seeds (Hanf, 1983)

The Identification of Weed Seedlings of Farm and Garden (Chancellor, 1966)

Weeds of Colorado, A Comprehensive Guide to Identification (Zimdahl, 1998)

Weeds of Hawaii's Pastures and Natural Areas (Motooka et al., 2003)

Weeds of Karnataka (Krishna Sastry et al., 1980)
Weeds of Nebraska and the Great Plains (Stubbendieck et al., 1994)
Weeds of North India (Arora et al., 1976)
Weeds of Rice in Asia (Caton et al., 2004)
Weeds of the West (Whitson et al., 1991)

The Weed Science Society of America has published a weed identification CD that includes an interactive format for identification of 1,000 weeds of North America (https://timssnet.allenpress.com/ECOMWSSA/timssnet/products/tnt_products.cfm), click on identification, photo gallery.

III. HARMFUL ASPECTS OF WEEDS

Definitions of weeds usually include trouble with crops, harm to people, or harm to animals. Most people do not consider plants to be bad. They are assigned the descriptive, derogatory term weed because of something they do to us or to our environment; they interfere with the activities or welfare of man. If they were benign we wouldn't be so concerned about them because there would be no detrimental effects. The nature of weeds' harmful effects will be explored briefly in this section. That harmful effects exist is not questioned. It is important to understand specific effects so appropriate action can be taken.

A. Plant Competition

From an agricultural perspective, we are concerned about weeds because they compete with crop plants for nutrients, water, and light. If they did not, those who grow things would be more willing to tolerate their presence. Weed-crop competition will be discussed in Chapter 6. If weeds did not compete, they would not need to be managed because crop yield would not be affected by their presence. But it is, and often complete crop failure (100% loss of marketable yield) can occur if weeds are not controlled.

B. Added Protection Costs

Weeds increase protection costs because they harbor other pests. A partial listing of diseases, insects, and nematodes that use weeds as alternate hosts is in Tables 2.1, 2.2, and 2.3. Weeds harbor a wide range of organisms thereby increasing opportunities for those organisms to persist in the environment and reinfest crops in succeeding years.

TABLE 2.1. **Plant Diseases Harbored by Specific Weeds.**

Plant disease	Weed host	Crop infested	Reference
Blackleg	Black nightshade Common Lambs quarters Mare's tail Redroot pigweed Smartweed	Potato	Dallyn and Sweet, 1970
Wilt diseases	Netseed lambs quarters Common purslane Redroot pigweed	Potato, alfalfa	Oshima et al., 1963
Stem canker	Netseed Lambs quarters	Potato, beans	Oshima et al., 1963
Soft rot	Annual sowthistle Dayflower Common Lambs quarters	Chinese cabbage and other vegetables	Kikumoto and Sakamoto, 1969
Powdery mildew	Wild oats	Wheat, oats, barley	Eshed and Wahl, 1975
Stripe mosaic virus	Common Lambs quarters	Barley	ARS, 1966
Leaf curl virus	Common Lambs quarters	Sugarbeet	ARS, 1966
Cucumber mosaic virus	Black nightshade	Several	ARS, 1966
Potato virus X and leaf roll virus	Redroot pigweed	Potato	ARS, 1966
Maize dwarf mosaic virus	Johnsongrass	Corn	Bendixen et al., 1979
Maize chlorotic dwarf virus			
White rust Early blight Leaf spot Vascular wilts Cottony rot White mold Watery rot	Redroot pigweed	Potato, tomato, annual vegetables and flowers, beans, cabbage, carrot, peanut	Commers, 1967
Leaf spot and Leaf blight Stalk rot Vascular wilt Damping off Soft rot	Tall morning glory	Sugarbeet, celery, peas, peanut, corn, tobacco, beans, fruits and vegetables	Commers, 1967
Stem rust Leaf spot and Leaf blight	Cocklebur	Wheat, barley, rye, celery, beets, tomato, soybeans	Commers, 1967
White rust Banana Leaf spot Takeall Stem rust Rusts	Canada thistle	Crucifers, banana, wheat, rye, barley, legumes, beans, peas, fava bean	Commers, 1967

TABLE 2.2. Insects Harbored by Specific Weeds.

Insect	Vector of	Weed host	Crop infested	Reference
Cabbage maggot	Blackleg	Common lambsquarters	Potato	Bonde, 1939
Seed				
Corn				
Colorado potato beetle		Black nightshade Buffalobur	Potato	Brues, 1947
Beet leaf hopper Corn borer	Curly top	Russian thistle	Sugarbeet	Brues, 1947

TABLE 2.3. Nematodes Harbored by Specific Weeds.

Nematode	Weed host	Crop infested	Reference
Criconemoides onoensis	Nutsedges, Junglerice	Rice	Hollis, 1972
Ditylenchus dipsaci	9 weeds from 7 genera	Soybeans, snapbeans, peas	Edwards and Taylor, 1964
Heterodera glycines	Bittercress Common foxglove Common pokeweed Oldfield toadflax Purslane Rocky Mountain beeplant Spotted geranium	Soybeans	Riggs and Hamblen, 1966
Heterodera marioni	47 weeds from 42 genera	Pineapple	Godfrey, 1935
Heterodera schachtii	Black nightshade Lamb's quarters Mustards Purslane Redroot pigweed Saltbush	Sugarbeet	Anderson, 1977
Hoplolaimus columbus	Henbit Johnsongrass Purple nutsedge Yellow nutsedge	Soybeans, cotton	Bendixen et al., 1979 Bird and Högger, 1973 Högger and Bird, 1974
Meloidogyne incognita	Chickweed Johnsongrass Purple nutsedge Yellow nutsedge	Soybeans, cotton	Bird and Högger, 1973 Högger and Bird, 1974
Pratylenchus sp.	Johnsongrass	Corn	Bendixen et al., 1979
Trichodorus spp.	19 weeds from 18 genera	Potato	Cooper and Harrison, 1973

Weeds that exist on the edges of crop fields serve as hosts when crops are not present and as sources of reinfestation. Volunteer wheat is a primary host of wheat streak mosaic virus. Its presence can be seen in disease transmission up to one-quarter mile from a stand of volunteer wheat. A virus carried by wheat curl mite (*Aceria tulipae*) causes the disease, and volunteer wheat must be controlled three weeks before planting to eliminate the mites and prevent crop infection. This is a complex management problem in which a disease, an insect, and a weed host interact. Another illustration is spread of potato blackleg disease (*Erwinia carotovora* var. *atroseptica*) and potato soft rot (*Erwinia carotovora* var. *carotovora*) by *Erwinia* bacteria via enduring infestations of common lambsquarters, redroot pigweed, or black nightshade that harbor the disease organisms (Cooper and Harrison, 1973).

In addition to direct attack on crops, insects are a primary means of dispersal for many pathogenic organisms. Aster yellows virus is carried by the leafhopper *Macrosteles fasifrons* from lettuce to broadleaf plantain after lettuce emerges and during lettuce harvest. Several aphids carry pepper veinbanding mosaic virus and potato virus Y from weeds to crops (Broadbent, 1967). Fungal spores such as the conidia of *Claviceps purpurea* (the cause of ergot in rye) are transported by fungal gnats. The insects are attracted to sticky substances secreted by wounds. The fungal disease caused by the spores infects a wide range of grasses, including wild species. Piemiesel (1954) found that leafhoppers and curly top virus of sugarbeets used weeds as breeding grounds to increase inoculum density for later crop infection.

A classic case of a weed serving as a host for a pathogen is the heteroecious stem rust fungus (*Puccinia graminis* var. *tritici*) of wheat which uses European barberry as an alternate host. King (1966) estimated that wheat yield losses from this fungal disease were over 600 million bushels per year in the early 1960s.

Over 20 years, from the 1970s to the 1990s, wheat rust has caused $100 million in crop losses annually. Eradication of European barberry and related species dramatically reduced stem rust and consequent epidemics. Several US states joined in an effort that was estimated to have saved farmers well over $30 million per year (Stakman and Harrar, 1957).

Russian thistle (Table 2.2) is an alternate host for the curly top virus of sugarbeets and tomatoes (Young, 1991) and the beet leafhopper (*Circulifer tenellus*) (Goeden, 1968). Goeden (1968) points out that hosting a potentially damaging insect may not be a sufficient reason to control a weed. Russian thistle hosts 32 economically important insects from five different orders. These are not all harmful because some may be entomophagous enemies of harmful insects, both of which are hosted by Russian thistle.

Crested wheatgrass is widely planted in the western United States for soil conservation. It and other species of *Agropyron* harbor the Russian wheat aphid

(*Diuraphis woxia*), an important wheat pest (U.S. Congress, 1993). Johnsongrass, a major weed in the southern United States, can hybridize with cultivated sorghum to produce the annual weed shattercane. Thus, a weed produces another weed (Mack, 1991).

C. Reduced Quality of Farm Products

Most grain growers are familiar with weed seed in grain crops and resultant decreases in quality and losses from dockage and cleaning. Weed seed in grain crops perpetuate the problem when the crop seed is replanted. A particularly bad problem is wild onion or wild garlic in wheat. Seeds and aerial bulblets of these weeds are similar in size to wheat grains and difficult to separate. They impart an onion flavor to flour made from grain and an onion odor to milk after cows have grazed them or eaten feed containing them.

Wild oats affect the quality of bread and other wheat products and infest many acres of small grains, most notably spring wheat. Wild oats also infest barley used for feed and for malting, and any brewer will verify that wild oats make bad beer.

Weeds reduce the quality of seed crops. Purchasers of hybrid or certified seed expect to receive a high-quality product that will give high yields and not be infested with weed seed. This necessitates weed control in seed crops, and failures lead to high cleaning costs before sale.

Weeds cause loss of forage and reduce the carrying capacity of pastures and rangeland. Surveys in the 1990s by the Nebraska Department of Agriculture showed over 2 million acres infested with musk thistle and over 400,000 with leafy spurge. Rangeland and pasture were the dominant sites, and carrying capacity (number of animals supported by the land) was reduced 8 to 100% by musk thistle and 10 to 70% by leafy spurge.

D. Reduced Quality of Animals

Many acres of western US rangeland are infested with poisonous larkspur that causes cattle death because cattle like it and often eat it selectively. In early growth stages as little as 0.5% of an animal's weight ingested as larkspur can, within an hour, lead to toxicity, and 0.7% may be fatal (Kingsbury, 1964). Locoweeds and crazyweeds are important poisonous range weeds. All ruminants are susceptible to loco poisoning but only when large amounts are consumed over weeks or even months. Horses are also poisoned, and symptoms appear at lower levels of intake for shorter periods of time than is true for ruminants (Kingsbury, 1964).

Halogeton grows on arid, alkaline soils and is found in many parts of the world, including the western United States. It is especially toxic to sheep due to its high oxalate content. Photosensitization or excessive sensitivity to light by cattle can be caused or aggravated by St. Johnswort and Mock bishopsweed (Anonymous, 1977).

Weed science usually emphasizes the negative effects of weeds on animals grown for profit and human food, but game animals are also affected by weeds. In western Montana, elks' use of rangeland decreased as spotted knapweed increased. On native bunchgrass sites, 1,575 pellet groups were found on each acre. On sites infested with spotted knapweed, there were only 35 pellet groups per acre (Hakim, 1975).

Poisonous plants may contain one or more of hundreds of toxins from nearly 20 major chemical groups, including alkaloids, glucosides, saponins, resinoids, oxalates, and nitrates (Kingsbury, 1964). There is no way to determine if a plant may be poisonous by noting where it grows, when it grows, or how it changes during growth.

Because poisonous plants can occur in many habitats, one must learn to recognize the important ones in each area. There are no good antidotes after ingestion of poisonous plants by humans or animals. Signs of poisoning differ in intensity, depending on the species, its stage of growth, when it is eaten, the soil the plant grew in, the amount of other food eaten with or before the poisonous plant, and each individual's tolerance. Once they have been identified, poisonous weeds can be managed. A few of the common poisonous weeds found in the United States, their toxic principle, the plant source, and some clinical signs of poisoning are shown in Table 2.4.

Weeds can affect animals by providing an inadequate diet or a diet that is unpalatable because of chemical compounds in the weed. They can directly reduce the quality of animal products by affecting milk production and fleece, or hide quality. Reproductive performance is affected through toxins that cause abortion or kill animals (see Table 2.4).

In addition to direct poisoning, weeds cause mechanical damage to grazing animals. Sharp spines on seed-bearing burs of puncture vine and sandbur are strong enough to penetrate tires and shoe-leather. Anyone who has ever stepped on a seed bur in bare feet can appreciate the pain and damage it can cause to tender mouth tissues. Seed burs of these weeds and those of common cocklebur and burdock also become entangled in the sheep's wool, decreasing cleanliness and saleability.

It is well known that many plants are poisonous to mammals. What is more interesting is that green plants dominate the terrestrial landscape. There are numerous insect and herbivore species that feed on plants, and it is interesting that the plants somehow still dominate the landscape. As this section notes, weeds can and do reduce the quality of animals through their toxic principles,

TABLE 2.4. Characteristics of Some Poisonous Weeds (Evers and Link 1972; Kingsbury 1964).

Name	Toxic principle	Source	Signs
Arrowgrass	Hydrocyanic acid	Leaves	Nervousness, trembling, spasms or convulsions
Bouncing bet	Saponin	Whole plant seeds are most toxic	Nausea, vomiting, rapid pulse, dizziness
Bracken fern	Unknown	Fronds	Fever, difficulty in breathing, salivation, congestion
Buffalobur	Solanin	Foliae and green berries	Most serious in nonruminants
Buttercup	Proto-anemonin	Green shoots	Loss of condition, production drops, reddish milk, diarrhea, nervousness, twitching, labored breathing
Chokecherry and other cherries	Glucoside-amygdalin, a cyanogenic compound	Leaves	Rapid breathing, muscle spasms, staggering, convulsions, coma
Cocklebur	Hydroquinone	Seeds and seedlings	Nausea, depression, weakness, especially in swine
Corn cockle	A glucoside githagin and a saponin	Seeds	Poultry and pigs are most affected, inability to stand, rapid breathing, coma
Horsetail	Thiaminase activity—an alkaloid	Shoots	Loss of condition, excitability, staggering, rapid pulse, difficult breathing, emaciation
Indian tobacco	Alkaloids similar to nicotine	Leaves and stems	Ulcers in mouth, salivation, nausea, vomiting, nasal discharge, coma
Jimsonweed	Alkaloids	All parts	Rapid pulse and breathing, coma
Larkspur	Alkaloid	All parts	Staggering, nausea, salivation, quivering, respiratory paralysis
Nightshade	Solanine—a glycoalkaloid	Foliage and green berries	Usually in sheep, goats, calves, pigs, and poultry, anorexia, nausea, vomiting, abdominal pain, diarrhea
Ohio buckeye	Alkaloid	Sprouts, leaves, nuts	Uneasy or staggering gait, weakness, trembling
Water hemlock	Cicutoxin	Young leaves and roots	Convulsions
Whorled milkweed	A resinoid—galitoxin	Shoots, especially near top	Poor equilibrium, muscle tremors, depression and then nervousness, slobbering, mild convulsions

but it is worthy of note that the toxic principles also protect plants from severe predation by insects and herbivores. Plants that are relatively harmless to humans and other mammals may be and often are highly toxic to other animals, birds, fish, and especially to insects (Harborne, 1988). These defensive toxicities of weeds and other plants are important determinants of ecological relationships. The harm that may be caused is trivial to humans and our animals but vital to ecological stability, which explains why plants dominate the terrestrial landscape.

E. Increased Production and Processing Costs

We are concerned about weeds because they do things to us or our products and increase production costs. Any weed-control operation, from hand hoeing to herbicide application, costs money. These costs are often necessary to prevent greater crop loss or even crop failure and are regarded as necessary to gain a profit. However, if the weeds weren't there, there would be no control cost. Unfortunately, the complete absence of weeds is rare, and the costs of their competition and control must be included when calculating profit or loss. Costs of control are relatively easy to calculate if hourly labor, equipment, fuel, and herbicide costs are known. It has been estimated that the cost of tilling cultivated land may equal as much as 15% of a crop's value. While tillage may be required on some soils for crop production, most is done only for weed control. There are sound agronomic reasons for tillage, including seedbed preparation, trash burial, soil aeration, promotion of water infiltration, and, of course, weed control. The ascendancy of minimum and no-tillage farming and availability of appropriate herbicides have brought many traditional tillage practices into question. Prior to herbicides, an experiment to investigate effects of tillage was always confounded by weeds and the need to control them by tillage. Experiments with herbicides in many soils have shown little benefit from tillage other than weed control.

There are other, less-obvious costs associated with weeds. Wild oats seed in wheat or barley, or black nightshade fruit in beans, leads to increased costs due to the necessity of cleaning. Failure to remove these can lead to loss in quality, dockage losses at the point of sale, or even loss of the crop if it should heat and spoil in storage because of unripened weed seed. If a harvested crop has large amounts of weed seed in it, one can assume that some of the crop was lost in the field from weed competition and that some additional quality was lost due to weeds at harvest and consequent harvest difficulty. Another cost of weeds at harvest is wear and tear on machinery. The extra bulk of weedy plants that pass through mechanical harvesting systems is bound to

TABLE 2.5. Soybean Harvest Losses from Two Weeds (Nave and Wax, 1971).

	LOSS (%)		
Weed	Header	Threshing and separating	TOTAL
Redroot pigweed	5.35	.73	6.08
Giant foxtail	1.55	.81	2.36

cause machinery to break down more frequently and wear out sooner. These kinds of things are not usually attributed to weeds because they are not recognized as contributors to increased costs of machinery breakdown, repair, and replacement. Weeds also cost money when they remain in the field and interfere with harvest (see Table 2.5).

F. Water Management

Weeds interfere with water management in irrigated agriculture. Water is consumed and flow is impeded by weeds growing in and along irrigation ditches. Weeds consume water intended for crops, cause water loss by seepage via root channels, transpire water, and reduce water flow in irrigation ditches, leading to increased consumption by weeds and more evaporative water loss. Aquatic weeds may impede navigation and can ruin fisheries.

Terrestrial criteria for assessing weed competition cannot be employed in aquatic environments. There are no known appraisals of direct crop losses due to aquatic weeds. However, Timmons (1960) reported nearly five decades ago, that manmade lakes above dams across major rivers in Africa, Asia, and Central and South America became so badly infested with weeds within 5 to 10 years of construction that their usefulness for power development, boat transport, and irrigation was greatly reduced, and, therefore, one must conclude that national development was impeded by weeds. Aquatic weeds quickly reduced designed flow of some irrigation canals in India by 40% to 50% and in others up to 80% (Gupta, 1973). Submerged weeds retard water flow up to 20 times, whereas floating weeds only retard it 2 times (Gupta, 1976). Decreased flow reduced the possibility of irrigating distant fields and accelerated opportunities for leakage and evaporation. In addition to agricultural concerns, those who use water for recreation or enjoy the aesthetic appeal of aquatic habitats are often disturbed by weeds. Aquatic weeds are often ugly, and their rotting remains are smelly, but the more important problem is that their presence and inevitable decay hasten eutrophication. There is more public concern about aquatic weeds in recreational waters than in agricultural waterways.

G. Human Health

Those not associated with agriculture may often think of weeds, if they think of them at all, as plants that impair human health. One who has never experienced the runny nose, sneezing, and watery eyes of plant allergies (often called hay fever) cannot fully appreciate the animosity sufferers may develop toward plants. The pollen that causes hay fever often (but not always) comes from weedy plants. Ragweed and goldenrod are common causes in many parts of the United States. Sagebrush is a leading cause in the western United States. While allergies may be an obvious weed menace to some people, others would choose poison ivy as the worst weed. Swelling and itching after contact with poison ivy are always bothersome and can lead to serious discomfort. The rash can be caused by contact with any portion of live plants or with smoke from fire in which plants are burned. Most people are quick to put poison ivy or poison oak in the category of unwanted plants after one or the other has disturbed their picnic or camping trip.

Many plants that poison when consumed are common garden plants that can be especially hazardous to children. Some weedy species can lead to aberrant behavior or death when consumed by people. Examples of household plants that are poisonous when consumed include narcissus, oleander, lily-of-the-valley, and iris.

Dead and dry weeds can be serious fire hazards, as anyone in the arid western United States knows. Fires spread rapidly in dry plants. Fire prevention is why weeds are controlled on roadsides, in vacant areas, and around homes in forested areas.

H. Decreased Land Value and Reduced Crop Choice

Perennial weeds (field bindweed, johnsongrass, or quackgrass) or the annual parasitic weeds dodder, witchweed, or broomrape can lead purchasers to discount offers to buy or bankers to reduce the amount of a loan because each recognizes a loss of productive potential. They also recognize the costs required to restore otherwise valuable land to full productivity. These weeds reduce land value and sale price because they restrict crop choice and increase the costs of crop production. Severe infestations of almost any perennial or parasitic weed will reduce yield of most crops, and dodder may completely eliminate successful growth of some crops.

I. Aesthetic Value

Weeds in recreation areas often must be controlled. No one wants their soccer field or baseball diamond to be weedy. Weeds are fire hazards around power substations and equipment, oil, or chemical storage areas. A very practical need for weed control exists near traffic intersections, where, in addition to being aesthetically unappealing, weeds reduce visibility and may contribute to vehicular accidents. Weeds can have serious environmental/ecological effects when they replace native vegetation (see Chapter 7 for a discussion of invasive species).

IV. COST OF WEEDS

There are no completely accurate estimates of the total cost of weed control and losses in agriculture due to weed competition, although several attempts have been made. One of the first estimates is reported in the 1969 United Nations Food and Agriculture Organization (FAO) International Conference on Weed Control. For example, US losses due to weeds in potatoes were estimated to be $65,000,000 in 1969 (Dallyn and Sweet, 1970).

In 1967, weeds caused an estimated 8% loss of potential US agricultural production (Irving, 1967). In 1967, Cramer summarized losses attributed to pests of all kinds in the world's major crops. He calculated that 9.7% of potential world crop yield was lost due to weeds. Parker and Fryer (1975) used Cramer's data and calculated that weeds eliminated 14.6% of the world's potential crop production. They estimated that weeds eliminated 11.5% of world crop production in 1975 (Table 2.6). A comparison made in 1980 (Ahrens et al., 1981) for wheat and rice shows losses were still about 10%, despite developments in control. Combellack (1989) estimated the total cost of Australian weeds to be $2 billion in 1986, of which $137 million was for herbicides.

An estimate of crop yield losses from weeds in Canada in 1935 was $69 million (Hopkins, 1938). In 1949, the cost had risen 2.7 times to $186.2 million (McRostie, 1949), and it rose to $255 million in western Canada alone (Wood, 1955). By 1956 the total loss was estimated to be $468.6 million, a 150% increase over 1949 (Anderson, 1956).

Friesen and Shebeski (1960) estimated the annual loss due to weeds in Manitoba grain fields was $32.3 million in 1959. Renney and Bates (1971) estimated losses due to weeds in British Columbia were $72 to $78 million per year in 1969. Their study showed that 38 to 42% of weed-caused yield losses in British Columbia were due to yield reduction of agricultural crops,

TABLE 2.6. Estimated Food Losses Caused by Weeds in Three Classes of Crop Production.

Class of crop production	Total cultivated area (%)	Relative production per unit area (%)	Total food production (%)	Loss to weeds (%)	Loss as of world food supply (%)	Estimated food loss per year (metric tons × million)
A. Most highly developed	20	×1.5	30	5	1.5	37.5
B. Intermediate	50	×1.0	50	10	5.0	125.0
C. Least developed	30	×0.67	20	25	5.0	125.0
Total	100		100		11.5	287.5

Note: Estimates in this table are not based on any firm statistical data but are approximations suggested by the authors. Where food loss is estimated in terms of metric tons, this is based on an approximate world total food production of 2,500,000,000 metric tons per year (Parker and Fryer, 1975).

TABLE 2.7. Estimated Average Annual Losses Due to Weeds in Several Commodity Groups (Chandler et al., 1984).

Commodity group	United States	Western Canada	Eastern Canada
		Average Annual Loss ($ × 1,000)	
Field crops	6,408,183	616,331	69,647
Vegetables	619,072	20,972	29,956
Fruits and nuts	441,449	8,418	—
Forage seed crops	37,400	75,661	—
Hay	—	—	89,507
TOTAL	7,506,104	722,634	189,110

increased insect and disease problems, dockage, harvest losses, and costs of control. If forest weeds were included, losses in yield and costs of control accounted for an additional 45 to 49% of total loss. By 1984, Canadian losses were estimated to be $911.7 million per year (722.6 + 189.1; see Table 2.7) in 36 crops, nearly double what they had been in 1956.

A US soybean loss survey (Anonymous, 1971) found weed competition caused an estimated 3.3 bu/A yield reduction in 28 states. Weeds were responsible for a 12% crop loss each year. Chandler (1974) summarized other estimates and concluded that weed competition in some southern US states caused as much as 20% soybean yield loss. For the entire country, 5% was regarded as an optimistically low level of loss, except on perhaps half of the most intensively farmed acreage.

Peanut farmers in the southeastern United States spend about $50 per acre for weed control. Annual losses from weeds were estimated to be $20,000,000 in Alabama, $8,000,000 in Florida, and $72,000,000 in Georgia in 1991 (Dowler, 1992). There are good herbicide choices for peanut weed control, so the reasons for the large losses are of concern to farmers and weed scientists.

A US Department of Agriculture report for the 1950s (Agric. Res. Serv., 1965) estimated annual losses due to reduced crop yield and quality and costs of weed control in the United States were $5.1 billion. This value, an educated guess, became enshrined in early weed science textbooks. While the estimate was never proven wrong, changes in the value of crops and inputs, as well as methods employed to arrive at such figures, have increased the loss due to weeds. In 1954, it was estimated that weeds caused an annual loss >$2 billion in 11 major US agronomic crops (Anonymous, 1962).

In the 1970s, poisonous plants alone may have caused a $118 million loss to livestock producers in the Great Plains area of the United States (Deloach, 1976). Shaw (1976) estimated that weeds caused a loss of 10% of the value of food, feed, and fiber crops and ornamental plantings. The total annual loss was >$6 billion. He also projected that $2.7 billion was spent for cultural, ecological, and biological control and another $2.3 billion for chemical control. The total cost of weeds was estimated to be $11 billion per year. In 1980, Shaw (1982) raised the estimated total annual loss to $18.2 billion, with $12 billion due to competitive loss, $3.6 billion for chemical control, and $2.6 for other controls.

From 1975 to 1979, the competitive loss due to weeds in US agriculture for 64 crops was estimated to be $7.5 billion per year (see Table 2.7; Chandler et al., 1984). In a separate publication, Chandler (1985) estimated total losses of $14.1 billion, with $8 billion due to weed competition, $2.1 billion to herbicide cost, and $4 billion for equipment and labor.

Bridges (1992) estimated the cost of weeds in the United States from 1989 to 1991. The report covered all US states, except Alaska, and 46 crops, including field crops, vegetables, fruits, and nuts. Research or extension weed scientists from each state estimated the percent yield loss from weeds competing in crops where the current best-management practices were employed. The same scientists also estimated losses with best-management practices without herbicides. The loss was $4.2 billion annually, just in field, nut, and fruit crops, with best-management strategies, and 82% of the total was lost in field crops. Without herbicides the loss rose to $19.6 billion. Total losses with best-management practices were $6.2 billion, and costs of control were above $9 billion, for a total loss of $15.2 billion per year.

By any measure, this is a large amount of money and significantly greater than the 1984 estimate. Pimentel et al., (2000) estimated that at least $5 billion is spent annually in the United States to control nonindigenous weeds introduced to the United States that are in pastures, and another $1.5 billion is spent just on lawns, gardens, and golf courses. Control costs for nonindigenous weeds in crops were estimated to be $3 billion, and weeds caused an additional $23.4 billion in crop losses (yield not obtained) and damage to crops. While the paper (Pimentel et al., 2000) specifically addresses nonindigenous weeds, the results can be applied to weeds in general because so many are nonindigenous. All estimates (by definition) are not absolutely accurate, but they are the best information available. Because they are estimates (educated guesses) rather than quantitative experimental data, they cannot be regarded as absolutely true.

Regional or more local estimates are often more accurate but extrapolation to other areas, while tempting, is often unwarranted. For example, leafy spurge now occupies more than 150 million acres of rangeland in the northern US Great Plains. Direct livestock production losses and indirect economic effects approached $110 million in 1990 (Bangsund and Leistritz, 1991). In North Dakota, losses of income by cattle producers due to leafy spurge were $8.7 million, and the producers reduced personal spending $14.4 million. That translates to reduced income for merchants who sell to cattlemen.

In 1990 leafy spurge reduced cattle-carrying capacity about 580,000 animal unit months, or by 63,100 cows over a 7.5-month grazing season. The total annual direct grazing land losses were $23.1 million. Indirect grazing land losses were $52.2 million, and wildland losses were $2.9 million. A 40% leafy spurge infestation reduced rangeland-carrying capacity by 50%, and leafy spurge can reduce carrying capacity 75%. Due only to leafy spurge, North Dakota lost $87.3 million and 1,000 jobs in 1980 (Leistritz et al., 1992).

World literature concerning domestic and international food production leaves no doubt that weeds cost money—*lots* of money! They are ubiquitous, and their effects on yield create large losses borne by producers and by consumers because production costs are inevitably reflected in food price. Present globalization trends and lack of a world or country database for each crop make it unproductive to attempt more accurate estimates of world, country, region, or crop losses due to weeds, even though present estimates lack precision.

Weed costs are calculated in dollars associated with commodities. There are other ways to estimate costs and associated benefits of weed management. One is to examine the number of acres of crops treated for weed control. This estimates the value of weed-management to farmers and is an accurate estimate of the extent of market penetration by herbicides (Table 2.8). These data do not estimate the use of other weed management techniques. Table 2.9 shows losses due to weeds by comparing weeded and unweeded crops in the Philippines and other Asian countries (Mercado, 1979) and more recent information (Baltazar, 2006) confirms the scale, if not the actual cost, of the 1979 estimates. The percent increase in yield due to weeding is an impressive statement about the value of weeding, regardless of the technique by which it is done. Similar data are shown in Table 2.10 for studies done on several crops in India where

TABLE 2.8. Percentage of Crop Acreage Treated with Herbicides and Total Herbicide Use in the United States in 1971 and 1982 (Chandler, 1985).

	Proportion of hectares treated with herbicide		Herbicide applied	
Commodity	1971 (%)	1982 (%)	1971 (%)	1982 (million kg ai)
Row Crops				
Corn	79	95	45.8	110.4
Cotton	82	97	8.9	7.8
Sorghum	46	59	5.2	6.9
Soybeans	68	93	16.6	56.8
Peanuts	92	93	2.0	2.2
Tobacco	7	71	0.1	0.7
Total	**71**	**91**	**78.6**	**184.8**
Small Grain Crops				
Rice	95	98	3.6	6.3
Wheat	41	42	5.3	8.2
Other grain	31	45	2.5	2.7
Total	**38**	**44**	**11.4**	**17.2**
Forage Crops				
Alfalfa	1	1	0.2	0.1
Other hay	[a]	3	[a]	0.3
Pasture and range	1	1	4.8	2.3
Total	**1**	**1**	**4.0**	**1.7**
TOTAL	**17**	**33**	**94.0**	**204.7**

[a]Included in alfalfa.

TABLE 2.9. A Comparison of Yield in Weeded and Unweeded Crops (Mercado, 1979).

	Yield (T/ha)		
Crop	Weeded	Unweeded	Increase from weeding (%)
Lowland rice			
Transplanted	3.9	2.9	34
Direct-seeded	4.1	1.0	310
Upland rice	2.8	0.6	367
Corn	5.1	0.53	862
Soybean	1.15	0.48	140
Mung bean	0.75	0.57	32
Transplanted tomato	9.2	5.5	67
Direct-seeded tomato	5.1	1.5	240
Transplanted onion	10.8	0.44	2,355

TABLE 2.10. Benefits from Weed Control at Various Dryland Centers in India, 1971–1981.

		Crop yield with		
Location	Crop	Traditional weed	Improved control (kg/ha)	Increase (%)
Varanasi	Upland rice	1,700	2,700	59
Dehra Dun	Maize	1,760	4,600	161
Hyderabad	Sorghum	1,500	3,740	149
Sholapur	Pearl millet	180	950	428
Dehra Dun	Soybean	920	1,840	100
Bangalore	Peanut	420	1,910	355

Unpublished data from Friesen, G.—Manitoba.

improved methods may mean only better cultivation and are not to be interpreted as a recommendation for all modern technology.

THINGS TO THINK ABOUT

1. What commonalities and differences can be found in the several definitions of the word *weed*?
2. How does the way we define something determine our attitude toward it?
3. What taxonomic, biological, morphological, and physiological traits do weeds share?

4. What is the best estimate of what weeds cost in the United States?
5. How are cost estimates obtained?
6. What are the problems with estimates of the cost of weeds?

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CHAPTER 3

Weed Classification

FUNDAMENTAL CONCEPTS

- The order in the world of weeds is recognized through systems of classification.
- Weeds can be classified in at least four ways. The most important and oldest system is based on phylogenetics or evolutionary ancestry.

OBJECTIVES

- To learn the fundamentals of weed classification based on phylogenetics or ancestral relationships.
- To learn why and how other weed classification systems are used and why they are important to weed management.
- To understand the unique habitat and role of parasitic weeds.
- To know the major groups of parasitic weeds.
- To understand the importance of a plant's scientific name.

One of the great, often unspoken, hypotheses of modern science is that there is order in the world. With careful study, scientists believe they can discover and describe the order. With each discovery and consequent description, science will improve our understanding of how our world functions. Among those who study the order in the natural world are taxonomists, who describe and classify species. Although not everyone agrees on whether a particular plant is a weed or exactly what a weed is, as members of the plant kingdom, most weeds have been classified by plant taxonomists.

There are at least 450 families of flowering plants and well over 350,000 different species. Only about 3,000 of them have been used by humans for food. Fewer than 300 species have been domesticated, and of these, there are about 20 that stand between humans and starvation. There are at least 100 species of great regional or local importance, but only a few major species dominate the human food supply. Only about 15 plants provide most of the food that humans have consumed for many generations.

Twelve plant families include 68% of the 200 species that are the most important world weeds (Holm, 1978). These weeds share certain characteristics, including the following:

1. Long seed life in soil
2. Quick emergence
3. Ability to survive and prosper under the disturbed conditions of a cropped field
4. Rapid early growth
5. No special environmental requirements for seed germination

They are also competitive and react similarly to crop cultural practices. Weeds are usually defined primarily by where they are and how that makes someone feel about them. The fact that they may have shared characteristics means we may be able to define and classify them based on what their genotype enables them to do. Some characteristics that weeds share are discussed in Chapter 9.

Table 3.1 lists the 12 plant families that include 68% of the world's important weed problems. The Poaceae and Cyperaceae account for 27% of the world's weed problems, and when the Asteraceae are added, 43% of the world's worst weeds are included. Nearly half of the world's worst weeds are in only 3 families, and any 2 of these include over a quarter of the world's worst weeds.

TABLE 3.1. Families of the World's Worst Weeds (Holm, 1978).

Family	Number of species	Percent of total*		
Poaceae	44			
Cyperaceae	12	27		
Asteraceae	32		43	
Polygonaceae	8			
Amaranthaceae	7			
Brassicaceae	7			68
Leguminosae	6			
Convolvulaceae	5			
Euphorbiaceae	5			
Chenopodiaceae	4			
Malvaceae	4			
Solanaceae	4			
Total	138**			

The Poaceae is the family with the most weedy species and also the family that includes many of the important crops that feed humans: wheat, rice, barley, millet, oats, rye, corn, sorghum, and sugar cane.

About two-thirds of the world's worst weeds are single-season or annual weeds. The rest are perennials in the world's temperate areas, but in the tropics, they are accurately called several-season weeds. The categories *annual* and *perennial* do not have the same meaning in tropical climates, where growth is not limited by cold weather but may be limited by low rainfall. About two-thirds of the important weeds are broadleaved or dicotyledonous species. Most of the rest are grasses, sedges, or ferns. The United States has about 70% of the world's important weeds and they may be classified in different ways.

I. PHYLOGENETIC RELATIONSHIPS

Weeds are classified by taxonomists and weed scientists the same way as all other plants and species. Based on phylogenetic (from the Greek *phylo* or *phulon*, meaning "race" or "tribe," plus the Greek *gen*, meaning "be born of" or "become") relationships, or a plant's ancestry. All good identification manuals include a key to the species, and all keys are based on a classification developed over many years and, for plants, brought near its present form by the Swedish botanist Carl von Linné [or in its Latinized form, Linnaeus (1707–1778)], who established the binomial system of nomenclature (Genus + species) that is based, primarily, on floral characteristics, especially the presence, number, and characteristics of stamens and pistils. Prior to Linnaeus, all creatures were described in Latin with names that were what Bryson (2005, p. 448) calls "expansively descriptive." Bryson's example is the common weed cutleaf groundcherry, which botanists now agree is known as *Physalis angulata* L. Before Linnaeus, it was known as *Physalis amno ramosissime ramis angulosis glabris foliis dentoserratis*. Students may abhor binomial nomenclature, but, as difficult as it is, it is much easier than descriptive names in Latin with eight terms.

Phylogenetic keys to plant species, based on ancestry and ancestral similarity, include division, subdivision, class, family, genus, and species. A brief description of a plant key for weed species follows:

Division I—Pteridophyta
- Description—Fernlike, mosslike, rushlike, or aquatic plants without true flowers. Reproduce by spores.
- Representative families:
  - Salviniaceae
  - Equisetaceae
  - Polypodiaceae

Division II—Spermatophyta
- Description—Plants with true flowers with stamens, pistils, or both. Reproduce by seed containing an embryo.

Subdivision I—Gymnospermae
- Description—Ovules not in a closed ovary. Trees and shrubs with needle-shaped, linear, or scalelike, usually evergreen leaves.
- Representative families: Pinaceae, Taxaceae
- Almost no weedy species.

Subdivision II—Angiospermae
- Description—Ovules borne in a closed ovary that matures into a fruit.
- Class I—Monocotyledoneae
  - Description—Stems without a central pith or annular layers but with woody fibers. Embryo with a single cotyledon. Early leaves always alternate. Flower parts in threes, or sixes, never fives. Leaves mostly parallel veined.
  - Representative families:
    - Poaceae
    - Cyperaceae
    - Juncaceae
    - Liliaceae
    - Commelinaceae
- Class II—Dicotyledoneae
  - Description—Stems formed of bark, wood, and pith with the wood between the other two and increasing with annual growth. Leaves net-veined. Embryo with a pair of opposite cotyledons. Flower parts mostly in fours and fives.
  - Representative families
    - Polygonaceae
    - Chenopodiaceae
    - Convolvulaceae
    - Asteraceae
    - Solanaceae

All classified plants have a genus and specific name. By convention, the genus is always capitalized (e.g., *Amaranthus*) and is commonly written in italics or underlined. The species name is not capitalized.

II. A NOTE ABOUT NAMES

The first question one asks about a weed is “What is it?” Of course, the most logical and best answer to this question is the weed’s name. But which name? Most plants have several names. Each has its own, distinctive scientific name plus one to several common names. Common names vary between languages and between regions that share a language. For example, *Zea mays* is the plant Americans call corn, but the British, and most of the rest of the world's people, call the plant maize or (in Spanish) *maíz*. In England, wheat and other small grains are often known as corn. The weed *Vulpia myuros* (L.) K.C.Gmel. is called rattail fescue in the United States but silvergrass in Australia. When common names dominate, more confusion arises when two different weeds share a common name. Southern sandbur and bristly starbur are different plants but have the same common name in the north and south of Brazil.

Reluctantly, but for the reader's convenience, common names have been used throughout this book. The scientific names for all plants mentioned in the book are included in Appendices A and B. The scientific name is accepted throughout the world or, at least, it is the name that can be used to resolve confusion that often occurs when just the common name is used.

Students resist learning scientific names because they are regarded as useless, boring, and perhaps even nonsense words designed to confuse and make remembering more difficult. The arguments against learning them are manifold. The first defense is that the names are difficult because they are in Latin, which, after all, is a dead language. Outside of the Roman Catholic Church, few speak it, and knowing Latin certainly doesn't score many points with one's peers. Besides, the argument continues, common names are widely accepted and convey real meaning. Latin is difficult, but difficulty should be dismissed as an objection not worthy of one engaged in higher education. Similar to most worthy goals, obtaining an education will not be achieved without some effort. Latin is dead, but therein lies its advantage as a medium to name things. A dead language doesn't evolve and assume new forms as daily use modifies it and introduces variation. The rules are fixed, and while the language can be manipulated, it is not pliable like a living language (Zimdahl, 1989).

As opposed to common names, scientific names have a universal meaning. Those who know scientific names will be able to verify a plant's identity by reference to standard texts or will immediately know the plant in question when the scientific name is used. Those who do not share the same native language can make use of Latin, an unchanging language, to share information about plants.

Scientific plant names have been derived from a vocabulary that is Latin in form and usually Latin or Greek in origin. Other peculiarities that make scientific nomenclature difficult are the frequent inclusion of personal names, Latinized location names, and words derived from other languages. Taxonomists have developed and accepted rules for name creation that provide latitude for imagination and innovation but not license for their neglect (Zimdahl, 1989).

III. CLASSIFICATION METHODS

Other common, and less systematic classification methods for weeds are based on life history, habitat, morphology, or plant type. Knowledge of classification is important because a plant's ancestry, length of life, the time of year during which it grows and reproduces, and its method or methods of reproduction provide clues about management methods most likely to succeed.

A. Type of Plant

The type of plant or general botanical group is an essential bit of knowledge but not very useful as a total classification system. It is important that we know whether a weed is a fern or fern ally, sedge (Cyperaceae), grass (monocotyledon), or broadleaved (dicotyledon). One should not even begin to attempt control or try to understand weedy behavior until this has been determined. However, when one knows the general classification, other questions about habitat or life cycle must be answered to acquire understanding necessary to control the weed or to create a weed management system.

B. Habitat

Cropland

The first, and most important, weedy habitat is cropland, where many annual and perennial weeds grow. While it is important to know the crop and whether it is agronomic or horticultural, it is not particularly useful. It tells us where the weed is, but it doesn't tell us much about it. It is not a precise way to classify because there is so much overlap among crops. Few, if any, weeds grow exclusively in agronomic or horticultural crops or in just one crop. Redroot pigweed, velvetleaf, Canada thistle, and quackgrass are commonly associated with agricultural crops. Others such as crabgrass, common mallow, prostrate knotweed, dandelion, and creeping woodsorrel commonly associate with horticultural crops. Each can occur in many different crops and environments.

Rangeland

Some weeds are almost exclusively identified with rangeland, a dry, untilled, and extensive environment. Sagebrush and gray rabbitbrush are rarely weeds in corn or front lawns. Only the worst farmer or horticulturalist would create an environment in which these weeds could thrive. Range weeds include those

TABLE 3.2. **Rangeland Weeds.**

Weed	Life cycle	Family
Big sagebrush	Perennial	Asteraceae
Sand sagebrush	Perennial	Asteraceae
Fringed sagebrush	Perennial	Asteraceae
Broom snakeweed	Perennial	Asteraceae
Gray rabbitbrush	Perennial	Asteraceae
Yucca	Perennial	Liliaceae
Greasewood	Perennial	Chenopodiaceae
Halogeton	Annual	Chenopodiaceae
Mesquite	Perennial	Leguminosae
Locoweed	Perennial or annual	Leguminosae
Larkspur	Perennial	Ranunculaceae

shown in Table 3.2, and while the list is not exhaustive, it shows that rangeland weeds are commonly perennial and include many members of the Asteraceae. There are poisonous weeds such as locoweed and larkspur on rangeland and many others including thistles (of several species), dandelion, groundsel, buttercup, vetch, and so on, but these also occur in other places.

Forests

There are over 580 million acres of forest in the United States, and in addition to common herbaceous annual and perennial weeds, there are others, unique to the forest environment (see Table 3.3). The woody perennials such as alder, aspen, bigleaf maple, chokecherry, cottonwood, oaks, and sumac, and the herbaceous perennial bracken fern (common in the acidic soils of Pacific Northwest Douglas fir forests) are unique forest weeds.

Red alder was nearly eliminated by herbicides from Douglas fir forests in the 1970s. Red alder can fix atmospheric nitrogen in soils that are deficient in nitrogen, and Douglas fir will grow better with than without red alder. In the 1990s, red alder wood increased in value, and some companies now cultivate it. Some weeds do so well that they become crops! Red alder has been the target of biological control with a fungus (Dorworth, 1995).

Aquatic

Agriculture is the largest user of fresh water in the world, and crops are sensitive to supply variation. Most of the world's major cities are located on a lake,

TABLE 3.3. **Aquatic Weeds.**

Growth habit	Weed	Life cycle	Family
Free floating	Waterhyacinth	Perennial	Ponterderiaceae
	Salvinia	Annual/Perennial	Salviniaceae
	Waterlettuce	Perennial	Araceae
	Duckweed	Annual	Lemnaceae
Submersed	Hydrilla	Annual/Perennial	Hydrocharitaceae
	Elodea, Western	Perennial	Hydrocharitaceae
	Pondweed	Perennial	Potamogetonaceae
	Eurasian watermilfoil	Perennial	Haloragaceae
	Coontail	Perennial	Ceratophyllaceae
Emersed	Cattail	Perennial	Typhaceae
	Alligatorweed	Perennial	Amaranthaceae
	Arrowhead	Perennial	Olismataceae

ocean coast, or major river. Water, a finite resource, has been and will continue to be essential for urban and agricultural development. Aquatic weeds (Table 3.3) interfere with crop growth because they impede water flow or use water before it arrives in cropped fields. They can interfere with navigation, recreation, and power generation. Free-floating plants (e.g., waterhyacinth) attract attention because their often massive infestations are so obvious. They move with wind and floods, and some have stopped river or lake navigation. They float free and never root in soil. Submersed plants (e.g., hydrilla) complete their life cycle beneath the water. Emersed aquatic weeds (e.g., common cattail) grow with their root system anchored in bottom mud and have leaves and stems that float on water or stand above it. They grow in shallow water, but all can impede flow, block boat movement, clog intakes of electric power plants and irrigation systems, and hasten eutrophication.

Environmental Weeds

This category includes plants particularly obnoxious to people, such as poison ivy and poison oak, both of which cause itching and swelling when many people come into contact with them. Other plants in the environmental group are goldenrod, ragweed, and big sagebrush—primary causes of hay fever-type allergies.

Parasitic Weeds

Parasitic weeds are often placed in other sections in weed science texts. They are here because theirs is a particular and peculiar habitat. Phanerogamic parasites, from the Greek *phaneros*, meaning "visible," and *gamos*, meaning "marriage," include more than 3,000 species distributed among 17 families, but only 8 families include important parasitic weeds. The economically important species (see Table 3.4) that damage crop and forest plants are all dicotyledons from five families (Sauerborn, 1991). Parasitic weeds from four families will be discussed briefly. Those who want more detailed information are directed to Parker and Riches (1993).

The Cuscutaceae, dodders, are noxious in all US states except Alaska and are distributed throughout the world's agricultural regions. A mature dodder plant, a true parasite, is a long, fine, yellow, branching stem. A single stem of field dodder, one of the most important species, can grow up to 10 cm in one day. It is nonspecific regarding hosts, and it coils and twines on many plants. Dodder flowers and reproduces by small, sticky seeds. Haustoria penetrate a host's cortex to the cambium, and the fine stems dodder (tremble) when the wind blows. Dodder seed emerges from as deep as 4 feet in soil as a rootless, leafless seedling. The fine, yellow stem, 1 to 3 inches long, emerges as an arch, straightens and slowly rotates in a counterclockwise direction (called circumnutation) until it touches another plant, which must be within about 1.25 inches. Seeds have sufficient resources to search for a host for four to nine days, after which they die (Sauerborn, 1991). After contact and attachment, the soil connection withers, and dodder lives as an obligate stem parasite.

The most important parasite in the Loranthaceae is mistletoe. Mistletoes occur in two families: the Loranthaceae and the Viscaceae. Some taxonomies

TABLE 3.4. Important Families of Parasitic Weeds.

Family	Genera	Common name
Cuscutaceae	Cuscuta	Dodder
Loranthaceae/Viscaceae	Loranthus	Mistletoe
	Arceuthobium	Mistletoe
	Viscum	Mistletoe
Orobanchaceae	Orobanche	Broomrape
	Aeginetia	Orobanche
Schrophulariaceae	Striga	Witchweed
	Alectra	Witchweed

combine both families in the Loranthaceae. Dwarf mistletoe is a photosynthetic, flowering plant that parasitizes ponderosa pine in the southwestern United States. It occurs on the trunk and branches as a dense tangle of short brown to yellow-brown stems. Seeds are dispersed by birds or by explosion of seed pods and expulsion of sticky seeds that adhere to adjacent trees. Seeds that burst from pods can travel up to 60 mph over 45 feet. The seeds are usually dispersed in August or early September in southwestern United States.

Witchweed is one of three weedy hemiparasitic species of the Scrophulariaceae in the world. It is called witchweed because it damages crop plants before it even emerges from the ground. There are 35 species of Striga; 23 are found in Africa, and at least 11 of them parasitize crops (Parker and Riches, 1993). Other important Striga species are *S. hermonthica*, which parasitizes sorghum, millet, and corn in Africa, and *S. gesnerioides* (cowpea witchweed), which is the only one that parasitizes dicots. The latter is important on cowpeas and groundnut in East and West Africa and Asia.

The desert locust (*Schistocerca gregaria*) gains a great deal of publicity when it swarms in Africa. Massive efforts are made to combat it, but in any single year, witchweed is more destructive to crops in Africa than desert locusts. The genus has the narrowest host range of the important parasitic weeds and a narrower range of distribution than dodder. Witchweed is a root parasite on corn, sorghum, and other grasses in Africa, India, and Asia. In the United States, it is limited to parts of North and South Carolina. Witchweeds are widely distributed in the world's tropical and subtropical regions. Secretions from corn (and some other grasses) roots encourage germination of witchweed seed. After parasitization, the corn is stunted, yellow, and wilted because of loss of nutrients and water. Many weeds, including crabgrass, serve as alternate hosts. Witchweed seeds are small (about $.2 \times .3$ mm). Therefore, 1,000 to 1,500 seeds placed end to end would be only 1 foot long. They survive up to 14 years in soil, and one witchweed plant can produce up to 58,000 seeds. It easily parasitizes corn because its 90- to 120-day life cycle is similar to corn's. One corn plant can support up to 500 witchweed plants. Witchweed seed will not germinate in soil without the host-excreted stimulant, but it may be induced to germinate with the artificial stimulant ethylene gas. USDA regulations currently have witchweed under quarantine in North and South Carolina to prevent its spread throughout the United States. The quarantine has been successful, and the infested area is decreasing.

Plant parasites such as witchweed have not been controlled in susceptible crops with standard herbicides or weed management methods prior to the occurrence of damage. Crop seed coating with the benzoate herbicide pyrithiobac or the imidazolinone herbicide imazypyr offers promise for control of witchweed in Africa (Kanampiu et al., 2003). Maize seeds were coated with very low rates of one of the herbicides to achieve season-long control of striga and three- to fourfold increases in maize yield over no striga control.

The Orobanchaceae (from the Latin *orobos*, meaning "bitter vetch, and the Latin *anchein, meaning* "to strangle") or broomrapes include over 100 species, 5 of which are important, obligate root holoparasites (lacking all chlorophyll) that attack carrots, broadbeans, tomatoes, sunflowers, red clover, and several other important small-acreage crops in more than 58 countries (Parker and Riches, 1993; Sauerborn, 1991). The broomrapes have the broadest host range of the parasitic families. They cause major yield losses and often complete loss of some crops in many developing countries where control is not possible. They are the most important weed of cool-season food legumes (e.g., cowpea, fava bean). Broomrape is found in California but is not a concern in most of the United States. It is, however, important in South and East Europe, West Asia, and North Africa. Seeds of some species can live in soil for up to 10 years. One plant can produce up to 200,000 seeds that are as small as witchweed seed, and 1 gram of seed contains up to 150,000 seeds. Similar to witchweed, germination of Orobanche seed is stimulated by secretions from the host's root or from roots of nonhost plants. Germination will not occur in the absence of host-excreted chemical stimulants. Most damage from root parasites occurs before the parasite emerges, and only 10 to 30% of attached parasites emerge (Sauerborn, 1991).

An important aspect of parasitic weeds is the present inability to manage them with other than sophisticated chemical technology or extended fallow periods. It has been noted that as little as 100 grams of glyphosate per ha (a sublethal dose) applied three times after rimsulfuron (a sulfonylurea herbicide) selectively reduced broomrape shoot numbers in potato (Haidar et al., 2005). Many of the world's people live in areas where food is scarce and agricultural technology is not sophisticated. These are the same places where parasitic weeds cause the greatest yield losses. Fields have been taken out of production, and production area of some crops has been reduced severely due to parasitic weeds.

C. Life History

Another way to classify weeds is based on their life history. A plant's life history determines in which cropping situations it might be a problem and what management methods are likely to succeed. All temperate weeds can be categorized as annual, biennial, or perennial. These groups are easy to define and observe and are very useful in temperate zone agriculture. As just mentioned, the concept of perennation is not as useful in tropical agriculture, where seasons do not change as they do in temperate zones.

Annuals

An annual is a plant that completes its life cycle from seed to seed in less than one year or in one growing season. They produce an abundance of seed, grow quickly, and are usually, but not always, easier to control than perennials. Summer annuals germinate in spring, grow in summer, flower, and they die in fall, and thus go from seed to seed in one growing season. Many common weeds such as common cocklebur, redroot pigweed and other pigweeds, crabgrass, wild buckwheat, and foxtails are annuals. The typical life cycle of an annual weed is shown in Figure 3.1. Weed ecologists are working to quantify many of the steps in this cycle. The sequence of events is qualitatively accurate, but neither rates nor quantities are defined for most annual weeds. For example, it is known that not all seeds produced by a weed survive in soil. Some die from natural causes at an unknown rate. Others suffer predation by soil organisms or enter the soil seed bank, where their life may be prolonged by dormancy. Quantitative understanding of the steps in a weed's life is essential to wise management.

Winter annual weeds germinate in fall or early winter and flower and mature seed in the spring or early summer of the following year. Downy brome, shepherd's-purse, pinnate tansymustard, and flixweed are winter annual weeds. They are particularly troublesome in winter wheat, a fall-seeded crop, and in alfalfa, a perennial.

Some parts of the world (southern European and North African Mediterranean countries) have a winter rainy season with little snow or subfreezing

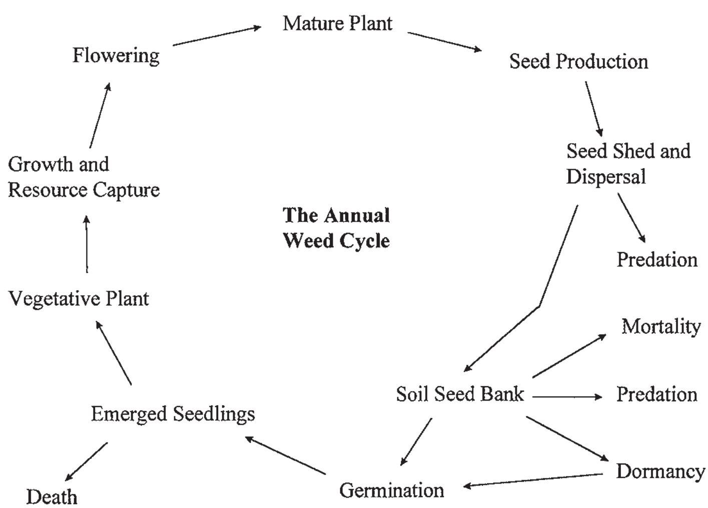

FIGURE 3.1. Life cycle of an annual weed.

temperatures. This is followed by a long, dry period. Crops are planted in the fall when, or just before, the rains begin, so the crops and their weeds begin to grow with the rain. Because the rains don't begin until late fall, the annual weeds live into the next calendar year, and their life cycle fits part of the definition of a winter annual. They are, however, best regarded and managed as annuals because their growth is continuous and not interrupted by a cold period when plants live but do not grow.

Biennials

Biennials live more than one but not more than two years. They should not be confused with winter annuals, which live during two calendar years but not for more than 12 months. Musk thistle, bull thistle, and common mullein are biennials. It is important to know that one is dealing with a biennial rather than a perennial. Spread of a biennial can be prevented by preventing seed production, which is not true for creeping perennials.

Perennials

Perennials are usually divided into two groups: simple and creeping. Simple perennials spread by seed and by vegetative reproduction. If the shoot is injured or cut off, simple perennials may regenerate a new plant vegetatively, but the normal mode of reproduction is seed. Simple perennials include dandelion, buckhorn and broadleaf plantain, and curly dock. Creeping perennials reproduce by seed and vegetatively. Vegetative reproductive organs include creeping above-ground stems (stolons), creeping below-ground stems (rhizomes), tubers, aerial bulblets, and bulbs. The life cycle of a typical perennial plant is shown in Figure 3.2. An excellent summary of the characteristics of 28 perennial weed species can be found in Anderson (1999). The following are the important kinds of vegetative reproduction and the weeds that use them (Leakey, 1981):

A. Rooting of detached shoots

1. turion	A scaly, often succulent shoot produced from a bud on an underground rootstock. *Eurasian watermilfoil*

B. Creeping stems

1. layers	Shoots that contact soil root at nodes *annual bluegrass*
2. runner	A plagiotrophic (tendency to grow obliquely or horizontally) shoot that may root, in some shoot areas, when in contact with soil *European blackberry, hedge bindweed*

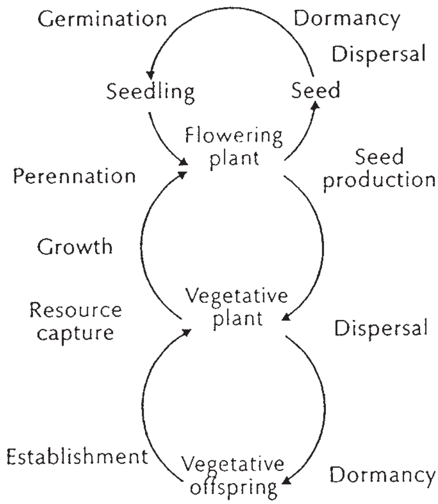

FIGURE 3.2. Life cycle of a perennial weed that produces seed and vegetative progeny (Grime, 1979).

3. stolons	Horizontally growing stems that root at stolon nodes *creeping buttercup, creeping bentgrass, waterhyacinth*
4. rhizomes	Horizontal subterranean stems that give rise to aerial shoots *leafy spurge, quackgrass, field bindweed, johnsongrass*
5. rhizomes and stolons	*bermudagrass*
6. tubers	Swollen portions of underground stems *purple and yellow nutsedge*
C. Creeping roots	
	Creeping roots that give rise to new shoots *Canada thistle, field bindweed, Russian knapweed*
D. Taproot reproduction	
	Roots that generate a new plant from root fragments *dandelion*
E. Modified shoot bases	
1. Bulbs	Underground storage organs composed of swollen leaf bases or scales *wild garlic*
2. Corms	Swollen stems with dormant bulbs in the axils of scale-like leaf remnants *bulbous buttercup, tall oatgrass*

THINGS TO THINK ABOUT

1. How are weed classification systems used?
2. What classification system is most likely to be used by horticulturalists, agronomists, and weed scientists?
3. Why are parasitic weeds such difficult problems, and where do they exist?
4. If parasitic weeds are not important problems in most developed countries, why do we bother to study them?
5. Why should we bother to learn the scientific names of plants?
6. How are the scientific names of plants created?

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CHAPTER 4

Ethnobotany

FUNDAMENTAL CONCEPTS

- Many weeds are also useful for food, animal feed, or medicine.
- Some weeds may be useful for fuel or insulation.
- The same plant can be a weed in one place and a beneficial crop in another.

LEARNING OBJECTIVES

- To understand the many ways weeds can be used.
- To encourage thought about the importance of doing research to find uses for weeds.

There are laws in the village against weeds.
The law says a weed is wrong and shall be killed.
The weeds say life is a white and lovely thing
And the weeds come on and on in irrepressible regiments.

"Weeds" Poem by Carl Sandburg

Ethnobotany is the study of the relationship between plants and people (Balick and Cox, 1996). It includes study of the uses of plants by man and the relationship between man and vegetation. It examines our dependence on plants and our effects on them. If weeds are just plants out of place and properly regarded as useless by humans, is it possible they could also be useful? Can a single species be both weedy and useful?

One longs for a weed here and there, for variety;
A weed is no more than a flower in disguise,
Which is seen through at once, if love give a man eyes.
"A Fable for Critics" Poem by James Russell Lowell (1890)

Ethnobotanical studies in Bolivia (Bentley et al., 2005) illustrate the multiple roles weeds play and affirm that the answer to the preceding question is *yes*! First, some plants are weeds, and farmers actively work to control them in crops. Some weeds are also used as cattle fodder, especially in areas where cultivated land is limited and holdings are small. Bolivian farmers are very familiar with the weeds and do not manage crops to preserve them. Some weeds are used as fodder when they grow on fallow land but are hoed out and left to rot when they grow in crops. Weeds are also used as construction material (cylindrical graneries), toys made by or for children, and as medicine (Bentley et al., 2005).

I. FOOD FOR HUMANS

There is much interest in possible uses for weeds. It is a sobering thought that only one new major food crop, the soybean, was discovered in the 20th century. It was first domesticated in China over 1,000 years ago. What would be the benefit of another food crop like the soybean? Would it be worth a mission to the Moon or a Trident submarine? I suggest it would be. It would be very wise to rediscover some of the crops grown by indigenous people in several world areas and to study the potential food or industrial value of weeds. There are sources of information to assist the search that range from an article in *Reader's Digest* (Daniel, 1974) to books on edible native plants (Harrington, 1967), edible weeds (Duke, 1992; Hatfield, 1971), potential dietary uses of wild and cultivated plants (Hylton, 1974), medicinal products (Swerdlow, 2000), ethnobotany (Balick and Cox, 1997), new crops (Janick, 1996, 1999), and many articles in the scientific and popular literature.

The tradition of using indigenous plants for human food is regarded by some as vegetarianism or food faddishness, but if looked at in its historical context, a long history of potentially useful food sources can be discovered. The world has more than 300,000 species of seed-bearing plants. Perhaps as many as 30,000 of these have been used to some extent by humans as a food source. Many of these have been lost or forgotten. Fewer than 300 seed-bearing plant species have become more or less domesticated, and of these, only about 30 are used to provide the majority of human food. Nine of these belong to a single plant family: the grasses. Vietmeyer (1981) calls these past foods "potential food sources." They are America's forgotten crops. The food crops include the tepary bean, groundnut, and amaranth. His article also includes jojoba, whose oil has potential as an engine lubricant, skin moisturizer, livestock feed, and leather softener, and guayule, a potential source of natural rubber. The advantage of each of the forgotten crops Vietmeyer identifies is that they grow well in arid soils where few present food crops do well.

Of 158 weed species collected from rice fields in two districts of West Bengal, India, 124 had economic importance to farmers (Vega, 1982). Young pigweeds may be eaten as salad greens, and pigweed seeds can be eaten raw or parched. Several species of amaranth grow rapidly and contain abundant, high-quality protein (Hauptil and Jain, 1977). Leaves of some species contain up to 33% protein, and their seeds have 16% to 19% protein (Hauptil and Jain, 1977). Young leaves of shepherd's-purse are eaten as greens, and dried roots can be eaten as a substitute for ginger or candied by boiling in a sugared syrup.

Instead of agonizing over dandelions in turf, why not learn to love and use them? In the late 1970s, Mayor Patrick R. Fiorello proclaimed his city—Vineland, New Jersey—to be the world's dandelion capital, a claim the city no longer makes. At one time, a cookbook with recipes ranging from dandelion jello to dandelion soup was available from the mayor's office (Anonymous, 1979). Although Fiorello's book is no longer available, others can be found in your library or bookstore (Gail, 1990; Wilensky, 2000). Dandelions are harvested and sold for conversion to dandelion corn chowder, wine, or Italian dandelion casserole. Some say dandelion flowers are quite good when dipped in batter and deep fried. Dandelion roots make a caffeine-free coffee substitute. Dandelions are part of the national cuisine of at least 54 countries (Gail, 1990, p. 12). Koreans can use them in kimchi (a pickled or fermented mixture of cabbage, onions, and fish with various seasonings). Germans make dandelion gravy to use on potatoes. The French use them in salads, and the Italians, who call them *chigoda*, use them in many dishes. The leaves are rich in vitamins A and C. More than 100,000 pounds of dandelion are imported to the United States annually for use in patent medicines (Duke, 1992). The root contains a diuretic (an old European common name for it is piss-a-bed). If you don't like the taste or price of your current brew, try some dandelion beer (Hatfield, 1971, p. 65).

Common purslane contains high levels of fatty acids, vitamin E at six times the level of spinach, and other nutrients. Europeans eat it in salads, and it could be developed as a new vegetable crop (Anonymous, 1992). Omega-3 fatty acid has been linked in some studies to reduced heart disease, and purslane contains more than any other green, leafy vegetable (Anonymous, 1992). It is well adapted to arid areas and could be an alternative crop. One farmer in Congerville, Illinois, grows common lambsquarters, common purslane, and many other plants that weed scientists (Patterson et al., 1989) consider to be undesirable weeds, and he sells his produce to high-end Chicago restaurants (Hale-Shelton, 2004).

Barnyardgrass seeds may be eaten dry or parched and have been ground into flour. Some thistle seedlings may be eaten raw in salads if the spines are removed. Young Canada thistle roots can be peeled and the pithlike interior eaten raw or as a condiment in some cooked dishes. There are recipes for thistle-leaf tea. Seeds of wild oat can be ground into flour, and wild oat seeds can be used to make fly lures for fly fishing. Seeds of crabgrass, green foxtail, wild oat, and the common reed have been eaten whole.

Iroquois Indians ate burdock leaves as greens and used its dried roots in soup (Duke, 1992). Before Viagra became available, Martin (1983) and Duke (1992) reported that eating raw burdock stems was supposed to increase libido and improve sexual virility. Duke (1992) wrote about its sale in Japan as an herb for sexual problems.

Wild mustard leaves have a hot, spicy flavor that blends well in salads with lettuce and dandelion. Wild onion has been used as a relish, to flavor cooked foods, and to improve the taste of gamey meat (Ross, 1976).

Martin (1983) reported that some Japanese eat kudzu root. It is ground into a fine powder and used as a condiment. The leaves are also eaten. Kudzu was promoted extensively by the US Department of Agriculture in the 1930s to stabilize eroding land (see Chapter 7). The Chinese have long relied on simple kudzu root extract to stop human craving for alcohol. It is sold as an over-the-counter drug in China and is 80% effective when taken for two to four weeks. The extract was evaluated in the United States and apparently did not gain approval for treatment of alcoholism. Weed scientists will not welcome fields of kudzu, but other priorities may prevail.

Before hops were used in beer, leaves of ground ivy, also called gill-over-the-ground (gill from the French *guiller*, meaning "to brew") were added to the brew to clarify and enhance flavor (Martin, 1983).

Alligatorweed is one of the worst weeds of waterways across the world (Holm et al., 1997). It is generally found in the warm tropics and warmer regions of the temperate zones. It forms dense mats, kills aquatic fauna, and reduces water flow and quality. Alligatorweed and the related, but not as vigorous, weed sessile joyweed are both used in vegetable dishes in southeast Asia. Using these plants as human food is not a problem, but when some Australians discovered that alligatorweed was being cultivated as an herb or green vegetable, concern heightened because of the great possibility of escape and rapid spread.

Duckweed is one of the world's tiniest flowering plants, but it has potential in the fight against world hunger. Rich in protein, with high levels of all essential amino acids save one, duckweed is nutritious and abundant. It is found in temperate and tropical regions growing in thick green masses on surfaces of ponds and lakes. People in Thailand have eaten duckweed for generations. It can be harvested every three to four days and eaten in soups or stir-fried with other vegetables and meat. Duckweed could become a valuable livestock feed as well. Ten acres of duckweed could supply 60% of the nutritional needs of 100 dairy cows for one year. Considering that more than 100 million people each year suffer from severe protein/calorie malnutrition, the food potential of duckweed should be studied carefully.

N. W. Pirie of Rothamsted Experiment Station in England conducted experiments on juice pressed from a random collection of jungle plants. He was able to extract a juice with 50 to 75% protein that, when coagulated, made a tasteless product that could be textured to resemble cheese.

The use of edible weeds is not new (see Duke, 1992, and Hatfield, 1971). DeFelice (2002) describes yellow nutsedge as "the snack food of the gods." Holm et al. (1977) classified it as one of the world's worst weeds. Both are right! This erect, perennial, aggressive, weedy herb came from the eastern Mediterranean and has spread to all continents, except Antarctica (DeFelice, 2002). Its tubers make it an especially difficult-to-control weed, but they are quite tasty after roasting. In fact, it was imported to the United States as a potential vegetable crop in 1854 (DeFelice, 2002), illustrating that not all imports have been good ones. Nevertheless, eating the roasted tubers—commonly known as chufa—can be traced to ancient Egypt. The tubers are not commonly available in the United States but are readily available in markets in West Africa.

The University of Nebraska has an active research program to assist farmers in the development of chicory as a crop. Nebraska farmers plant and harvest 750 to 1,000 acres of chicory each year (Howlett et al., 2006). Chicory has been grown in Nebraska since the latter part of the 19th century, primarily for use as a flavoring in hot drinks such as coffee. It is now grown as a source of inulin (a root-borne carbohydrate used to manufacture fructose (a very sweet sugar), which is subsequently used in the manufacture of pet foods. The roots can also be roasted for use in coffee.

Readers are cautioned that these examples are intended to be illustrative of the range of potential uses for plants and are not a recipe book or set of recommendations. Because of the danger of poisoning or digestive upset, specific references should be consulted before casual experiments lead to unanticipated problems.

Increased agricultural production has relied on low-cost energy and rapid genetic improvement for several decades (Boyer, 1982). These have allowed farmers to use dense plant populations adapted to high production on soil amended with purchased resources. Weeds grow well in cropped fields and in some environments with limited resources. Weeds have been self-selected to do well with both limited and abundant resources. Their genetic abilities may be important resources for plant breeders and crop producers.

A natural stand of giant ragweed in Champaign County, Illinois, had an above-ground biomass similar to corn and greater than soybeans. Its seed biomass was lower than corn or soybeans but equal to the average soybean grain yield in the United States in 1975 (1,610 Kg/ha). Giant ragweed is not a food crop and won't become one, but its high productivity with low inputs provides a valuable lesson for the future of food crops (Boyer, 1982) as energy and water resources decline or are directed away from agriculture.

II. FEED FOR ANIMALS

Weed seed screenings are used in many US states as animal feed, a practice with some disadvantages (see Chapter 5). Some rangeland plants are weeds, but cattle grazing on native blue grama and buffalo grass range achieved better gains when weeds and shrubs constituted 10 to 70% of total vegetation. One should not neglect the contribution of sagebrush and other weedy range species to the diet of browse animals such as deer, elk, and antelope.

Cattle ranchers in the western United States often use kochia hay as feed. When immature, its protein content can be 17%—equal to alfalfa. However, it becomes woody as it matures, and because it is an annual, it will not reseed when harvested immature for hay. An important warning is that it can accumulate high amounts of nitrates, and cattle may become intoxicated and lose weight when kochia is 90% or more of their diet.

The forage and nutritional value of many weed species is equal to that of cultivated forage crops. Marten and Anderson (1975) and Temme et al. (1979) reported that the annual broadleaved weeds redroot pigweed, common lamb' squarters, and common ragweed had digestible dry matter, fiber, and crude protein concentrations about equal to good alfalfa hay when alfalfa and weeds were harvested at the same growth stage. Giant foxtail, Pennsylvania smartweed, shepherd's-purse, and yellow foxtail all had lower nutritional value than alfalfa. Dutt et al. (1982) concluded that yellow rocket reduced the feeding value of alfalfa hay, but white campion and dandelion didn't. Yellow rocket reduced nutritive value index, animal intake, and digestibility.

The perennial quackgrass is a serious weed problem in the perennial crop alfalfa. It invades and decreases hay consumption by cattle. While its nutritional value is high, its palatability is lower than alfalfa or smooth bromegrass (Marten et al., 1987). A biotype, selected for broad leaves, was equal or superior to smooth bromegrass and equal to alfalfa in palatability in Minnesota (Marten et al., 1987). Marten et al. (1987) investigated the forage value of nine perennial broadleaved and grass weeds compared to alfalfa and smooth bromegrass. Smooth bromegrass and quackgrass consistently had more neutral detergent fiber, less crude protein, and an in-vitro digestibility similar to alfalfa. Jerusalem artichoke, Canada thistle, dandelion, and perennial sowthistle had crude protein and in-vitro digestibility equal to or greater than alfalfa (Marten et al., 1987). Broadleaved species generally had lower palatability than alfalfa or smooth bromegrass. Jerusalem artichoke, Canada thistle, curly dock, and hoary alyssum were completely rejected by grazing lambs and are therefore always weedy species in sheep pastures.

Weed forage and hay quality are correlated with plant maturity. More mature plants have lower forage quality. Marten et al. (1987) showed this to be true for nine perennial species in Minnesota, where forage quality measured as digestible dry matter, fiber, or crude protein declined with maturity. Crude protein of curly dock declined 22% from the vegetative to the mature seed stage (Bosworth et al., 1985). In hay crops, the decision to control weeds must be site specific and is dependent on the weeds present and their growth stage when hay is to be cut. Alfalfa stands often become weedy because of death of alfalfa plants, not because weeds crowd them out (Sheaffer and Wyse, 1982). Control may reduce hay yields and produce hay of lower quality if all weeds are controlled just because they are perceived to be weeds and therefore undesirable. As just illustrated, some weeds make good pasture and forage.

The ragweeds are palatable to grazing animals, with common being more so than giant ragweed. Equally as important, seeds of both species of ragweed and many other weedy species provide food for finches and other birds in the winter in the US midwestern states.

Balick and Cox (1996, pp. 34–35) list 50 drugs used in human medicine that have been discovered from ethnobotanical leads. The list includes seven species that are also listed in the Weed Science Society of America (WSSA) composite list of weeds (Patterson, 1989) and five other plants from genera that are included in the WSSA list. One wonders how many common weeds may be sources of new pharmaceuticals.

Until the early 1960s, a diagnosis of childhood leukemia was a death sentence. Now the long-term survival for victims of childhood leukemia is 90+% (Swerdlow, 2000). The common weed (in the WSSA view) Madagascar or rosy periwinkle changed certain death from childhood leukemia to probable complete recovery. The pharmaceutical potential of vinblastine (a vinca alkaloid) was one of the most significant discoveries of ethnobotany. Researchers at the Eli Lilly Company screened a collection of 400 potentially medicinal plants against cultures of P-38 mouse-cell leukemia and found that Madagascar periwinkle killed leukemia cells. Up to 250 kilograms of leaves are required to make a single 500-milligram dose, and this is unlikely to make the plant an effective folk medicine, but it was a healer's claim of its effects against diabetes that led to further investigation (Balick and Cox, 1997, p. 33).

Rosy periwinkle is one of more than 10,000 known plant species in Madagascar, a Texas-sized island off the southeastern African coast. Many are not known elsewhere. In the past 40 years, there have been few new pharmaceutical drugs developed from plant sources. Part of the reason is the cost of finding the plants and verifying potential utility. Second, there are the manufacturers' legitimate concerns about unpredictability and lack of scientific verification. Rosy periwinkle worked as a folk medicine for diabetes (as a tea it lowers blood sugar), but not for leukemia; that test was a random stroke of luck. Science-based development, testing, and formulation are more sure routes to commercial success. But two-thirds of the world's people rely on the healing power of plants and the healers that use them. They could not afford modern medicines even if they were available (Swerdlow, 2000).

Many plants contain bioactive chemicals with potentially beneficial effects on humans and animals. Many of them may be just weeds. We will never know until we listen to healers and study their plants.

III. MEDICAL USES

Plants move in one place but do not move in space while growing, as animals do. Because they are immobile and cannot escape from predators, they have evolved elaborate chemical defenses. Plants are full of mostly unknown, frequently unusual chemical compounds that may have medicinal properties (see Swerdlow, 2000). Most (perhaps as many as 99% of the flowering plants) have never been tested (Bryson, 2005, p. 461). A few are known to traditional tribal healers (often called shamans). Scientists have been interested in the actual and potential use of plants in medicine for a long time. Henkel (1904) wrote one of the early publications that included medical uses for 26 common weeds. She notes that farmers in their fight to exterminate weeds may also be able to "turn some of them to account." In a reflection of the cultural attitudes of the time, she says that "the work of handling and curing them is not excessive and can readily be done by women and children." Stepp and Moerman (2001) showed the significant representation of weeds in the medicinal floras of the Highland Mayas in Chiapas, Mexico, and in the medicinal flora of native North Americans. The frequency of the appearance of weeds as pharmaceutical products is significantly larger than would be predicted by the frequency of the appearance of weedy species in the general flora.

Plants and plant extracts have been used to treat almost every ailment known to humans, ranging from venereal disease and rheumatism to colds and bleeding. Plants with the word *officinale* (or its derivatives) were at one time included on an official drug or medicinal list. *Wort*, a common suffix in plant names (e.g., common St. Johnswort), means "healing." A plant with *bane* added to its common name (e.g., henbane) was probably once used for medicinal purposes. You can probably think of plants that fit in one or more of these categories. St. Johnswort is now a nonprescription natural remedy for mild depression.

Roots of yucca can be chopped and soaked in water to extract a soapy substance that western American Indians used for washing and cleaning. One must assume this is a source of the common name *soapweed*. The next time you get stung by a bee, try to be standing near a curly dock plant. Quickly rub some of its leaves between your hands and press them, with their juice, against the sting. Within 10 to 20 minutes the stinging sensation will be gone. Curly dock has more vitamin C than oranges, and extracts of its yellow root have been used to treat jaundice. (Plantain has similar properties.) Curly dock leaves have also been boiled in vinegar to soften the fibers and then combined with lard to make an ointment for treatment of inflammations.

A persistent human problem is the common cold. If you boil a few ounces of sunflower seed in a quart of water, add some honey and gin, and drink the mixture three or four times a day, irritating mucus will be discharged from the nose and mouth. (Of course, you have to ask whether the sunflower seed extract or the gin, which is also a plant product made by distilling rye or other grains with juniper berries, is really what's making you feel better.)

Yarrow and big sagebrush have been used as a tea to relieve the fever that accompanies a cold. Yarrow leaves were chewed by western pioneers to settle an upset stomach. Extracts were also used to regulate menstrual flow and to stop blood flow from a wound. Modern medicine has confirmed its efficacy (Martin, 1983).

The common European herb/weed queen-of-the-meadow has long been used in folk medicine to treat fever and pain (Balick and Cox, 1997, p. 32). It is also (and, according to Balick and Cox, incorrectly) known as meadowsweet. In 1839 (Balick and Cox, 1997) salicylic acid was isolated from flower buds of queen-of-the-meadow. Pure salicylic acid was used for pain relief but frequently caused stomach problems. In 1899, the Bayer Company combined acetic acid and salicylic acid to create acetylsalicylic acid, the effective painkiller and still one of the world's most widely used analgesics. The name *aspirin* was derived from "a" for acetyl and "spirin" from the genus *Spirea* (Balick and Cox, 1997, p. 32). Aspirin was first synthesized by Felix Hoffmann in Germany in 1897, patented in February 1899, and marketed the same year as aspirin by Bayer Chemical Company. It was a success because it had better pharmacological activity and fewer side effects than pure salicylic acid. Salicylic acid is also found in the bark of the willow tree (*Salix*). North American Indians would chew willow bark to relieve pain.

Dandelion has been used as a laxative, and shepherd's-purse and common St. Johnswort have been used to control diarrhea. Common burdock has been used to make a tonic and a diuretic. Young shoots and the pith of young leaf stalks can be eaten raw with salt or after boiling in salt water. Water-lettuce has been used to cure coughs and heal tubercular wounds. The Chinese use its leaves as external medicine for boils; American Indians used the leaves to cure hemorrhoids (Harrington, 1967). Extracts or preparations of several weeds have been used as sedatives including poison hemlock, jimsonweed, poppies, and, marijuana, which has achieved rather widespread use and popularity (albeit illegal) for its sedative and relaxant properties. Many people have experienced the latter.

Healers used to grate the dried root of wild carrot and apply it to burns. Modern science has shown that the roots contain carotin, and when mixed with oil, it can help burns heal (Martin, 1983). Modern science has also proven the utility of extracts of bouncing bet to treat jaundice and liver problems (Martin, 1983). Backpackers and campers should know bouncing bet. When torn or bruised leaves are added to cold water, a bubbly lather ensues. This source of soap has been known since the Middle Ages (which ended about AD 1450). Its unusual name comes from the white, reflexed petals that someone apparently thought resembled the posterior view of a washerwoman (named Bet?) with her petticoats pinned up.

Drury (1992; based on Gerard, 1597) reported that sprigs of common tansy were placed in beds and bedding to discourage vermin. Tansy tea tastes terrible, but it has been used to treat a variety of illnesses and to cure rheumatism and intestinal worms (Martin, 1983). Scientists in the Philippines have studied antifertility and abortive characteristics of the common weed sensitiveplant.

IV. AGRICULTURAL USES

Kochia, as just mentioned, is a good source of protein for ruminant animals. It is a self-seeding, high-yielding, water-efficient plant with no serious disease or insect pests. It is a serious annual weed in many crops and common in many parts of the United States. Kochia can accumulate high levels of nitrate and will escape from cultivation and become a weed. It may cause photosensitization in cattle. In some experiments cattle have lost weight, and some have even died when fed only kochia.

At least one farmer has used kochia as a cover crop to suppress wild proso millet (Cramer, 1992). A thick stand of unirrigated kochia grew through the summer and was mowed before seed set. It was hard to plow because of all the biomass, but millet was suppressed effectively the next year.

Farmers in southeastern Mexico classify plants as crops or noncrops (Chacón and Gliessman, 1982). The latter are classed according to potential use and their effects on soil or crops. Chacón and Gliessman (1982) argue that local farmers understand the contribution of noncrop plants to agriculture. The authors contrast the farmers' view with the dominant view in developed countries that a weed is any plant other than the crop (see Chapter 2).

Weeds have practical, but often unappreciated, value when used as ground cover for wildlife or for prevention of soil erosion on sites that cannot be cropped or otherwise managed by man. Weeds can conserve nitrogen in some situations. Weeds have been introduced in many places because someone thought they would be useful (see Chapter 7 for other examples). Cogongrass was introduced into the United States in Grand Bay, Alabama, and McNeil, Mississippi (Tabor, 1952). At Grand Bay in 1912, bare-root satsuma orange plants were boxed for shipping with cogongrass, and then the grass was discarded. The McNeil introduction was part of a search for a superior forage. Cogongrass is now a weed in many southern US states. Catclaw mimosa was introduced to Thailand from Indonesia in 1980 as a green manure cover crop in tobacco plantations and for control of ditchbank erosion (Thamsara, 1985). It was successful for both things, but then it spread and became a weed problem. The aggressive, weedy annual paragrass was introduced into Africa from several tropical countries for fodder, pasture, and as a cover crop in banana plantations. There are many examples of plant introductions that someone thought would be helpful, only to discover that they would be problems as well (see Chapter 7).

V. ORNAMENTAL USES

Many species of weeds have been used as ornamentals, and several species that are now weedy were first imported into the United States for ornamental purposes (see Chapter 7 for a discussion of invasive species). One US study (Williams, 1980) documented 33 imported species that became weedy. Of these, 2 were imported as herbs, 12 as hay or forage crops, and 16 as ornamentals. Henbane was imported for its potential medicinal value. One was imported for use in aquaria (hydrilla), one as a fiber crop (hemp or marijuana),

TABLE 4.1. Plants to Avoid in Gardening, Reclamation, and Restoration.

Type	Name	Problem
Forb	Purple loosestrife	Displaces native wetland or marsh plants
Forb	Mediterranean sage	Forms monoculture and outcompetes native plants
Forb	Yellow toadflax	Displaces native vegetation
Grass	Timothy	Competes with native plants in arid areas
Shrub	European buckthorn	Competes with native vegetation in riparian areas
Shrub	Scotch broom	Displaces native vegetation in US west coast area
Tree	Tamarisk or salt cedar	Uses large amounts of water and displaces native vegetation
Tree	Russian olive	Seed dispersed by birds; displaces native plants

and one privately, just for observation (wild melon). Imported plants, including bermudagrass, jimsonweed, kochia, musk thistle, johnsongrass, and waterhyacinth, have become some of our most detrimental weeds. Some people use weeds as ornamentals in spite of, or in ignorance of, their weedy nature.

Several forbs, grasses, shrubs, and trees have been and still are used in gardening and landscaping, reclamation, or restoration. Some are widely acknowledged as weeds, and others may become weedy because of their ability to invade and dominate. All show the ability to escape their intended habitat (see Table 4.1). Not everyone may agree that the plants shown are weeds or could become weedy. At present, there is no civil or criminal penalty for planting any of them. The choice of what to plant is the landowner's. When an escape occurs, everyone pays the price if the species becomes weedy.

VI. INSECT OR DISEASE TRAPS

A disadvantage of weeds is that they can shelter insects and disease organisms. They can also be used intentionally in agriculture as traps for insect or disease pests (see Table 4.2). They do this in one of the following three ways (see Norris, 1982; Norris and Kogan, 2000):

1. As hosts for adult insect parasites
2. As hosts for noneconomic insects that serve as alternate hosts or food for parasites or predators
3. By increasing effectiveness of biological control organisms and thereby reducing damage to crops

Norris and Kogan (2000) provide an extensive review of the interactions between weeds, arthropod pests, and natural enemies in managed ecosystems

TABLE 4.2. **Weeds and Control of Other Pests.**

Cropping system	Weed species	Pest regulated	Reason
Beans	Goosegrass Red sprangletop	Leafhoppers (*Empoasca kraemeri*)	Chemical repellency and masking
Vegetable Crops	Wild carrot	Japanese beetle (*Popillia japonica*)	Increased activity of the parasitic wasp *Tiphia popilliavora*
Corn	Giant ragweed	European corn borer (*Ostrinia nubilalis*)	Provision of alternate host for the tachinid parasite *Lydella grisesens*
Cotton	Common ragweed	Boll weevil (*Anthonomus grandis*)	Provision of alternate hosts for the parasite *Eurytoma tylodermatus*

(i.e., cropped fields). Their review identifies more than 90 insects that are involved in resource and habitat-driven interactions. A separate table identifies more than 50 resource and habitat-driven influences of weeds on beneficial arthropods. The extensive review also illustrates the effects of beneficial and detrimental effects of tillage and several herbicides used for weed management on arthropod populations. Norris and Kogan (2000) cite Altieri (1994, p. 40), who in turn cited Bendixen and Horn (1981) to report that more than 70 families of arthropods are known to be potential crop pests and that the members of these families are primarily associated with weeds. Some associations may be beneficial to crops, but most are not. Without much more understanding of these associations and how management of one pest may affect other pests and crops, integrated pest management programs are less likely to be successful.

Johnsongrass is an alternate host of the sorghum midge (*Contarinia sorghicola* Coquillet), an important pest of grain sorghum. Larvae develop and feed in the sorghum spikelet and prevent normal seed development. Johnsongrass maintains the first two or three generations of the insect until grain sorghum flowers are available. Time and duration of johnsongrass flowering (that can be determined by management) may affect the sorghum midge population (Holshouser and Chandler, 1996).

Showy crotalaria, a legume weed in Hawaii, is used in macadamia nut orchards to attract Southern green stinkbugs (*Nezara viridula* L.) away from macadamia nut trees. Showy crotalaria was introduced to Florida in 1921 as a green manure crop because, as a legume, it fixes nitrogen. However, the foliage and seed are toxic, especially to poultry. It is a weed in soybeans in the southern United States, where, because of the toxicity of its seeds, contaminated soybean seed cannot be sold.

In parts of California, wild blackberries are grown with grapes as hosts of a noneconomic leafhopper that hosts a parasite of the grape leafhopper (*Erythroneura elegantula* Osborn). Japanese farmers graft tomato scion (shoot or bud tissue) onto the rootstock of some weedy members of the *Solanaceae* to avoid root diseases. Other examples of this kind of use can be found in Altieri (1985), Norris and Kogan (2000), and Zandstra and Motooka (1978).

Chapter 2 described how weeds serve as hosts for damaging insects and diseases. It is important to realize that not all insects or microorganisms damage other plants. If one plant harbors harmful organisms, it is only logical to assume that other plants may harbor beneficial organisms. The preceding examples verify this, and Altieri (1985) and Norris and Kogan (2000) provide many other examples.

The agricultural quest for high-yielding monocultures has reduced plant diversity to the point where beneficial insects have been reduced in crop fields. One way to regain a desirable diversity in crop fields is to manipulate the abundance and composition of the weed flora. Weed borders, occasional weedy strips, or weeds at certain times in the crop growth cycle are all possibilities. Weed scientists and farmers may even want to consider planting weeds in attempts to optimize plant protection and crop yield while striving to minimize other inputs.

VII. POLLUTION CONTROL

In addition to the foregoing uses, which most weed scientists would readily acknowledge, there are other, less well-known, perhaps esoteric, but interesting and potentially valuable, uses that a few creative minds have explored.

Star chickweed has been used as a vegetable and is a good source of vitamins A and C. In Elizabethan England, it was used to reduce fever (Martin, 1983). Martin reported it has been used to predict rain. If it blooms fully there will be no rain for at least four hours. If blossoms shut, rain is on the way (although if you look at the sky, you could get the same prediction).

Waterhyacinth will remove the heavy metals selenium, manganese, and chromium from water and may be useful to detect them. It concentrates heavy metals up to 2,000 times the level found in water. Waterhyacinth can be used, in what is called bioremediation, to remove nutrients from water and reduce eutrophication (Murray, 1976; Rogers and Davis, 1972). One hectare of waterhyacinth growing under optimum conditions could absorb the average daily nitrogen and phosphorus waste of over 800 people if maximum uptake and plant growth for a whole year were assumed. The hectare would contain 1.6 million plants and capacity would be reduced to 300 to 400 people if less than year-round growth was achieved. Under optimum growth conditions one hectare of waterhyacinth produces 8 to 16 tons of plant material per day that can be dried, ground, and added to corn silage for cattle feed. The supplementary feed value is comparable to cotton seed meal or soybean oil meal. Anaerobic fermentation of the plant residue produces methane gas that can be used for heating or light. One pound of dried plants yields up to 6 cubic feet of methane or up to 2 million cubic feet of gas per acre of plants per year. There are problems because waterhyacinth does best in warm water and warm climates, and cold weather can kill it (fortunately). There are questions about the cost of establishing and maintaining a processing facility. An obvious problem if waterhyacinth is to be used for bioremediation is disposal of plants and prevention of eutrophication of ponds if no use for the plant residue has been developed.

Because waterhyacinth can be used for bioremediation when there is heavy metal pollution, others have looked at it as a way to harvest valuable heavy metals. Limited research indicates that an acre of waterhyacinth could yield 0.45 kg of silver every four days, and work on gold harvest has been done (Anonymous, 1976).

In India and Indonesia, researchers have made paper products (blotting paper, cardboard) from waterhyacinth mixed with rice straw. India may have as much as 4 million hectares (9.8 million acres) of water infested with (*covered with* may be more accurate) waterhyacinth. The average yield is 50 tons per hectare, which means, if all were harvested as much as 200 million tons of nonforest raw material could be available for paper production. If only half were used and there was only a 10% conversion efficiency, 10 million tons of paper could be produced from waterhyacinth. This has not happened, but it is possible if factories were built and harvest procedures were developed. Paper making seems to be a better option than enduring the weed's bad effects or continuing to try to control it, which has been largely unsuccessful.

The bulrush has been identified as a way to remove pollutants from water (Zandstra and Motooka, 1978). Sudanese tribesmen have used it cheaply and effectively. Muddy water from the Nile River is stored in jars containing bulrush, and soon one has clean, pure water. A German company designed a municipal water treatment facility using bulrushes to take up pollutants such as phenols, cyanide, phosphates, and nitrates. Commercialization may not be possible, but we should be cognizant of potential uses for the plants we so easily call weeds. Germans have also experimented with Sakhalin knotgrass, which takes up cadmium and lead without self-injury. They hope it will be useful to reclaim soil treated with metal-contaminated sewage sludge so crops can be grown.

During the 1970s, there was great interest in developing systems to use plants to process sewage. Jewell (1994) reported on a hydroponic or nutrient film technique originally developed in England. The technique does not require deep water or a growth-supporting medium. Most terrestrial plants can be grown in a nutrient film system. Cattails, a common weedy species, have been a good choice for the initial stages of sewage treatment in a nutrient-film system (Jewell, 1994).

VIII. OTHER USES

Bliss (1978) includes 50 common weeds that can all be used to make dye. Some produce quite durable colors; some, in Bliss's words, produce "more exciting and richer shades"; and some produce colors that are more resistant to fading in light. None of those she identifies are rare or endangered; some are invaders, some native, and some are introduced—but they are all just weeds. Plants useful as a source of dye include common ragweed, showy milkweed, dandelion, field bindweed, leafy spurge, musk thistle, redroot pigweed, and yellow sweetclover.

The common water reed, ground into powder, can be used as a home heating fuel, according to Swedish scientists (Bjork and Graneli, 1978). One kilogram of dry reeds will yield 5 kilowatts of energy. About 10 times more energy can be obtained from the powder than is required to cultivate, harvest, grind, and transport it. Cultivation of the weed could greatly increase production per unit area and may have the added advantage of preserving and using some portions of wetlands now threatened by development. Preservation of such lands has positive environmental benefits in terms of habitat for marsh animals and waterfowl.

Scientists at the University of Arizona have compressed Russian thistle to make fireplace logs (Tumble Logs™) with an energy value equal to lignite. Scientists are also investigating the biomass potential of mesquite, saltbush, and johnsongrass for energy production.

During World War II, allied forces lost the world's Far Eastern sources of natural rubber. The war could not be fought without rubber for tires, and there was a great effort in the early 1940s to develop alternative sources or substitutes for natural rubber. Gray rabbitbrush and guayule (wy-oo-lee) were among the plants studied. Gray rabbitbrush contains a high-grade rubber called chrysil that vulcanizes well (Ross, 1976). One-fourth of guayule's entire weight is natural rubber. It can be grown on land not suited for many other crops and can be mechanically harvested. There is interest in guayule and other plants as sources of hydrocarbons for replacement of expensive and increasingly scarce petroleum oil. There are several latex-bearing plants from the *Euphorbiaceae* (spurge) and *Asclepiadaceae* (milkweed) families. Many are common weeds or perhaps just plants that aren't even sufficiently noticed or bothersome to be raised to the defined category of *weed*.

For a brief period, the US military used "down" from mature cattail heads (actually part of the female flower) to fill life jackets, which had been filled with kapok, the silky fiber from the fruit of the silk-cotton tree. It has also been used to insulate clothing and as stuffing for quilts and pillows. Western Indians ate young shoots, roots, stem bases, and seeds. The same "down," the pappus from female flowers, was used to make dressings for burns, for padding, and in talcum powder.

If none of these ideas interests you and you like plants, buy a few acres of land and plant milkweed, a hardy perennial that competes well with most plants and, once established, should thrive with care and pest control. A crop of milkweed can be grown with about three-quarters of the inputs and about one-quarter of the water that corn requires. For years most agriculturalists have regarded milkweed not as a crop but as a persistent, perennial, hardy weed. One must grant that it is a survivor but also that it has never been an aggressive invader or a troublesome weed in crops. It is commonly found in pastures, roadsides, and open fields. There are at least 107 species of milkweed (Schwartz, 1987). The genus propagates by seed and by vegetative buds on the spreading underground root system. The interaction between milkweed and the monarch butterfly is a classic in ecological studies. Monarchs feed on milkweed foliage and store its toxic alkaloids in their tissues, which makes the butterfly unpalatable to birds (Morse, 1985). But it can be and is being grown as a crop in western Nebraska (Witt and Knudson, 1993; Witt and Nelson, 1992). Milkweed was first grown as a crop after research by Melvin Calvin in California suggested that plant biomass could be used to produce oil. Milkweed was attractive because its seeds contained high quantities of compounds from which oil could be extracted. Standard Oil of Ohio began a research program and found that the cost of producing synthetic crude from milkweed was too high and the yield was too low to make the operation profitable. The work also revealed that the seed pappus (floss) had potential as a substitute for goose down and for use in disposable products that required absorbency (e.g., diapers).

Milkweed's produce, in the form of the seed pod, can be harvested, carded to remove seeds, dried, and the pappus or floss can be used as an acceptable substitute for expensive goose down in jackets, sleeping bags, and other items designed to trap air and keep us warm (Lione, 1979); it also has absorbance qualities. Natural Fibers, Inc. of Ogallala, Nebraska, has made great strides toward commercial production of milkweed fiber for use in down comforters and pillows. Their advertisements proclaim, "Nothing warms you up like Ogallala down." (Further information about the company can be found in the 1992 US Department of Agriculture yearbook.)

THINGS TO THINK ABOUT

1. How many uses can you think of for a plant you thought was just a weed?
2. Are there situations where we ought to encourage weed growth in crops?
3. Should genetic engineering be used to create useful weeds?

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CHAPTER 5

Weed Reproduction and Dispersal

FUNDAMENTAL CONCEPTS

- The soil seed bank in most agricultural soils includes millions of weed seeds per acre and is the primary source of yearly weed problems.
- There are many methods for dispersal of weed seeds in space. These involve plant mechanisms, man-aided, mechanical, water-aided, and animal-aided systems of dispersal.
- Continued development of understanding of the processes of seed germination and the physiological and environmental factors that affect it is essential to development of good weed management systems.
- Seed dormancy is dispersal of seeds in time.
- Vegetative reproduction creates some of the most difficult weed management problems because vegetative reproductive organs are hard to reach with available control measures.

OBJECTIVES

- To learn the size and role of the soil seed bank and aerial seed sources.
- To understand how seeds are dispersed in space.
- To understand how seeds are dispersed in time via seed dormancy.
- To understand the causes, classification, and role of weed seed dormancy.
- To know the methods of vegetative reproduction and understand its role in weed management.

Indeed, as I learned , there were on the planet where the little prince lived—as on all planets—good plants and bad plants. In consequence, there were good seeds from good plants, and *bad seeds from bad plants. But seeds are invisible. They sleep deep in the heart of the earth's darkness, until some one among them is seized with the desire to awaken. Then this little seed will stretch itself and begin—timidly at first to push a charming little sprig inoffensively upward toward the sun. If it is only the sprout of radish or the sprig of a rose-bush. One would let it grow wherever it might wish. But when it is a bad plant one must destroy it as soon as possible, the very first instant that one recognizes it.*

The Little Prince by Antoine de Saint-Exupéry

Look at the seed in the palm of a farmer's hand. It can be blown away with a puff of breath and that is the end of it. But it holds three lives—its own, that of the man who may feed on its increase, and that of the man who lives by its culture. If the seed dies, these men will not, but they may not live as they always had. They may be affected because the seed is dead; they may change, they may put their faith in other things.

West With the Night by B. Markham

Weed biology is a part of weed science devoted to the study of the growth, development, and reproduction of weeds. While this is not a book about weed biology, biological knowledge is essential to understanding the fundamentals of weed science and to the development of appropriate weed management systems. It is widely agreed among weed scientists that weed biology is an important but, sad to say, largely ignored part of weed management (Forcella, 1997).

This chapter is divided into four sections that examine the reproduction and dispersal of weeds. The first section discusses seeds and their production, the second includes dispersal of seeds in space, and the third deals with seed germination and dispersal of seeds in time or seed dormancy. The last section covers vegetative or asexual reproduction.

I. SEED PRODUCTION

Seeds are alive, and they are a source of life. A seed is a mature fertilized ovule or plant embryo that has stored energy reserves (sometimes missing) and has a protective coat or coats. It is a small plant, packaged for shipment. Survival of many flowering plants depends on production of a sufficient number of viable seeds. This is especially true for annual weeds that reproduce by seed, and, therefore, prevention of seed production is the key to elimination of future problems. Failure to prevent production of weed seed results in increasing numbers of seed in soil and, subsequently, weeds in crops and landscapes.

The damage done to soil by the moldboard plow and how such plowing made the weed problem worse were not discovered in the last few decades, with the advent of minimum tillage and no-till farming. Faulkner (1943) questioned the very basis of agriculture: the plow. Organic material was not well incorporated into soil by the moldboard plow, but weed seeds were. Faulkner proposed that farmers should be able to farm without weeds. It was what he called a "fantastically improbable" proposition, and it may still be regarded as highly improbable. He suggested that what the moldboard plow did was bury weed seeds "for future recovery every time" the land is plowed. For him it was the secret of weed perpetuation and more recent research indicates he was right. In a five-year Iowa study, prior to plowing a hay sward, weed seeds were concentrated in the upper 10 cm of the soil. After moldboard plowing, weed seeds were uniformly distributed throughout the upper 20 cm of soil (Buhler et al., 2001). Farmers thus became victims of their system of handling the land and many still are. Weed seeds are difficult to manage because they are (1) small, (2) abundant, and (3) produce a lot of seed.

A. Seed Size

Seeds produced by most weeds are small. For example, broadleaf plantain has over 2 million seeds per pound, and shepherd's-purse nearly 5 million. Small seeds are easily dispersed by wind and water, and their size precludes easy detection until they germinate and a plant emerges above the soil surface.

B. Seed Abundance

The number of weed seeds in arable soil is large. Koch (1969) estimated that the average arable soil has 30,000 to 350,000 weed seeds per square meter (300 million to 3.5 billion per hectare, or 120 million to 1.4 billion per acre).

In lowland (paddy or irrigated) rice fields in the Philippines, 804 million seeds from 12 different species (sedges dominated) were found over 1 hectare 6 inches deep (Vega and Sierra, 1970). Samples of soil on Minnesota farms averaged 1,600 seeds per square foot, 6 inches deep, or 70 million seeds per acre (Robinson, 1949). Other estimates range from 10.8 to 332 million seeds per hectare (Klingman and Ashton, 1982).

C. Seed Production

In a 15-acre field that had been regularly cropped for several years, seven species were 90% of the total weed population. Good weed control reduced this up to 54% in continuous corn (Schweizer and Zimdahl, 1984b) and 26% in rotational crops in one year (Schweizer and Zimdahl, 1984a). Redroot pigweed populations declined 99% from 1.07 billion to 3 million seeds per hectare 25 centimeters deep (10 inches) after six years of weed control in continuous corn. Common lambsquarters declined 94% from 153.6 billion to 8.6 million seeds per hectare 25 centimeters deep. The total number of seeds declined 98% from 1.3 billion to 20.7 million seeds per hectare, 25 centimeters deep (Figure 5.1). Despite this great reduction, there would still be 192 weeds per square foot of soil if all seeds germinated in one year, but that never happens. The seed bank, enormous at the beginning of the experiment, was still large after six years of good weed management. It is generally assumed that 2% to 10% of weed seeds in the soil seed bank emerge each year. With 192 weed seeds per square foot, we would expect 4 to 20 plants per square foot—still a weed problem that must be dealt with. Emergence from

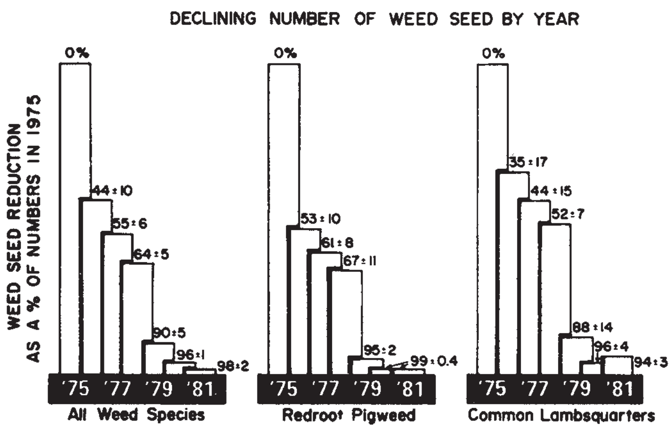


FIGURE 5.1. Percentage decline in the number of weed seeds for all weed species, redroot pigweed, and common lambsquarters after six years of continuous corn. Standard errors shown for each weed species and year (Schweizer and Zimdahl, 1984a). Reprinted with permission of Weed Sci. Soc. Am.

weed seed banks from Ohio to Colorado and Minnesota to Missouri showed for 15 species found on three or more sites; average percent emergence varied from 0.6 for prostrate knotweed to 31.2 for giant foxtail. Six species had greater than 15% emergence in three or more years, four had between 5 and 8.5, and five others had less than 3.5% emergence (Forcella et al., 1992, 1997). Two to 10% is a reasonable average emergence percentage, but there is large variation among species.

In a study with continuous corn (Schweizer and Zimdahl, 1984b), when atrazine was discontinued as the primary herbicide after three years, redroot pigweed seed numbers rose to 608 million (Figure 5.2). Common lamb's quarters rose to 22.8 million, and the total number of seeds rose to 648.1 million per hectare 10 inches deep. This contrasts with a steady decline with continued weed management (Figure 5.2). The point is that in this system, and in all cropping systems, if weeds are neglected even for just one cropping

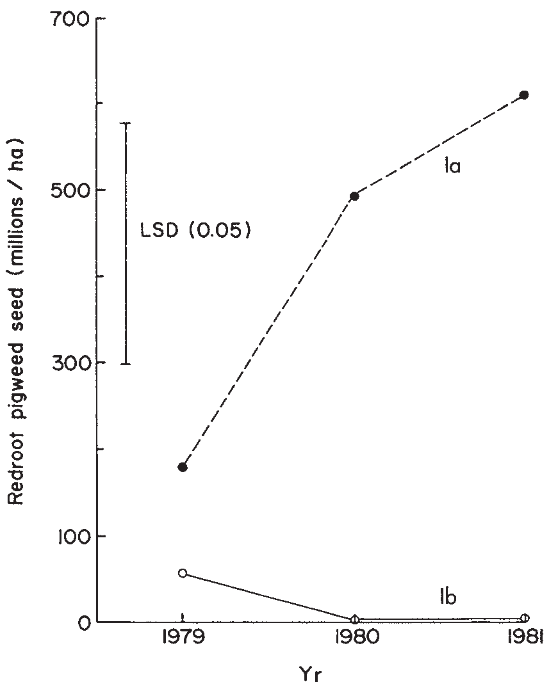


FIGURE 5.2. Number of redroot pigweed seeds present in soil each spring following conventional tillage and atrazine use in continuous corn. In weed management system Ia, 2.2 kg/ha atrazine was applied preemergence for six consecutive years, beginning in 1975. In weed management system Ib, the same rate of atrazine was applied for the first three years, and then discontinued (Schweizer and Zimdahl, 1984a). Reprinted with permission of Weed Sci. Soc. Am.

season, soil seed populations and the annual weed population rebound rapidly.

In rotational crops of barley, corn, and sugarbeets, the total number of weed seeds declined 96.4% from 1.4 billion to 50 million per hectare 10 inches deep after six years of weed management (two rotational cycles) (Schweizer and Zimdahl, 1984a). The number of redroot pigweed seeds declined over the six-year period, but the percentage of *Chenopodium* species increased because oakleaf goosefoot was more tolerant of cultivation and to the herbicides used than common lamb's quarters.

After one cropping year, the decline in the number of redroot pigweed and *Chenopodium* species seeds was 34 and 22%, respectively (Figure 5.3). The next significant decline did not occur until after the fourth cropping year. After the sixth cropping year, the decline in the number of redroot pigweed and *Chenopodium* sp. seeds was 99 and 91%, respectively (Schweizer and Zimdahl, 1984a). These data illustrate that weed seed populations can be reduced quickly, but continued attention is required to prevent a rapid increase when a few plants survive.

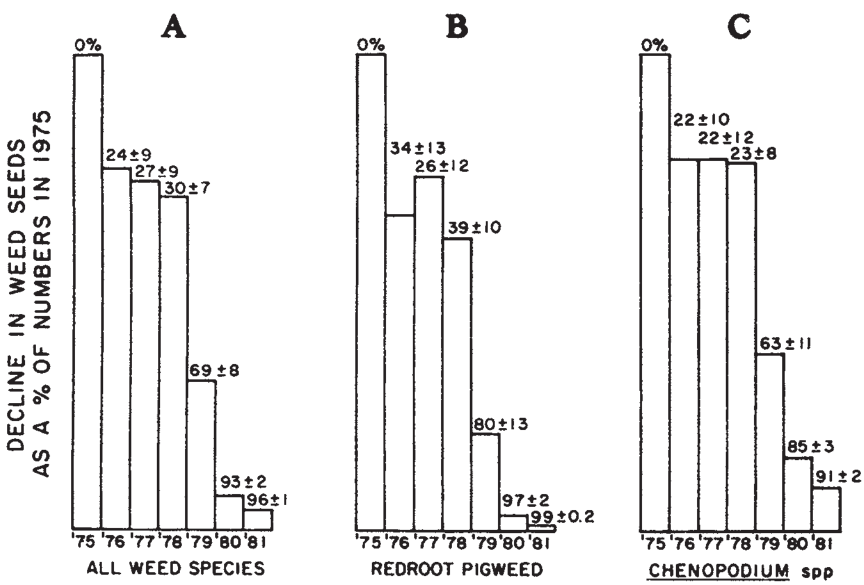


FIGURE 5.3. Percentage decline in the number of weed seeds for (A) all weed species, (B) redroot pigweed, and © *Chenopodium* spp. when averaged over cropping sequence and weed management systems after six years of crop rotation. Standard errors shown for each weed species and year (Schweizer and Zimdahl, 1984a). Reprinted with permission Weed Sci. Soc. Am.

Some weeds can produce viable seed by apomixis (nonsexual reproduction, e.g., dandelion), and others are wholly self-fertile (e.g., shepherd's-purse). Weather before or during flowering is not important because with apomixis, seeds are set without pollination and with self-fertility, fertilization occurs before flowers open. These plants escape normal photoperiodic effects on flowering.

When one examines the seed-producing capacity of several weed species, it is not surprising that a few survivors rapidly increase the number of seeds in the soil bank. Data from single, undisturbed plants are shown in Table 5.1 (Stevens, 1932). The data purport to show maximum seed production and illustrate that production potential is high for many common weeds. These data have been cited in many weed science textbooks and are regarded as accurate, but there are reasons to question their accuracy. Stevens's (1932, 1957) work on 234 species was done with seed collected from diverse habitats in several US states. If the studies were redone with carefully controlled conditions, identified seed sources, and plants growing in isolation with free root growth, seed production would likely be higher.

TABLE 5.1. Number of Seeds Produced per Plant and Number of Seeds per Pound for Several Common Weeds (Adapted from Stevens, 1932, 1957).

Plant common name	Number of seeds per plant	Number of seeds per pound[a]
Stevens 1932		
Barnyardgrass	7,160[b,c]	324,286
Black nightshade	8,460	197,391
Buckwheat, wild	11,900	64,857
Charlock	2,700	238,947
Common cocklebur	440	2,270
Toadflax	2,280	3,242,857
Dock, curly	29,500	324,286
Dodder, field	16,000[c]	585,806
Field bindweed	50	14,934
Foxtail barley	2,420	403,555
Giant ragweed	1,650	26,092
Kochia	14,600	534,118
Common lambsquarters	72,450	648,570
Black medic	2,350	378,333
Common mullein	223,200	5,044,444

(*Continues*)

TABLE 5.1. (*Continued*)

Plant common name	Number of seeds per plant	Number of seeds per pound[a]
Black mustard	13,400	267,059
Yellow nutsedge	2,420[d]	2,389,484
Wild oats	250[b]	25,913
Redroot pigweed	117,400[b]	1,194,737
Broadleaf plantain	36,150	2,270,000
Common evening primrose	118,500	1,375,757
Prostrate knotweed	6,380	672,593
Common purslane	52,300	3,492,308
Common ragweed	3,380[b]	114,937
Sandbur	1,110[b]	67,259
Shepherd's-purse	38,500[b,c]	4,729,166
Pennsylvania smartweed	3,150	126,111
Leafy spurge	140[d]	129,714
Stinkgrass	82,100	6,053,333
Common sunflower	7,200[b,c]	69,050
Canada thistle	680[b,c]	288,254
Witchgrass	11,400	698,462
Stevens 1957		
Annual bluegrass	2,050	2,270,000
Catchweed bedstraw	105	59,737
Chicory	4,600	567,500
Common chickweed	600	1,173,127
Common milkweed	600/stem	77,080
Dandelion	12,000	709,375
Giant foxtail	4,030	238,947
Prickly sida	510	142,320
Prostrate knotweed	4,600	504,444
Redroot pigweed	229,175	1,335,294
Toothed spurge	835	97,634
Velvetleaf	4,300	51,885
Venice mallow	58,600	181,600
Wild radish	1,875	53,412

[a]Calculated from the weight of 1,000 seeds.
[b]Many immature seeds present.
[c]Many seeds shattered and lost prior to counting.

Barnyardgrass illustrates the point. Stevens (1932) reported that one plant produced 7,160 seeds. Barrett and Wilson (1981) reported 18,000, and Holm et al. (1977) up to 40,000. Research in California (Norris, 1992) predicts that barnyardgrass growing in sugarbeets averages nearly 100,000 seeds/plant and some larger plants produce more than 400,000. Reeves et al. (1981) found that wild radish produced 1,030 seeds per plant with only one plant per square meter. When there were 247 wild radish plants on each square meter, seed production dropped to 67 per plant. Russian thistle plants typically produce about 250,000 seeds (Young, 1991).

Research in irrigated row crop rotations suggests cropping sequence is the dominant factor that influences species composition of the soil seed bank (Ball, 1992). Herbicides and other cultural techniques vary between crops and shift seed bank composition in favor of less susceptible species. In irrigated row crops dominant species were more prevalent near the surface after chisel as opposed to moldboard plowing (Figure 5.4). The number of species increased more after chisel plowing, and there was a greater decrease after moldboard plowing (Ball, 1992). In a similar study, weed seed numbers dropped more under continuous corn and increased in mechanically weeded plots (Posner et al., 1995).

Forcella et al. (1992) studied weed seed bank size in eight US corn belt states and found total density ranged from 600 to 162,000 seeds/square meter for three annual grasses, redroot pigweed, and common lambsquarters and

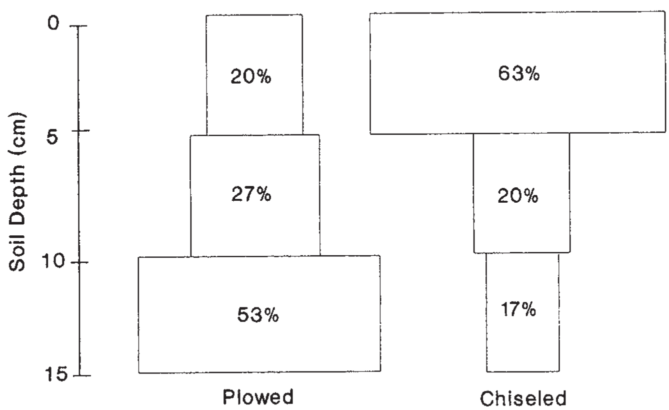


FIGURE 5.4. Influence of primary tillage on vertical distribution of total weed seed to a 15 cm depth in the soil after a dry bean crop (Ball, 1987). Reprinted with permission Weed Sci. Soc. Am.

that 50 to 90% of the total seedbank was dead. Seedling emergence was inversely related to rainfall and air temperature in April and May, presumably because anoxia from high water content and high soil temperature induced secondary dormancy or killed the seeds. Forcella et al. (1992) found viable seedlings were less than 1% of the seedbank for yellow rocket to 30% for giant foxtail.

II. SEED DISPERSAL

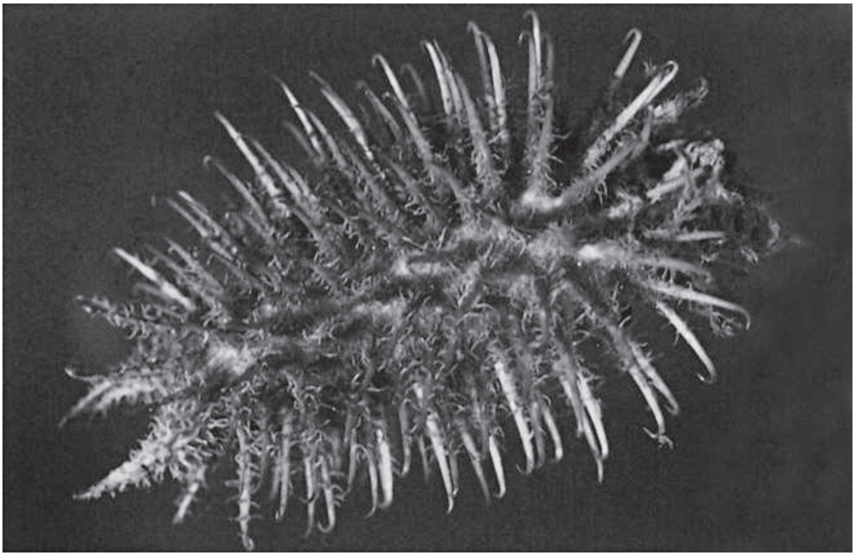
Weed problems would be much less complicated if weed seeds just fell off plants and gravity determined their destination. One of the most obvious features of many weed seeds is some structure that gives seed buoyancy in air or the ability to attach to something.

A. Mechanical

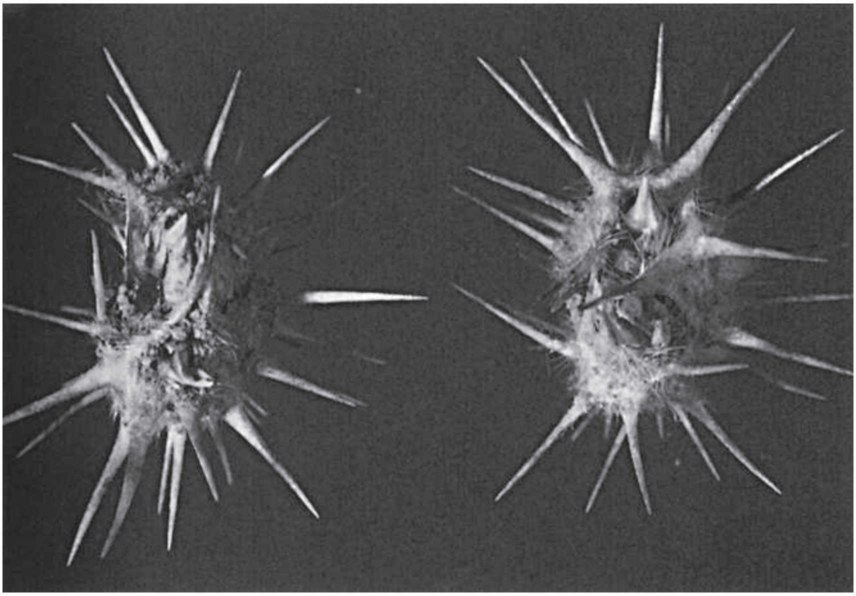
The long, slender awn of needle and thread grass moves about easily by attaching to socks and other articles of clothing or to an animal's fur. The hooks on the aggregated cluster of flowers, properly called the capitulum, that form the burlike structure of cocklebur (the fruit) and hold its seeds (achenes) facilitate transport.

Burs of sandbur consist of one to several spikelets surrounded by an involucre of spiny, scabrous bristles. The burs of sandbur and the spines on the fruit of puncturevine penetrate shoe leather and tires. Bicycle riders are familiar with the hazards of puncturevine and sandbur because the bristles so easily penetrate bicycle tires. Seed transport is facilitated by their sharp spines.

The seed pod of devil's-claw is 2 to 4 inches long, with a curved beak longer than the body of the pod. At maturity, the pod divides into two opposite incurved claws with an inwardly hooked, pointed tip to form an ice tong-like structure that easily attaches to livestock or equipment. The seed pods of devil's-claw, a stout, much-branched, bushy plant, fall to the ground at maturity. When they dry and dehisce, those in-curved hooks can easily grab socks or legs and enlist them, involuntarily, to move their seeds. Another form of mechanical transport of seed is illustrated by curlycup gumweed, a biennial or short-lived perennial that reproduces by seed. The flower heads are bright yellow, ½ to 1 inch across and covered with a sticky resin. The sticky achenes facilitate seed transport.



The bristly capitulum of cocklebur.



The spikes of puncturevine seed pods.

In 1948, a Swiss amateur mountaineer and inventor, George de Mestral, was walking with his dog in the mountains near Geneva. When he returned, he noticed that he had burdock burs attached to his pants, jacket, and wool socks, and they were also in his dog's fur. De Mestral must have been a good observer—the type of individual who sees what he is looking for when it's there, who does not see what he is looking for when it's not there, and who sees what he is not looking for when it is there. De Mestral did not go walking just to collect burdock burs on his clothing. However, he saw them and observed what he was not looking for when it was there. Microscopic examination revealed the unique hook of the burdock bur that allowed it to attach to the wool of his clothing. Following his observation, and after more than seven years of study, he duplicated the grasp of the bur with nylon, and in 1955, he patented his invention, Velcro™ (from the French *velour*, meaning "velvet," and *cro*, meaning "croc or crochet" hook). De Mestral formed Velcro industries, which was able to sell more than 60 million yards of Velcro each year. Now Velcro is a generic term, and Velcro fasteners seem to be everywhere in modern society: children's clothing, airplanes, shoes, and artificial heart valves. It is worth considering that this amazing invention was the result of a good observer's interest in how one weed disperses its seed into space.

B. Wind

Many seeds have structural modifications that permit transport by the wind. One commonly observed example, although not a weed, is the winged seed of maple trees. Among the weeds examples of modification for transport by wind include the silky, white pappus on dandelion achenes, the white, downy pappus on Canada thistle achenes, and the tuft of silky hairs on seed of showy milkweed. Many people have seen seed of one or more of these species moving with a summer breeze. Most seed is light (see number per pound in Table 5.1) and can move over great distances with very light winds. The data in Table 5.2 illustrate seed dispersal by wind. On bombed sites in London after World War II, 140 different species of flowering plants were observed, and those that established first, about 30% of the total, were distributed by wind (Salisbury, 1961).

Another method of wind dispersal is found in Russian thistle or tumbleweed. A mature Russian thistle plant is nearly round. When mature, it breaks

TABLE 5.2. Rate of Fall of Seeds Through Still Air (Salisbury, 1961).

	Time to fall 10 feet (seconds)	
Plant	Average	Range
Coltsfoot	21.3	14–45
Annual sowthistle	8.5	4.5–12
Groundsel	8.0	6.0–12
Smallflower galinsoga	3.4	2–5

off at the base, and because it's round, it can tumble or roll with the wind. The seeds, held by a series of twisted hairs, are released gradually as the plant rolls and bumps and the hairs break. Other plants that roll to disperse seed include tumble pigweed and witchgrass. In the latter case, only the inflorescence breaks off and rolls.

C. Water

In the western United States and other areas where irrigation is common, many seeds are dispersed by water. In Nebraska, Wilson (1980) found seeds of 77 different plant species in three main irrigation canals over two seasons. He collected a total of 30,346 seeds. Approximately 30% were viable, and about 26 times more were found at the end than the beginning of canals. Most seed floated. Redroot pigweed was 40% of the total seed. He estimated 120,000 seeds per acre per year entered fields from irrigation water. In the western United States, surface water irrigates more than 19 million acres each year and is an often unrecognized source of weeds in irrigated fields.

It is not illogical to assume that because seeds are living organisms they will die quickly when submerged in water. In fact, seeds live a long time under water (Table 5.3). The curly dock fruit is a winged achene, and the entire structure floats a long time before sinking. When seeds are deposited in water, the potential problem hasn't disappeared, it's moved. A Washington study (Comes et al., 1978) found 82 species in irrigation water. Twenty-four species lost viability after storage in water for 12 months or less; however, 27 endured more than 12 and some as long as 60 months. After 12 months, seed of 22% of annual monocotyledons germinated, and seed of 75% of perennial monocotyledons and annual and perennial broadleaved species germinated.

The dandelion seed ready for wind dispersal.

TABLE 5.3. Germination of Weed Seeds After Storage in Fresh Water (Sources: Bruns and Rasmussen, 1953, 1957, 1958).

Species	Period of storage (months)	Germination (%)
Field bindweed	54	55
Canada thistle	36	About 50
	54	None
Russian knapweed	30	14
	60	None
Redroot pigweed	33	9
Quackgrass	27	None
Barnyardgrass	3	Less than 1%
	12	None
Halogeton	33	Less than 1%
	12	None
Hoary cress	2	5
	19	None

D. Human-Aided

Even though humans have the burden of controlling weeds in our crops, we are a primary source. We fail to screen or clean irrigation water and facilitate spread by mechanical means. The pattern in which the United States was populated offered a unique opportunity for spread of weeds from the east to the west coast and from the two coasts inland. Fogg (1966) pointed out the predominance of species of European origin in the United States. Fogg found that about 12.5% (1,051) of the flowering plants and ferns of central and northeastern United States and adjacent Canada in *Gray's Manual of Botany* were of foreign origin, and 692 of these were from Europe. About 14% (1,200) of the species in Gray's manual are recognized as weedy, and European species dominate. Not all of them are weeds, but 60% of the 1,200 plants are from only seven plant families (Table 5.4). The species in the seven plant families are primarily herbaceous (not woody), produce abundant seed, and are aggressive invaders or pioneering plants (see Chapter 7)—that is, they have some of the traits that make weeds successful.

The United States, a major recipient of weeds because of immigration, has also distributed weeds to others. A good example is parthenium ragweed, imported to India from the United States with shipments of grain during the early 1960s. It is an annual that has spread over large areas of southern India and is especially problematic because it contains an irritating, human skin toxin. The weed's common name in parts of India is AID weed, from its identification with grain distributed by the US Agency for International Development (US/AID). Weeds and their seeds have been imported to many countries in forages and feed grains.

TABLE 5.4. Families of Introduced Weed Species Introduced from Europe to the United States (Fogg, 1942, 1966; Hill, 1977).

Family	Number of species introduced from Europe
Asteraceae	112
Poaceae	65
Brassicaceae	62
Labiatae	60
Leguminosae	54
Caryophyllaceae	37
Scrophulariaceae	30

There is a story, perhaps apocryphal, that Canada thistle was brought from Canada to the United States to feed the horses in British General John B. Burgoyne's army during the Revolutionary War. The British plan in 1777 was to divide the states by the line of the Hudson River. General Burgoyne was to proceed from Canada by way of Lake Champlain, which forms part of the boundary between northern New York and Vermont. The campaign began in January, and Burgoyne was defeated on October 7 at the second battle of Bemis Heights (near Saratoga, New York). He surrendered his entire force on October 17. Burgoyne had to feed his army's horses and brought hay contaminated with Canada thistle from Canada. The weed is now ubiquitous in the northern United States. It is worth noting that Canada thistle is called California thistle in Australia, a name indicative of where the Australians think it came from.

Weed seeds are also regularly transported in feed for cattle. Millers usually clean seed received for storage or processing. Screenings can contain weed seed and are routinely transported and used as cattle feed. There is nothing wrong with their nutritional value. Seed viability can be destroyed by cooking, but screenings are of low value, and this is usually not done; the seeds are fed whole. Tables 5.5 and 5.6 show examples of seed screenings that have been transported into Colorado. It is obvious that these sources of animal feed can be important sources of weed seed, and similar examples can be found for most places.

Grinding in a hammer mill does not completely destroy seed viability (Zamora and Olivare, 1994). Less than 1% of spotted knapweed, sulfur cinquefoil, timothy, and alfalfa seeds were intact after passing a 1 mm screen in a hammer mill. Of the four plants, only sulfur cinquefoil failed to germinate.

It is common for farmers to assume that once a crop is harvested and weeds are ensiled (stored in a silo) weed seed can be forgotten about. In general, this is true (Table 5.7). The pH of corn silage is between 4.5 and 5.8 and decreases with age. Most seed will completely lose germination after three weeks' storage in silage. It is also true that the organic acid content of silage is 1.5 to 2%, and silos quickly become anaerobic, both of which lead to seed death (Table 5.7). Downy brome, foxtail barley, and barnyardgrass lost all viability after being ensiled for eight weeks or undergoing rumen digestion for 24 hours (Blackshaw and Rode, 1991). The same study showed 17% of green foxtail seed was viable after 24 hours of ruminant digestion. No wild oats survived rumen digestion in the first year, but 88% did in a second year of the study. This was

TABLE 5.5. Composition of Seed Screenings Analyzed by the Colorado State Seed Laboratory.

Seed	Number/pound	Number in average truckload ($\times 10^6$)
Common Lambsquarters	155,700	6,228
Redroot pigweed	9,225	369
Kochia	1,800	72
Russian thistle	900	36
Common sunflower	225	9
Foxtail		
Yellow	225	9
Green	1,575	63
Total noxious	2,700	108

TABLE 5.6. Composition of Seed Screenings Analyzed by the Colorado State Seed Laboratory.

Item	Number/lb.	Number of seeds in shipment ($\times 10^6$)
Sample I		
Noxious weed seeds	13,511	540.4
Common weed seeds	142,650	5,706.0
Crop seeds	8,280	
Sample II		
Noxious weed seeds	2,700	113.4
Common weed seeds	279,665	11,745.9
Crop seeds	30,150	1,266.3

TABLE 5.7. Effect of Ensiling on Viability of Weed Seeds (Tildesley, 1937).

	Percent germination		
Weed species	Month before	2 Weeks after	4 Weeks later
Quackgrass	99	0	0
Barnyardgrass	61	0	0
Yellow foxtail	20	0	0
Wild buckwheat	64	0	0
Common lambsquarters	82	34	0
Cowcockle	68	0	0
Field pennycress	77	0	0
Wild mustard	93	0	0

attributed to the different diet in the two years of the study that changed the rumen bacterial population.

E. Animal-Aided

One might think that if seed is fed to cattle, there is no problem because cattle chew things and rumen digestion is thorough. There is, however, a potential problem. In one experiment (Beach, 1909), a Jersey cow was fed 6 pounds of flax seed containing 212,912 weed seeds per pound. The seed had 26.4% viability—not atypical for weed seed in feed. The cow voided 40 pounds of feces per day, and 1 ounce of feces contained about 1,000 weed seeds, of which 4.5% were viable. Harmon and Keim (1934) confirmed that passage through an animal's digestive tract reduces but does not eliminate weed seed viability, with viability after digestion ranging from 6.4% for sheep to 9.6% for calves. Chickens destroyed all but 0.2% of viable seed.

Even after weed seeds have been voided in manure, they can reinfest soil. Seeds left in cattle manure in the field had only 3.1% germination, whereas top-dressed manure hauled directly from the barn had 12.8%. Plowing under fresh manure increased seed germination to 23% (Oswald, 1908).

Ridley (1930) listed 124 species whose seeds were dispersed by cattle. In 36 samples of cattle manure from 20 New York dairy farms, viable seed from 13 grasses and 35 broadleaved species were found (Mt. Pleasant and Schlather, 1994). Four of the farms had cattle manure with no weed seed, while the others averaged 75 to 100 weed seeds/kg of manure. The authors concluded that manure can add seed to fields, but the numbers are small compared to the soil seed bank. In contrast, in Iran, sheep manure added 10 million seeds/hectare each time it was put on soil and was a more important source of new weed seed than the crop seed the farmer planted (182,000 seed/ha) or irrigation water (120 seed/ha) (Dastgheib, 1989).

Other research from several areas confirms the successful passage of weed seed through cattle (Atkeson et al., 1934; Burton and Andrews, 1948; Dore and Raymond, 1942; Gardner et al., 1983). Data from a study (Thill et al., 1986) of common crupina, an introduced winter annual invader of rangelands in Idaho, show that its seed can be spread by cattle, deer, horses, and pheasants, but achenes were not found in sheep feces. The data support the contention that weeds are spread by game birds, wildlife, and domestic livestock.

The previous data established that many weed seeds can pass through the digestive tract of several different animals without loss of viability. Some seed remains viable even after passage through the digestive tract and storage in manure (Harmon and Keim, 1934) (Table 5.8). These data are confirmed by

TABLE 5.8. The Effect of Storage in Cow Manure on the Viability of Weed Seeds (Harmon and Keim, 1934).

Weed	Viability before storage (%)	Viability after storage for months (%)			
		1	2	3	4
Velvetleaf	52.0	2.0	0	0	0
Field bindweed	84.0	4.0	22.0	1	0
Sweetclover	68.0	22.0	4.0	0	0
Peppergrass	34.5	0	0	0	0
Smooth dock	86.0	0	0	0	0
Smartweed	0.5	0	0	0	0
Cocklebur	60.0	0	0	0	0

TABLE 5.9. Germination Tests on Weed Seeds Before and After Passing Through the Digestive Tract of Cattle and After Three Months' Storage in Manure (Atkeson et al., 1934).

Weed species	Percentage germination before feeding	Percentage germination after 47 hours digestion	Percentage germination after 47 hours digestion plus storage in manure	Percentage decrease due to manure storage and digestion
Redroot pigweed	98	36.0	11.5	88
Common lamb-squarters	70	58.0	22.0	69
Alfalfa	86	17.0	80.0	7
Buckhorn plantain	94	16.0	0.0	100
Curly dock	95	58.0	3.0	97
Green foxtail	21	19.5	0.0	100
Wild oats	74	10.0	0.0	100

studies that show the effect of digestion and manure storage on germination of seed of several different species (Table 5.9).

Common crupina seed (Thill et al., 1986) passes through the digestive tract of pheasants without loss of viability. Other data (Proctor, 1968) show that viable seed can be retained 8 to 12 hours in the digestive tract of birds. Seed smaller than 1 millimeter in diameter and having a hard seed coat can be retained more than 100 hours. Birds are agents for weed seed distribution. Still viable field bindweed, little mallow, and smooth sumac seeds were regurgitated from the digestive tract of killdeer (*Chiradrius vociferus*) after 144, 152, and 160 hours, respectively. Velvetleaf seed was intact for 77 hours. Seed of many species can remain intact and viable in the intestinal tract of some birds long enough to be transported several thousand miles.

F. Machinery

An important source of weed seed is the farmer's grain drill box. A 1965 study on the western slope of Colorado included 42 drill box samples, obtained by going to the farmer's field during planting. A grain probe removed a sample from the drill box in the field, and analysis of the 42 samples showed that 33% contained prohibited noxious weed seed and 74% contained restricted noxious weed seed. The farmers surveyed were planting an average of 2,300 noxious weed seeds per acre. One farmer was planting 13,000 field bindweed seeds and another 14,000 wild oat seed per acre. A second Colorado study included 22 random samples. Fourteen percent of the drill boxes had prohibited noxious weed seed, and 77% had restricted noxious weed seed. The average was 6,600 noxious weed seeds planted per acre. An Iowa study showed 73% of oat seed was combine-run and had greater than 20 weed seeds per pound. Sixty-three percent of all the oats tested contained prohibited or restricted noxious weed seed.[1] In Minnesota, 343 drill box samples averaged 150 weed seeds per pound. One sample of red clover had 24,000 dodder seeds per pound and was, therefore, 10% dodder (Dunham, 1973).

The wide availability of certified seed has reduced this problem, but it still exists. As late as 1988, 31.3% of wheat, barley, and oat samples taken from grain drills in Utah were infested with an average 313 weed seeds/pound of grain (Dewey and Whitesides, 1990). The worst sample found had 11,118 weed seeds in each pound of grain. Non-noxious weed seeds were found in 107 samples (23.8%), and noxious weeds were in 76 samples (16.9%). Wild oats were the most common noxious weed seed, occurring in 14% of samples at an average density of 2,136 seed per 100 kg of crop seed (Dewey and Whitesides, 1990). A decline from 52% of contaminated drill boxes in a 1958 survey was noted.

The cardinal rule of weed management is to buy and plant clean seed. Most farmers in the world's developed countries buy seed from a dealer and are confident it is free of weed seed and diseases and has high germinability. This is not true in most of the world's developing countries, where farmers keep harvested grain for planting the next year. Seed is often contaminated when harvested with weed seeds and seed-borne pathogens, and the harvested grain

[1]Personal communication. Colorado State Seed Laboratory, Colorado State Univ.

may have poor germination. The best, the most efficient weed management method in these situations is one that emphasizes prevention of the problem before it occurs rather than weed control in the following crop.

Another important way people affect weed seed dispersal is through movement of farm machinery, especially itinerant grain combines and accompanying trucks. Spread of many weeds is aided by itinerant combine harvesters that move from field to field, often across large areas of the country. Itchgrass has grown wild in Louisiana sugarcane since the 1920s. It started to migrate when soybean farming expanded. Sugarcane has long been grown in Louisiana, and cane processing machinery is a likely vector, but it rarely leaves a farm. Soybean farming has expanded, and because soybean harvesting machinery is often itinerant, itchgrass has spread with itinerant soybean combines.

Some weeds are dispersed by combines because weeds are harvested with the crop, and weed seed is dispersed by the combine as straw is spread on the field. Other weeds (e.g., wild mustard and field pennycress) shed seed before harvest in the US Northern Great Plains. Wild oats, downy brome, and Canada thistle shed seed before and during harvest. Green and yellow foxtail, barnyardgrass, quackgrass, redroot pigweed, kochia, wild buckwheat, common lamb's quarters, field bindweed, and Russian thistle shed seed during and after harvest, and combine harvesting facilitates seed dispersal (Donald and Nalewaja, 1991). These weeds make harvest more difficult by accumulating on the harvester's cutting bar and adding weight and green material to the combine's load and to harvested grain.

Movement and storage in combines are of concern because it has been shown that seed of slimleaf lambsquarters, venice mallow, and curly dock grew better when collected from combines that were harvesting hard red winter wheat than when the seed was harvested by hand from weedy plants in the same field (Currie and Peeper, 1988). Mechanical abrasion or scarification in the combine was the likely cause.

Johnson and Mullinix (1995) suggest that soil tillage distributes weed seed because it affects weed emergence and hence seed production. Crop cultivation, a useful weed management tactic, has been correlated with midseason emergence of Florida beggarweed in peanut (Cardina and Hook, 1989). Mechanical control is discussed more fully in Chapter 10.

The number of weed seeds in the plow layer of soil can be reduced by repeated tillage (Chancellor, 1985). With optimum rain, 50% of the weed seed in the plow layer of vegetable crop fields germinated within six weeks of cultivation (Bond and Baker, 1990). Egley and Williams (1990) increased weed emergence with frequent tillage over four years. Subsequently tillage had no effect on emergence, suggesting the seed bank had been depleted. In Minnesota, wild mustard seed in soil was reduced 97% after seven years of tillage (Warnes and Anderson, 1984). In Alabama, purple nutsedge was eradicated after five months of weekly or biweekly harrowing (Smith and Mayton, 1938). Therefore, it is logical to conclude that soil tillage plays an important role in the availability of seed for dispersal by encouraging seed germination and in reducing seed production by destroying emerging seedlings.

G. Mimicry

Gould (1991), in discussing the evolutionary potential of crop pests, said "Of all the crop pests, weeds boast the longest recorded history of adapting to agricultural practices." Weeds use two mechanisms to survive between cropping seasons: seed dormancy and crop seed mimicry. The second technique is basically hiding in crop seed to be planted the next year. It was the easiest technique because it avoided all the perils of remaining in the field, exposed to the environment and to predators. Weedy plants, by evolving to mimic the seed size, shape, or color of the crop they infest, are passed on by humans who plant contaminated seed. Gould (1991) cites mimicry of lentil seeds by common vetch, flax seed by species of falseflax, and rice by barnyardgrass. In the latter case, the mimicry is in plant morphology and growth habit, not seed (Barrett, 1983). Because the plants are very hard to distinguish visually, they are not removed by hand. The foregoing examples are of unrelated plants, but Gould (1991) also cites mimicry in closely related wild and domestic rices.

H. Other

Other sources of weed infestations are associated with human activities. It has been suggested that downy brome first entered California in packing material for glassware shipped from Europe. We also spread weeds growing in nursery stock and ornamentals. Highway construction that demands "fill" soil can easily spread weeds and their seed over wide areas.

I. Consequences of Weed Dispersal

It is useful to know that weeds are dispersed in many ways, but it is more important to understand that dispersal of seeds has real consequences. For example, data from the US Bureau of Land Management show that alien plants (some of which may be weeds) are expanding their territory by 14% each year or, in other terms, 2,300 acres each day (Culotta, 1994). Leafy spurge landed in the Great Plains in 1909 and found no natural enemies. It now covers 1.2

million acres in North Dakota (McGrath, 2005). More than 60% of the 1,350 acre Devil's Tower National Monument in Wyoming has been taken over by leafy spurge which some regard as the worst of the bad weeds. Leafy spurge cost the Dakotas, Montana, and Wyoming an estimated 140 million dollars each year in lost revenue and control costs (McGrath, 2005).

Rush skeletonweed, originally from the Balkans, was first spotted near Banks, Idaho, in 1954. In 10 years it had invaded 40 acres, and by 1994 it was on 4 million acres in Idaho alone (Culotta, 1994). The land occupied by rush skeletonweed now has very low species diversity and high soil erosion.

Weeds don't just affect crop and rangeland. The Sellway-Bitterroot Wilderness in Idaho has prime stream habitat for salmon, but some areas of riverbank are covered with spotted knapweed. Other species don't grow with spotted knapweed, so the soil is bare between the plants. When it rains, erosion increases, soil enters the water, and the quality of the salmon spawning area declines (Culotta, 1994).

The weedy tree melaleuca (see Chapter 7) has invaded and taken over more than 450,000 acres of the Everglades and tropical wetlands of south Florida (Schmitz, 1995). Melaleuca is a native of Australia, where it is kept in check by over 400 insect species. It is expanding its range in Florida by 50 acres a day.

In their book, Randall and Marinelli (1996) describe 83 foreign invaders and correctly note that they can "change fundamental ecosystem processes such as the frequency of wildfires, the availability of water or nutrients, and the rate of soil erosion." Weedy invaders such as melaleuca "change the rules of the game." Invaders that don't change basic ecosystem processes cause other problems. In forests, invading trees and vines can grow into the canopy and shade desirable species. Shrubs can dominate midstory areas, and herbaceous species can colonize and dominate the forest floor. Prairies and other grasslands across the United States and in other countries are severely infested by nonnative weedy species that are also crop weeds, such as leafy spurge and yellow starthistle. Randall and Marinelli (1996) also point out that on wetlands in the northern third of the United States and southern Canada, purple loosestrife has formed large, dense stands that have displaced native plants and changed, and in many cases eliminated, waterfowl habitat. Chapter 7 is a presentation of the relationship between invasive species and the fundamentals of weed science.

III. SEED GERMINATION—DORMANCY

So far, two steps involved in plant reproduction have been considered: seed production and seed dispersal in space. The third aspect of reproduction of concern to weed managers is seed germination. What is really of interest is not the fact that seeds germinate but the fact that they *do not* germinate because they are dormant. Dormancy is dispersal in time as opposed to dispersal in space. Dormant seeds can be dispersed in space without losing their dormancy. Dormancy is not well defined. To be dormant is to be sleeping or inactive. In biology, it's regarded as a state of suspended animation—alive but not actively growing. Thus, dormancy is defined as something that seeds *don't* do—germinate—as opposed to something they do. Scientists have described types of dormancy but because the basic regulatory processes are unknown, it is difficult to define types of dormancy or to extrapolate from one species to another (Dyer, 1995).

The interaction of several factors that affect seed germination and seedling survival is illustrated well by the work of Rice (1985, 1987, 1990) on *Erodium* species in California. He examined (1985) the role of germination cueing in the dynamics of introduced broadleaf filaree and a second species (*Erodium brachycarpum*) populations exposed to local environmental variation in California grasslands. Temperature fluctuations were more important than temperature maxima for increasing germination rates. Light during germination had no effect on germination rate. There was a significant adaptive value for germination cueing in both species. Increased germination observed for both species exposed to temperature fluctuations supported the contention that high temperatures and temperature fluctuations were major factors that promoted the softening of hard seed. Softening (dormancy breaking) was most affected by temperature fluctuations. The persistence of both species was enhanced by periodic soil disturbance by pocket gophers (Rice, 1985, 1987). Small mammal (voles and pocket gophers) herbivory prevents *Erodium* from colonizing areas of disturbed soil in grasslands that have not been grazed by sheep. Vigorous herbivory of seedlings and flowers by small mammals has a strong negative effect on *Erodium* growth. Grasslands protected from sheep grazing do not have either species of *Erodium*. Sheep grazing, because it removes surface litter on which small mammals feed, is an important factor in preventing *Erodium* colonization of gopher mounds that occurs in the absence of sheep grazing. Sheep grazing promotes growth of *Erodium* populations.

Reproductive inequality of both species increased with increasing plant density and productivity (Rice, 1990). Seed production was controlled by rainfall. The magnitude of reproductive inequality was dependent on the interactions of sowing density and rainfall distribution. The importance of rainfall as a determinant of population is illustrated by the observation that at low sowing density, rainfall pattern had no effect on reproductive inequality. Rainfall's effect was seen only at the highest sowing density. "Effective population number was relatively insensitive to increases in population density because of increased inequality in reproduction at higher population densities" due to the rainfall effect.

A. Causes

Chepil (1946) was one of the first to report on periodic seed dormancy and germination among weeds. The phenomenon has since been documented for seed of many annual weeds (Dyer, 1995; Karssen, 1982). Dormancy is a highly developed specialization and a complex research problem. Most seed will germinate when proper environmental conditions exist, but not all do. Soil disturbance may or may not initiate special germination mechanisms. Changes in soil temperature, soil water content, light, surface drying and wetting, or percent of oxygen or carbon dioxide in soil air can create or break dormancy. Soil microflora play a role, as they control oxygen and carbon dioxide content of soil air. One microsite location, a habitable site, may provide appropriate conditions for germination, while a nearby, uninhabitable site may not. There is a range of special requirements for germination and other special conditions that impose dormancy.

If one wants to become famous in weed science—indeed, in agricultural science—it could be accomplished by figuring out how to do one of two things. The first is to make most (perhaps all) weed seed in soil or those shed from plants dormant forever. The second is to make most or all weed seed in soil germinate immediately. Because seed dormancy is a complex environmental/physiological/biochemical phenomenon, it is unlikely any magic bullet solution will ever be found. As weed science moves closer to understanding seed dormancy, it could greatly reduce the need to control annual weeds and perennials that reproduce by seed. It would take time to deplete soil seed banks, but once that was done, the need to control most annual weeds would decrease. If we could make most seed of annual weeds in the soil seed bank germinate just before frost in the temperate zones, frost would kill most of them. In the tropical dry season, weeds could be managed with tillage. Because weeds have periodicity of germination, timing of tillage and planting is now altered when possible to encourage or discourage weed seed germination (Dyer, 1995; Gunsolus, 1990).

Weeds share many traits with what ecologists call early successional species (Roberts, 1982). Indeed, they are often the same species. For early successional species, seed germination is closely linked to soil disturbance that ensures the availability of resources for growth. Germination soon after soil disturbance reduces the probability of competition with later successional species or crops. Early successional species and many weed seeds usually require light for seed germination, and exposure to light is increased by tillage. Seed germination is favored by fluctuating temperatures and low carbon dioxide concentrations, and it may be affected by alternate wetting and drying cycles that tend to break seed coats. All of the conditions favorable for seed germination occur on disturbed sites, and cropped fields are good examples of disturbed sites.

Seeds of early successional species and many weeds are dormant when shed and can quickly develop secondary dormancy. Induced dormancy (dependent on environmental interaction) is common. Early successional species grow rapidly above and below the soil and thereby escape the surface zone of maximum environmental variability and stress. Early successional species have a high photosynthetic rate over a wide range of soil water conditions. Photosynthetic rate and environmental resource demand decline quickly with declining soil water potential, permitting survival. Weeds and successful early successional species compress environmental extremes. They are able to maintain constant leaf temperatures to ameliorate stress. They also acclimate rapidly to variable environments. Genotypic plasticity facilitates their adaptation.

Seed dormancy is the most important characteristic for perpetuation of annual weed species and perennials that reproduce by seed. Seeds of annual weeds germinate under a narrow range of environmental conditions; they are specialists in utilizing their opportunities.

Most weed control techniques treat symptoms rather than the problem itself. Weed control acts on problems either just before they appear (preemergence) or after they have appeared (postemergence). There are no reliable methods for eliminating weed problems by preventing seed dormancy or encouraging germination of dormant seed. Improved weed management depends on better understanding of seven environmental conditions that cause or terminate seed dormancy.

Light

Of the known causes of dormancy, light may be the most important. At least half of the annual weeds in crops have seed that requires light for germination. This is especially so for small-seeded annual weeds. Length of day and the quality of light are also important. The light requirement is regarded as an evolutionary advantage for small-seeded plants that may not survive germination from lower in soil (Pons, 1991). Light only penetrates 1 or 2 mm in soil, so dormancy can be induced even by shallow burial. Germination of mullein, curly dock, common evening primrose, and buttercup seed is favored by light. Seed of common chickweed, common purslane, johnsongrass, kochia, lambsquarters, prostrate knotweed, and redroot pigweed require light for germination. However, seed germination of wild onion and jimsonweed is favored by darkness. Dormancy of crop seed has been nearly eliminated by breeding light response out of the genome, and most germinate in light or dark.

The phytochrome group of photoreceptors, the primary system responsible for light interactions in plants, controls breaking dormancy with light. In a simple, but accurate, sense, phytochrome exists in two forms: a promoter and inhibitor. The promoting form is favored by red light and the inhibitor by far-red light. This is the same general response and the same pigment that is involved in flowering. The quantity of each form of phytochrome present at a given time is related to light and more precisely to the ratio of red to far-red light. Sunlight has abundant red light and promotes germination of imbibed seeds. Seeds do not respond to light unless they have taken up water (imbibed).

Light effects on phytochrome and seed germination

Inactive form (P_r) + red light, 600–680 nm → P_{fr} and germination promotion

Active form (P_{fr}) + far-red light, 700–760 nm →
P_r and germination inhibition

Light is needed for seed germination of many species, though it is clear that burial in soil will inhibit germination and should be used as a weed control technique. Continued seed burial is encouraged when farmers shift to minimum and no-tillage practices.

Unfiltered light contains a preponderance of the red wavelength that shifts phytochrome to the active (P_{fr}) form and promotes seed germination. Leaf canopies filter red light because chlorophyll absorbs it strongly. A leaf canopy shifts light transmission toward far-red and depresses germination of seeds below.

Immature Embryo

A second cause of dormancy is the presence of an immature embryo. Smartweed and bulrush seeds are typically shed from the plant with an immature embryo and are incapable of immediate germination. This is another example of a mechanism evolved to prevent germination at the wrong time.

Impermeable Seed Coat

Seeds of redroot pigweed, wild mustard, shepherd's-purse, and field pepperweed often have seed coats impermeable to water, oxygen, or both, and the seeds are called "hard." It is another dormancy mechanism. The seed coat can be changed (often referred to as "broken") by scarification, action of acids, or microbes. A hard seed coat presents mechanical resistance to germination because the radicle can't penetrate it. Even though water and oxygen can be absorbed, the hard seed coat prevents germination. In the laboratory, scarification or breaking of a hard seed coat can be accomplished by rubbing on sandpaper, dipping in acid, or pricking with a pin. Such techniques are obviously inappropriate for the field, but the same thing is accomplished by tillage. Anything that stirs or moves soil will inevitably move seeds and abrade seed coats.

Inhibitors

Some seeds are shed with endogenous (internal) germination inhibitors (e.g., abscisic acid). These varied and complicated chemical inhibitors prevent seed germination until they are removed by leaching with water or by internal metabolic activity. There are also exogenous (external) germination inhibitors that will be discussed in Chapter 8.

Oxygen

Partial pressure of oxygen affects seed dormancy. Percent oxygen in soil varies from less than 1% in flooded soil to 8 or 9% in a soil with good tilth, cropped with corn. Soil carbon dioxide content may vary from 5 to 15%. One of the reasons most seed germinates only near the soil surface is higher oxygen concentration. Soil compaction reduces seed germination, and the mechanism may be reduction of the partial pressure of oxygen.

Temperature

There is a minimum temperature below which no seeds will germinate and a maximum temperature above which germination will not occur. The precise minimum and maximum vary among species, as does the optimum temperature for germination. In late spring, Russian thistle seed germinates readily between 28° and 110°F (Young, 1991). Wild oats will germinate at 35°F (1.7°C), which is lower than the temperature at which seed of wheat or barley germinate. Temperatures of 40° to 60°F (4° to 15°C) are required for germination of seed of some winter annual weeds. Higher temperatures lead to dormancy. Redroot pigweed seed kept in a germinator at 68°F (20°C) will remain dormant up to six years. It can be induced to germinate at any time by alternating storage temperature or by partial desiccation. Germination can be induced by raising the temperature to 95°F (35°C) for a short time, rubbing the seed, and then lowering the temperature to 68°F.

After-Ripening Requirement

There is an after-ripening requirement for some seed. This is not the same as an immature embryo. It is a poorly understood physiological change. A seed's embryo is fully developed, but it will not germinate even if oxygen and water are absorbed in the appropriate concentration. Everything appears to be normal, but the seed will not germinate until it has ripened.

B. Classes of Dormancy

Dormancy classifications are based on observed seed behavior, not, as mentioned earlier, on complete understanding of the physiology or biochemistry of seed dormancy. Two classification systems will be presented. In the first, a seed dormant when shed from the plant has primary dormancy. All other manifestations of dormancy are secondary. After primary dormancy has been lost, secondary dormancy may be induced by environmental interactions or other special conditions.

The second system of classification includes three types of dormancy (Harper, 1957). The first is **innate** and has three possible causes. It could be an inherent property of the ripened seed based on genetic control when the seed leaves the plant. There may be an after-ripening requirement, perhaps dependent on receipt of a specific environmental stimulus. There could be a rudimentary or physiologically immature embryo, which is not fully developed when seed is shed, such as smartweed. Innate dormancy can also be caused by impermeable or mechanically resistant seed coats—that is, hard seed. Redroot pigweed, several species of mustard, and all species of wild oats have innate dormancy. A third cause is the presence of endogenous chemical inhibitors. Some species of sumac and fireweed proliferate after forest fires because fire creates permeability in the seed coat and rain leaches out the inhibitor. The amount of an inhibitor is often adjusted to the rainfall of an area. In its simplest form, the presence of an endogenous chemical inhibitor restricts germination to the temperature range where survival is assured. Innate dormancy interacts with the environment because for some species, hot, dry weather during seed maturation yields less dormancy than cool, moist conditions that are more favorable to seedling survival.

When a seed develops dormancy after exposure to specific environmental conditions such as dryness, high carbon dioxide concentration, or high temperature and the acquired dormancy persists after the environmental conditions change, Harper (1957) said it had **induced dormancy**. Seed of winter wild oats and white mustard have induced dormancy that often develops in late spring in temperate climates and persists into fall. Seed buried by tillage may not germinate when brought to the soil surface because of induced dormancy.

Induced dormancy develops due to environmental interaction after seed has been shed from the plant and persists after environmental conditions change. **Enforced dormancy** also depends on environmental interaction but does not persist when conditions change. In the latter case, dormancy can be caused by lack of water, lack of oxygen, low temperatures, and so on. When this external limitation is removed, the seed germinates, and, according to Harper (1957), the seed had enforced dormancy. There is a positive correlation between termination of dormancy and predictable environmental changes.

Wild oats exhibit all three of Harper's classes of dormancy. Harper's system is a classification of mechanism, not of species. In general, termination of dormancy requires exposure to cool, moist conditions, the normal attributes of the transition from summer to fall in temperate zones. Seeds in tropical climates have less and sometimes no seed dormancy.

Figure 5.5 shows how common ragweed succeeds as an early successional plant and a weed. It illustrates integration of Harper's (1957) three dormancy classes (Bazzaz, 1979). Early and late successional environments are different with respect to light intensity and spectral quality. Seed of early successional

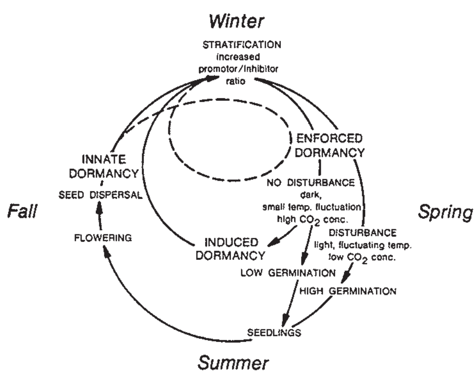


FIGURE 5.5. Schematic representation of seed germination in common ragweed, a common colonizer in old field succession and a spring annual weed. The dashed line represents seeds that require more than one stratification cycle to germinate and thus ensure germination and establishment across a number of seasons (Bazzaz, 1979).

plants (many of which are common weedy species) are sensitive to light, and seed germination is inhibited by light filtered through plant leaves (P_r form). This is not a problem for weeds that germinate early in the season before crop leaves filter light. Their germination is favored by fluctuating temperatures and low carbon dioxide concentrations in soil. They are not sensitive to soil-water fluctuations and other conditions commonly encountered in cropped fields.

C. Consequences of Weed Seed Dormancy

Dormancy is important because seeds survive for long times in soil and are a continuing source of infestation. It ensures survival for many years, and the aphorism that one year's seeding equals seven years' weeding is reasonably accurate. One of the first experiments to investigate consequences of seed dormancy was conducted by Duvel near Rosslyn, Virginia (Toole and Brown, 1946). In 1902, the seeds of 107 different species were buried 8, 22, or 42 inches deep in porous clay flowerpots covered with clay saucers. Samples removed at intervals showed no effect of depth of burial on survival but a tendency toward longer survival at 42 inches than at 8 inches. The results, summarized in Tables 5.10 and 5.11 show significant seed survival for 38 years. Even after 38 years, 91% of jimsonweed seed was still viable and presumably capable of quickly reinfesting a cropped field.

In 1879, William J. Beal (Darlington, 1951), a pioneer in development of high-yield corn hybrids, began an unusual experiment. He buried 20 pint bottles, each containing 1,000 seeds of 20 weed species near his lab on the campus of Michigan State University. His aim, in an era before scientific weed control began, was to find out how long seed buried by plowing could survive and thus how long fields had to be left fallow to ensure a weed-free crop when replanted. Over 100 years later, we know the answer to Beal's question: a very *long* time!

TABLE 5.10. Number of Weed Species Surviving (Toole and Brown, 1946).

Burial period	Species germinating
1 year	71
6 years	68
10 years	68
20 years	57
30 years	44
38 years	36

TABLE 5.11. Germination of Weed Seeds After 38 Years (Toole and Brown, 1946).

91% of Jimsonweed
48% of Mullein
38% of Velvetleaf
17% of Evening primrose
7% of Lambsquarters
1% of Green foxtail
1% of Curly dock

TABLE 5.12. Results of Beal's Buried Seed Study (Darlington, 1951).

Elapsed time (years)	Species still viable	
70	Curly dock	(8)*
	Evening primrose	(14)
	Common mullein	(72)
50	Black mustard	
	Marshpepper smartweed	
40	Common ragweed	
	Common purslane	
	Redroot pigweed	
	Virginia pepperweed	
	Broadleaf plantain	
30	Foxtail	
	Shepherd's-purse	

*( ) = % germination

Beal buried bottles upside down, uncorked, and at an angle so water and oxygen but not light could enter. Initially, bottles were dug up every five years, and since 1950, every 10 years. Results for 30, 40, 50, and 70 years are reported in Table 5.12. After 70 years, curly dock, common evening primrose, and common mullein still germinated. In 1960, three species germinated. In 1970, only one species germinated. In 1980, seeds were planted as usual in soil sterilized by steam. At first, nothing happened. After several weeks, the first seedling emerged; within five months, 29 seedlings had germinated, and 6 died. Of the survivors, 21 were common mullein, 1 was another species of mullein, and 1 was a mallow species that had not germinated since 1899. Enough bottles remain to carry on Beal's experiment until 2040. His work shows that fallowing is not a feasible method of weed control for all species, at least in northern temperate climates.

A study in England (Lewis, 1973), in undisturbed soil, showed that seeds reveal their survival potential during the first four years of burial. Rarely did a species that survived four years not survive 20 years. Seed deterioration occurred more rapidly in acid peat soil than in loam. Seed of the *Poaceae* were generally short-lived, except timothy. Legumes generally persisted for the full 20 years. The weeds that survived best were common lambsquarters (23%), curly dock (18%), and creeping buttercup (53%).

In Mississippi, seeds of several species were buried in plastic, porous bags to simulate natural conditions and avoid the clay pots of Duvel's experiment and the glass jars of Beal's study (Egley and Chandler, 1983). In contrast to Beals's northern temperate study, the primary lesson of the Mississippi experiment is that only about six of the species investigated remained viable after five years' burial if no new seed was introduced (Table 5.13).

Seed of 41 economically important weed species of the Great Plains region of the United States were buried 20 cm deep (plowing depth) in eastern and western Nebraska in 1976 (Burnside et al., 1996). There were 11 annual grass, 14 annual broadleaf, 4 biennial broadleaf, and 12 perennial broadleaf species. Seeds were exhumed after 1, 9, 12, and 17 years. After 1 year, germination was 57% for all annual grasses, 47% for all annual broadleaf species, 52% for biennials, and 36% for perennial broadleaf species. Germination dropped steadily with time for each class. After 17 years, germination was 4% for annual grasses, 11% for annual broadleaf species, 30% for biennials, and 8% for perennial broadleaf species. No explanation was offered for why biennial species survived so well. A conclusion of this study is that after burial at plow depth, germination of annuals will decline rapidly, but biennial species will survive well and become problems in crops. The species with the highest survival after

TABLE 5.13. Viability of Weed Seeds After Burial (Egley and Chandler, 1983).

	Mean viability after burial for years ____ % ____			
Species	0	1.5	3.5	5.5
Velvetleaf	99	89	71	30
Purple moonflower	100	84	65	33
Hemp sesbania	100	77	60	18
Common cocklebur	99	27	10	01
Redroot pigweed	96	24	2	01
Common purslane	99	21	2	01
Johnsongrass	86	75	74	48

17 years was common mullein with 95% germination in western Nebraska. Common mullein was one of the species that survived longest in the Beal (Darlington, 1951) experiment. Weed seed germination tended to be greater in the low rainfall and more moderate soil temperatures of western Nebraska.

Soil in Alaska is cold for more of the year than soil in temperate areas. Two studies in Fairbanks, Alaska (Conn, 1990; Conn and Farris, 1987), showed viability was higher after burial in mesh bags, 15 rather than 2 cm deep after 21 months and after 4 to 7 years. Four of 17 species had 5 to 10% viable seed after 4.7 years, and 8 species ranged from 21 to 39%. Viability of American dragonhead did not change during 4.7 years, whereas viability of common hempnettle and quackgrass was zero after 2.7 and 3.7 years, respectively, and viability of two other species was less than 1%.

Taylorson (1970) found initially that nondormant seed of several weed species lost viability after burial sooner and to a greater extent than initially dormant seed. Zorner et al. (1984) found the same thing for kochia seed. Initial rates of loss were much greater in nondormant than in buried dormant populations. After 24 months of burial, the number of viable seed remaining and the depletion rates were similar for the two populations.

Woolly cupgrass seeds are dormant at physiological maturity and lose dormancy while after-ripening over winter. Seeds buried below the soil surface were less dormant than those that remained on the soil surface (Franzenburg and Owen, 2002).

Studies in Michigan and Indiana showed that seed mortality of giant foxtail and velvetleaf were greatest in soil managed conventionally (using recommended rates of fertilizer and herbicide) and less in soils prepared with reduced management (nutrients from compost or organic amendments and weed control only by cultivation) (Davis et al., 2006). However, it is interesting to note that no measured soil properties were associated with seed mortality. Only management history and the soil fungal population were related to seed mortality. A 35-year study of the effect of tillage and rotation on soil weed seed banks in Ohio showed that the weed seed population in soils with a corn-oat-hay rotation differed in structure and composition from those developed under a corn or corn-soybean system (Sonoskie et al., 2006). Germinable weed seed populations differed in soils tilled conventionally with no tillage or with minimum tillage. One assumes that such things will be true but it is always nice to have confirming data. Because such studies prove that crop sequence and tillage system affect weed seed populations and community structure, it follows that this information can be used to develop weed management systems.

An important problem in all buried seed studies is the necessity of recovering seed from soil, a complex medium. It is hard to find seed, and if longevity is to be estimated, one must be sure the seed found is the seed that was buried.

Therefore, all studies use containers. Recent studies use porous, mesh bags that allow transfer of air and water but don't allow other natural processes, such as abrasion. Because seeds are concentrated, microbial action and seed interactions may be abnormal. It is generally thought that burial studies overestimate seed longevity. Seed dormancy is a major cause of continuing weed problems, and while a great deal is known about what causes dormancy and how to break it, no one knows how to create it, or use it to manage weeds.

In the laboratory, it is easy to create or break dormancy with a variety of seed treatments (Anderson, 1968). These include abrasion, temperature manipulation, and chemical methods. Abrasive methods include rubbing, dehulling, dipping in sulphuric acid, and alternate wetting and drying to break the seed coat. Temperature manipulation is useful to break dormancy and is common in nature. Alternate freezing and thawing often break dormancy. Stratification or exposure to extremely low temperatures will break dormancy in some seed. Stratification is commonly required to break dormancy in temperate weed species but rarely works for tropical species. It may act by decreasing the level of an endogenous inhibitor. Finally, chemical methods are used. Leaching with water may remove a chemical inhibitor, and exposure to light will create chemical changes in seed. Chemicals such as potassium nitrate, gibberellic acid, cytokinins, and auxins are all used and their action is considered to be directed at overcoming the action of or inactivating an inhibitor.

In the field, breaking dormancy, on demand, is more difficult. Laboratory methods are obviously not suitable to field operations where seed can't be seen. Plowing soil is a good way to break dormancy, and, conversely, not disturbing soil is a good way to maintain dormancy of buried seed. Tillage exposes seed to light (see Chapter 10) and temperature changes. Field methods are nonselective and affect all seeds, so in some species dormancy may be promoted, while in others it is broken. Weed management will continue to emphasize weed control until a better understanding of weed seed dormancy is obtained and methods are developed to use that understanding in weed management.

Kremer (1993) points out that "successful weed management in agroecosystems depends on manipulating the weed seed bank in soil, the source of annual weed infestations." In spite of the many successful methods for controlling weed infestations each year, they inevitably appear, and Kremer (1993) correctly suggests the source is the persistent soil weed seed bank. His work describes the many interactions of soil microorganisms and weed seeds. Figure 5.6 shows the potential interactions. The interactions are important to study to understand the survival of weed seeds in soil. But they are also important because, as Kremer (1993) suggests, they reveal that microorganisms may be used to deplete the weed seed bank, an unexploited method of weed management.

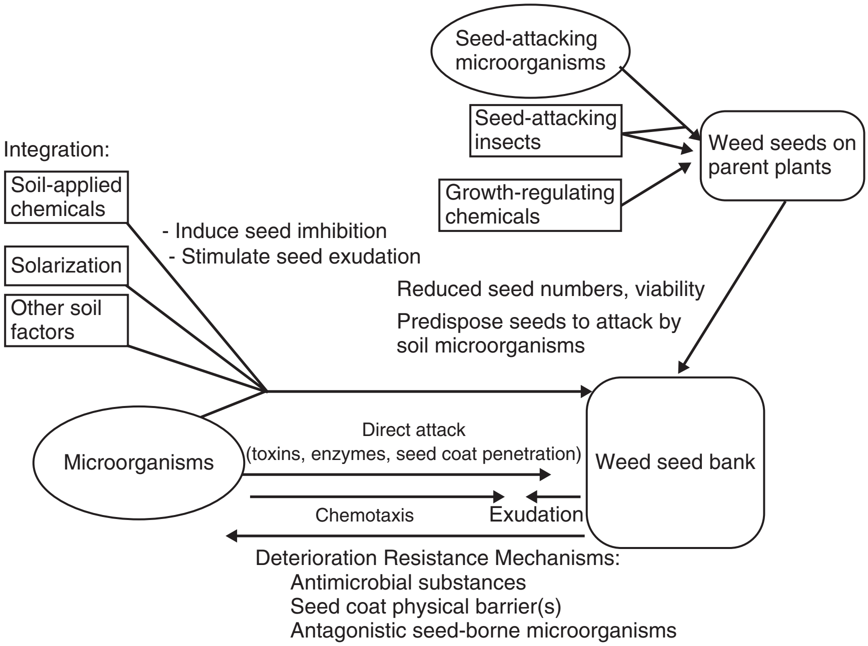


FIGURE 5.6. Relationship of microorganisms and weed seeds in the soil environment. Several methods for depleting the weed seed bank with potential for integration with an approach including microorganisms are indicated. Source: Kremer, 1993. Reprinted with permission.

IV. VEGETATIVE OR ASEXUAL REPRODUCTION

Perennial weeds reproduce vegetatively, a most unfortunate aspect of weed management. Simple and creeping perennials also reproduce by seed, but the importance of seed production varies. A good example is waterhyacinth, whose pretty flowers produce seed pods with up to 300 seeds that can live 5 to 15 years submerged in water. But vegetative reproduction can double the size of an infestation in open water in 10 to 15 days (Leakey, 1981) and produce floating mats that can weigh up to 200 tons per acre. Transpired water losses from mats of waterhyacinth will be three to five times the loss from an open water surface.

The reproductive organ, the depth to which it penetrates soil, and the importance of seed production for several important perennial weeds are shown in Table 5.14. Seed production is not of great importance for Canada thistle, which is dioecious and while the pappus is always produced, it does

TABLE 5.14. Characteristics of Important Perennial Weeds (Roberts, 1982).

Species	Reproductive parts and overwintering state	Depth of vegetative reproductive parts[a]	Importance of reproduction by seed
Bermudagrass	Creeping rhizomes, decumbent stems spread laterally	Shallow	Moderately
Bracken fern	Rhizomes; leaves die	Deep	Reproduces by spores
Canada thistle	Creeping roots overwinter; shoots die	Deep	Occasionally produced
Coltsfoot	Rhizomes; leaves die	Very deep	Important
Common nettle	Rhizomes; short green shoots overwinter	Very shallow	Very important
Creeping bent	Aerial creeping stems overwinter	Above ground	Unknown
Creeping buttercup	Procumbent stems; a few leaves overwinter	Above ground	Very important
Curly dock	Tap roots; rosette of leaves overwinter	Very shallow 7 to 10 cm	Very important
Dandelion	Fleshy tap root; few leaves overwinter	Shallow	Important
Field bindweed	Creeping roots overwinter; shoots die	Very deep	Important
Field horsetail	Rhizomes with tubers that overwinter	Deep	Reproduces by spores
Hedge bindweed	Rhizomes overwinter; shoots die	Deep	Rarely produced
Hoary cress	Creeping roots; small rosettes of leaves overwinter	Deep	Important
Japanese knotweed	Rhizomes, dormant underground buds; shoots die	Shallow	None produced
Leafy spurge	Creeping roots overwinter	Very deep	Very important
Oxalis sp. (woodsorrel)	Bulbils, tap roots, and rhizomes; leaves	Shallow	Important in some
Perennial sow thistle	Creeping roots; shoots die	Very deep	Important
Quackgrass	Rhizomes with dormant underground buds; shoots overwinter	Shallow	Moderately
Red top	Rhizomes with dormant underground buds; shoots overwinter	Shallow	Very important

(*Continues*)

TABLE 5.14. (*Continued*)

Species	Reproductive parts and overwintering state	Depth of vegetative reproductive parts[a]	Importance of reproduction by seed
Roughstalk bluegrass	Short stolons; a few leaves overwinter	Above ground	Very important
Slender speedwell	Stems creeping on the surface	Above ground	None produced
Wild onion	Offset bulbs and bulbils overwinter	Aerial or very shallow	Rarely produced
Yarrow	Stolons; terminal rosettes of leaves overwinter	Very shallow	Very important

[a]Depth varies: Very shallow, 6–10 in.; shallow, 12–18 in.; deep, down to 40 in.; very deep, greater than 120 in.

not always have viable seed attached. On the other hand, seed production is important for leafy spurge, nettles, and curly dock.

Many methods of vegetative reproduction are found among weeds. Stolons or creeping above-ground stems are found in creeping bentgrass and yarrow. Rhizomes are found in Bermudagrass, quackgrass, red top, hedge bindweed, and field horsetail. Bulbs and aerial bulblets are found in wild onion and wild garlic. Goldenrod has corms—thickened, vertical, underground stems that are reproductive organs. Tubers are produced by yellow and purple nutsedge and Jerusalem artichoke. Vegetative reproduction of simple perennials, such as dandelion, is from their taproot.

A seedling of a perennial species growing from seed has not yet assumed perennial characteristics (especially the ability to regenerate vegetatively) when it first emerges from soil, and it can be controlled more easily than after it assumes these characteristics. It is generally considered that quackgrass assumes perennial characteristics within six to eight weeks of emergence and johnsongrass after only three to six weeks. Field bindweed becomes a perennial when it has about 20 true leaves and yellow nutsedge four to six weeks after it emerges from seed. These young plants can be controlled by tillage or hoeing before they assume perennial characteristics.

Seed production of perennials may be unimportant relative to vegetative reproduction (Table 5.14), but it should not be neglected. In April 1990, one field bindweed seed was planted in a small planter and on April 25, the two-leaf seedling was transplanted to a 2 by 4 by 16 foot box. The plant was harvested on October 19 by opening the box and washing all the soil away with water. The seedling had colonized the entire box, and 197 vertical roots, each about 4 feet long, grew a total of 788 feet. Horizontal root runners from the tap root numbered 34, averaged 4 feet long, and totaled 136 feet of length. They had produced 141 new plants. The creeping roots of field bindweed can grow up to 1 and ½ yards in a little more than three months (Frazier, 1943). One little seed produced a major new weed.[2]

A similar experiment was conducted in Colorado[3] with Canada thistle. One seed was planted in a 2 by 4 by 8 foot box of soil in April 1994. In July 1995, the plant was harvested. If the height of all 142 shoots was added together the plant would have been 157 feet tall. There were 331 flowers on 60 shoots. Vegetative buds producing new shoots were found up to 4 feet below the soil surface. Total root length was estimated to be 1,700 feet. Canada thistle roots have been reported to spread up to 5 yards in a single season (Bakker, 1960).

Tillage can worsen the problem after plants become perennial. Canada thistle spreads by creeping roots, and pieces as small as ¼ inch long have produced new plants. Field bindweed spreads by creeping roots, and while they seldom emerge from greater than 4 feet, they can emerge from 20 feet. Pieces as small as 1 inch that contain a bud can produce a new field bindweed plant. Most quackgrass plants, developed from rhizomes, emerge from the top 12 inches of soil. Deep plowing may therefore be a control method if rhizomes can be permanently buried. Most quackgrass roots are 2 to 4 inches below the surface, and shoots do not emerge from deep in soil. The ability of root segments to produce new plants varies with season and is highest in spring and lowest in fall (Swan and Chancellor, 1976). Many root segments produced shoots but regeneration of roots was largely from vertical roots.

Leafy spurge roots penetrate up to 20 feet deep. Over 56% of the total root weight is in the upper 6 inches of the soil profile, and the majority of leafy spurge shoots originates from buds in the top foot of soil. Shoots emerge freely from 1½ feet deep, and some emerge from as deep as 6 feet.

Vegetative buds are not killed by winter freezes. Studies in Iowa on the winter activity of Canada thistle roots showed that buds on horizontal roots continued to develop new shoots until soil was frozen 50 cm deep (Rogers, 1929). When soil finally froze, the shoots were killed but the root bud was not. In January when soil was still frozen the latent buds on large roots were larger than they had been in December. By mid-January these buds had developed thick, vigorous shoots up to 20 mm long. By February, shoots were 4 to 7 cm long, and each had roots 10 to 20 cm long. When the soil thawed, root growth increased rapidly, and green shoots appeared by mid-April. Rogers (1929) noted the cycle of bud and root formation in field bindweed and skeletonleaf bursage was similar to that described for Canada thistle.

[2]Adapted from *Agrichemical Age*, May 1991, p. 16.
[3]Westra, P. 1995. Colorado State University. Personal communication.

THINGS TO THINK ABOUT

1. What is a reasonable range for the number of weed seeds likely to be found in the plow layer of a cropped field?
2. Describe the influence of seed dormancy on weed management.
3. How many different ways are weeds dispersed in space?
4. What are the causes of seed dormancy?
5. What are the classes of seed dormancy? How can these classes be used?
6. How many types of vegetative reproductive organs do weeds possess and why do they make weeds hard to control?

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CHAPTER 6

Weed Ecology

FUNDAMENTAL CONCEPTS

- Weed ecology is the study of the adaptive mechanisms that enable weeds to do well under conditions of maximum soil disturbance.
- There is a strong human influence on weed ecology.
- There are good reasons for the shift toward ecologically based weed management systems.
- Ecological theory has gradually assumed a more prominent role in the development of weed management systems.
- Species are products of natural selection that interact with their environment to obtain the resources for growth. The rate of supply and amount of resources determine growth.
- Plant competition occurs when two or more plants seek what they need and the immediate supply is below combined demand.
- Some plants possess characteristics that make them more competitive than others.
- The effect of weeds on crop yield is best described by regression analysis that yields a straight line relationship for lower densities but a curvilinear relationship over all possible densities.
- Mathematical models are used in research studies of weed management but are not yet widely used by farmers to manage weeds. Models will be used more in the future as they are perfected and tested against biological knowledge.

LEARNING OBJECTIVES

- To understand the importance of ecological relationships to weed management systems.
- To know the components of the weed-crop ecosystem.

- To understand weed-environment interactions.
- To know the factors affecting weed-crop associations.
- To understand the role of fundamental ecological concepts in weed management and weed establishment.
- To be able to define plant competition and to know what resources plants compete for.
- To understand the characteristics that make a plant competitive.
- To appreciate the magnitude of crop yield loss from weeds.
- To understand the current and potential role of mathematical models in crop-weed interference research and weed management recommendations.

American scientific interest from the 18th to the 20th century was dominantly focused not on theory but on the immense practical benefit to be derived from discovering the secrets of the natural world.

Freethinkers—A History
Of American Secularism Book by S. Jacoby

Plant ecologists study the reciprocal arrangements between plants and their environment. The goal is to understand how climate, soil or edaphic, and biotic factors affect plant growth, development, and distribution. Weed scientists are concerned with how weed management affects weed and crop growth and development. For many years, ecologists emphasized only natural environmental factors in studies of reciprocal arrangements, plant distribution, and behavior. Ecologists and weed scientists now realize the importance of the role people play in ecological interactions. The human role is particularly evident with weeds. Integration of ecology and weed science is increasing and will benefit both disciplines.

Ecology is the study of the interactions between individuals and their environment. Weed ecology differs only in that the organisms being studied are weeds (Booth et al., 2003). It gives special emphasis to the adaptive mechanisms that enable weeds to survive and prosper under conditions of maximum soil disturbance. Weed ecologists study the growth and adaptations that enable weeds to exploit niches in environments disturbed by people who must practice agriculture. The most successful weed management programs will be developed on a foundation of adequate ecological understanding. The special questions asked by weed ecologists are those posed by Booth et al. (2003, p. 11):

1. Are there specific characteristics or traits of weed populations?
2. Do weeds function in a certain way within communities?
3. Does the invasion by a weed change plant community structure or function in a predictable way?
4. What types of communities are easier to invade?

High food production from annual crops requires repression of ecological succession (to the left in Figure 1.1). Production of food for humans from natural vegetation is presumed to be low (Figure 1.1). Fiber and food crops have high food production potential, but the fields in which they are grown are disturbed ecological sites. Farming must often work against, rather than with, the natural order to produce high-value food and fiber crops useful to humans. Perennial crops (coconuts, apples) may create a permanent pre-climax state and, although more ecologically stable, will revert to the left side of the curve in Figure 1.1 if not managed to maximize production of what humans want.

Rangelands, forests, and other areas of native vegetation present relatively closed habitats that may resist but are not immune to invasion (see Chapter 7). Most agricultural weeds are not good invaders of natural sites and may not be weedy in the ecological sense on those sites. The dominantly monocultural cropping systems of developed world agriculture seldom use all the moisture, nutrients, or light available in a given field and create open ecological niches that weeds occupy. There are fewer open niches, although there may be unused resources, in undisturbed prairies and forests.

I. HUMAN INFLUENCES ON WEED ECOLOGY

Those who grow crops try to provide pure culture conditions for them and limit the incidence and spread of weeds. The task is complicated because people have carried weed seed across the globe while traveling, in grain, in seed shipments, with armies, and when moving animals. As discussed in Chapter 5, many weeds of temperate Europe and North America migrated west from the early centers of civilization in the eastern Mediterranean region to Europe and hence to the United States with immigrants from Europe to the new world. That is a major reason many (not all) of the dominant US weeds can be traced to Europe rather than Asia. A few examples of people's major, but usually unwitting, influence on weed ecology follow.

When the first settlers came to the US Great Plains and parts of the Pacific Northwest, they found bluebunch wheatgrass and blackseed needlegrass dominating the sides of wagon trails. When roads were cut, downy brome invaded and dominated roadsides. When chemical weed control became available, roadsides were sprayed with the triazine herbicide, simazine, to control downy brome. Simazine worked well, and because it persists in soil, it prevented reinvasion by downy brome and other grasses. It does not control sandbur, which became the dominant species on many western roadsides (Muzik, 1970).

Downy brome had arrived in the interior Pacific Northwest by 1889 (Mack, 1981). It was deliberately introduced at least once in the search for new grasses for overgrazed, denuded range. By 1928 it reached its present distribution (Mack, 1981), although not its current density or ubiquity on over 100 million western US acres (Devine, 1993). Devine calls it the nation's most destructive plant. Downy brome has more than half of the 12 features that Baker (1974) considered characteristics of the ideal weed (Mack, 1981). It thrived in two human-created ecosystems of the intermountain west: winter wheat and rangeland. It persisted as land was converted from one use to the other.

Russian thistle was introduced in grain imported from Russia to a farm in Bonhomme County, South Dakota, about 1877 (Dewey, 1894). By the 1890s the infestation was so extensive in North Dakota that the value of wheat production lost exceeded the taxes collected by the state (Young, 1988). Agriculture created the conditions for the weed's success and humans aided its dispersal. Without agriculture it would have survived but remained innocuous (Young, 1991). The pioneer farmer's practice of destroying tall and midheight prairie grass land to plant cereal grains created the right ecological niche to ensure Russian thistle's success. Russian thistle, similar to many annual weeds, competes poorly with established plants. It cannot tolerate shade or long periods of high moisture (Young, 1991). But it thrived on dry, disturbed, cereal grain land that often was fertilized.

An examination of early weed science literature reveals that the dominant weed problem in many different crops, and especially in small grain crops such as wheat and barley, was annual broadleaved weeds. After the development and widespread use of selective phenoxy acid herbicides (e.g., 2,4-D, MCPA), there was a gradual shift from annual broadleaved weeds, which are controlled effectively by the phenoxy acid herbicides, to annual grass weeds and broadleaved species not susceptible to phenoxy acid herbicides. This induced ecological change was not intentional, but it was inevitable. A similar change has been seen in corn, where the widespread use of triazine herbicides eliminated many annual broadleaved and grass weeds and created an ecological niche for invasion by annual and perennial grass weeds and yellow nutsedge.

Green revolution cultivars created during the 1960s helped feed the world and prevent starvation in many of the world's developing countries. The new cultivars changed the architecture (the shape) of wheat and rice plants and led to higher grain yields when appropriate production needs (fertilizer and irrigation) were provided. The green revolution cultivars also changed the harvest index (proportion of the total plant harvested as grain). Snaydon (1984) posits the main factor leading to an increase in harvest index over several years was selection for shorter straw length, which had important effects on weeds. Short stiffer straw (stems) was less likely to lodge with higher rates of nitrogen fertilizer. This same characteristic also opened the plant canopy to more light and changed the light environment for weeds. This change in plant architecture had the potential to worsen the weed problem by providing more light to stimulate seed germination and growth of seedling weeds. In fact, while weed problems may not have become worse, they did change as new weeds emerged in the changed habitat.

Agricultural practice nearly always has changed for reasons of convenience, to save labor, or to increase profit. Rarely has it changed to intentionally reduce weed growth. The opposite has happened. Indian balsam, a Himalayan wet woodland native, is a showy plant, 2 meters tall, with pink flowers. It found the European climate favorable and escaped but did not become a common weed in Britain until about 1930 when use of artificial fertilizer became widespread. Until then, in attempts to maximize yield, hay was harvested right up to riverbanks where Indian balsam flourishes. When fertilizer was used, yields increased, and harvest of river banks was no longer necessary. The weed then flourished along previously harvested riverbanks. It has been reported that Indian balsam is invading river banks in the Czech Republic and moving to wet woodlands, where it crowds out the forest's less aggressive species (Anonymous, 1995). A shift from annual to perennial weeds has been documented in Japanese rice culture and attributed to the extensive use of herbicides that controlled annual weeds.[1]

United States agriculture has shifted from a mix of crops on a farm to extensive monoculture. Wheat is the dominant crop in the central Great Plains of the United States and soybeans and corn dominate the midwestern states. Cotton and soybeans dominate in the southern states. These monocultural environments create ecological changes that determine what weeds will succeed.

Conscious introduction, multiplication, and release of parasites and predators for biological control of pests are also ecological change. To date, this is a less important shift in ecological relationships than those just mentioned, but the careful weed manager must be aware that such changes may affect weeds.

Each agricultural practice has a potential to influence the density and survival of species in a cropped field. The foregoing is a few examples of how human activity influences weeds. Production practices that influence weeds are shown in Table 6.1 with an estimate of the relative importance of each to species composition and weed density.

[1]Itoh, K. Mat. Agric. Res. Center, Isukuba, Ibaraki, Japan, personal communication.

TABLE 6.1. Components of Production Systems Controlled by Man That Are Relevant to Weed Management.

	Influence on*	
Component	Species composition	Density
Soil tillage	9	9
Water—irrigation	9	5
Nutrient supply—fertilization	9	7
pH—liming	9	5
Date of planting	7	7
Growing period of crop	6	3
Shading period and intensity	6	8
Seed dispersal at harvest	3	5
Seed cleaning before planting	4	2
Weed control	9	9

Source: Koch, W., 1988. Personal communication.
*Influence is ranked on a scale of 0 to 10, with 0 indicating no influence and 10 equaling maximum influence.

Ghersa et al. (1994) state that "in modern agriculture, social and biological systems have diverged" in their influence. Weed management practices are more and more uncoupled from biology. They are controlled and designed by social and economic forces that are often devoid of a biological base. This represents the ultimate human influence on weed ecology because it is neglect of ecology.

II. THE WEED-CROP ECOSYSTEM

Herbicide use has masked the importance of weed prevention and the need to understand weed-crop ecology. Understanding weed-crop ecology will lead to more effective weed prevention, management, and control. The shift toward ecologically based weed management systems is occurring for at least six reasons:

1. Weeds highly susceptible to available herbicides have been replaced by species more difficult to control.
2. Herbicide resistance has developed in many weed species, and some weeds are resistant to several herbicides. Multiple resistance to herbicides from chemical families with different modes of action has occurred.

3. There are weed problems in monocultural agriculture that cannot be solved easily with present management techniques.
4. New weed problems have appeared in reduced and minimum tillage systems.
5. Economic factors have forced consideration of alternative control methods.
6. There is increased awareness of the environmental costs of herbicides.

Aldrich (1984, p. 17) diagramed the weed-crop ecosystem (Figure 6.1). For too long, weed scientists have focused primarily on weed-crop interactions and on protecting crops from weeds. Aldrich strongly suggests that weed management must deal with interaction of all factors rather than just two. There is a lack of knowledge about these interactions. It is not the intent of this book to discuss all ecological interactions in depth; other available books do that well (Aldrich, 1984; Aldrich and Kremer, 1997; Booth et al., 2003; Cousens and Mortimer, 1995; Harper, 1977; Radosevich and Holt, 1984; and Radosevich et al., 1997). It is the intent of this book to introduce the fundamental concepts essential to development of improved weed management systems. Consulting one or more of the preceding seven books will permit those who want to pursue weed ecology in depth to do so.

Weed science has been dominated by control technology that focused on how to control (usually kill) weeds in a crop. As weed management systems are developed, ecological knowledge will be essential and the complexity shown in Figure 6.2 must be considered. As complex as Figure 6.2 is, it is too simple to represent all factors that affect weed-crop relationships that should be considered as management systems are developed.

From genes to organisms (individuals) to populations and communities, relationships are the essence of life. The weed-crop system is a product of

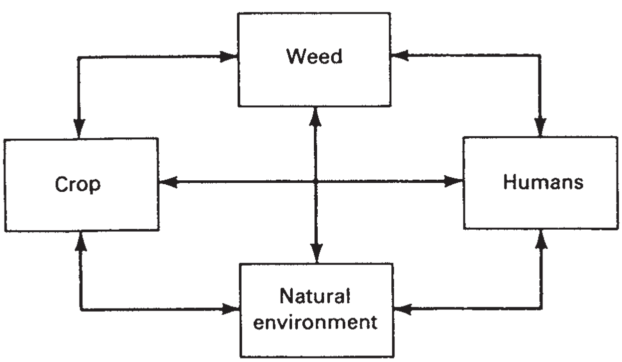

FIGURE 6.1. The weed-crop ecosystem (Aldrich, 1984).

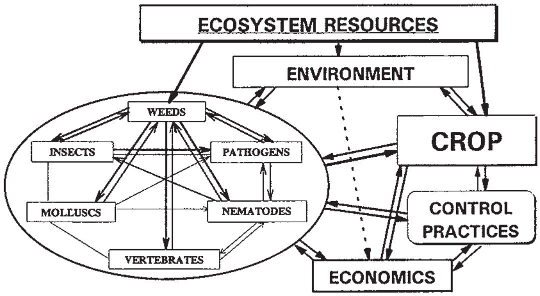

FIGURE 6.2. The interaction of weeds and other components of the agricultural production system (Norris, 1992).

interactions—its essence is relational as illustrated in Figures 6.1 and 6.2. All levels of life are interdependent, and no level can exist independent of another. The individual cannot survive for long independent of its population, nor can a population survive without individuals. Weed management systems directed only at weeds are founded on error and while they may succeed temporarily, they are doomed to fail.

III. ENVIRONMENTAL INTERACTIONS

There are three important weed-environment interactions: climate, soil, and biota or living organisms. These will be discussed separately but cannot be separated in nature, which is characterized by interactions.

A. Weeds and Climate

The important factors that determine a weed's ecological interactions are light, temperature, water, wind, humidity, and their seasonal aspects—the climate. Yellow nutsedge does well in the subhumid tropics and warm, temperate regions. It does not survive well in temperate areas with prolonged frost. Purple nutsedge thrives in the humid tropics and subtropics with some excursions into subhumid temperate regions. Halogeton thrives under desert conditions of low rainfall and sometimes high alkalinity. Waterhyacinth, an important aquatic weed in the tropics and subtropics, has not yet invaded temperate waters.

Weeds are found in the environment they prefer, and weed control or weed management often may be aided by changing the environment. Irrigation and tillage are major environmental changes that lead to shifts in species composition in the affected areas. Changes in tillage practices employed for weed management can affect populations of other crop pests and such changes may also affect weeds (Norris, 2005). Light intensity, quality, and duration affect weed presence and survival. Photoperiodic responses govern flowering and determine the time of seed maturation. If light is too intense or days too long or short, particular plants won't flower and a species may not endure. Light and temperature response determines a species latitudinal limits. Some weeds tolerate shade well and their ability to grow under a crop canopy is one reason they succeed. The length of frost-free period or the time soil is frozen determines any plant's ability to survive in an environment; it determines its ecological relationships. Soil temperature is a primary determinant of seed germination and survival, especially where soil freezes. Freezing also affects winter survival of vegetative reproductive organs. Air and soil temperature are important determinants of species distribution and ecological interactions. Common chickweed survives well in cold climates because it continues to grow in winter without injury (King, 1966). When temperature is below freezing, common chickweed is often erect, and it continues to flower, although the flowers are cleistogamous (without petals and closed). The self-pollinated seeds are fertile.

Karibaweed is sensitive to salinity and grows only in fresh water. The government of Kuttanad, Kerala, India, wanted to develop rice production. Kuttanad is close to the sea, and salt water decreases or eliminates rice production. Traditionally, farmers had built soil barriers across canals and rivers to prevent incursion of heavier salt water during the growing season. After the harvest, the barriers were removed to allow incursion of sea water. Experts in the government planning office "knew" the farmer's practice was not going to be adequate for extensive rice production. Therefore, they built a spill-way channel into the open sea, and salinity was regulated with a 1,400-meter-long regulator channel that checked the advance of salt water. The channel and regulator worked well, and the advance of salt water was halted. Invasion of karibaweed was encouraged because salt water no longer invaded the land annually and killed the weed. Karibaweed stopped rice production because engineers were very good at building structures to stop the sea but knew nothing about weed ecology. The weed won.

Seasonal distribution and total supply of water determine species' survival. Shortage of water at critical stages is often responsible for reproductive failure, death, or both. The world's arid areas would produce far less food if we did not affect seasonal distribution and total supply of water by irrigation.

Wind can affect water supply through evaporation and an increase of transpiration loss. Wind also affects the microclimate within a plant canopy and the relative concentration of carbon dioxide and oxygen.

Climate will change because of increasing concentration of CO_2 and other tri-atomic gases that interact with radiant energy. There are reliable scientific data that show the world is warming and these changes will affect weeds. Agriculture has always been aided and hindered by climate. Crops are vulnerable to unfavorable weather and weed management may be more difficult during rapid climate change (Patterson, 1995b). It is likely that the negative effects of all agricultural pests will increase with rapid climate change, particularly in less intensively managed production systems. Crops affected by environmental (global warming) stress will be more vulnerable to attack by insects and diseases and less competitive with weeds (Patterson, 1995b).

B. Edaphic Factors

Edaphic comes from the Greek *edaphos*, meaning "soil" or "ground." Soil water, aeration, temperature, pH, fertility, fertility source, and the cropping system and associated practices imposed on a soil determine what weeds survive to compete. Many weeds do well in soils too low in fertility for crop production, but others grow only in well-fertilized soil. Few weed species associate with a soil type. Most weeds can be found in soils differing widely in physical characteristics, moisture content, and pH. This adaptability explains, in part, why they are successful weeds. Some species of *Asteraceae* and *Polygonaceae* grow in soils with 1.2 to 1.5% sodium chloride, and while this may not make them better weeds, it illustrates their ability to adapt to diverse environments. Kochia grows well in alkaline or saline soils but not in acidic soil. Saltgrass can be a weed in turf in alkaline areas where soil pH is 8 or above. Alkaliweed grows only at pH 8 and above. Other species, including common mallow and plantain, are relatively intolerant of alkaline conditions. Crabgrass, a turf weed, grows well on acid soil. Kentucky bluegrass is sensitive to acidity, and common chickweed is not common in acid soil (King, 1966).

Soil pH is an important determinant of what plants grow in an area. However, no generalizations can be made about the influence of pH on weeds. LeFevre (1956) reviewed the pH tolerance of 60 weeds and grouped them into Basophile (love high pH, e.g., sow thistles, green sorrel, quackgrass, and dandelion), acidophile (love acid soil, e.g., red sorrel, corn marigold), and neutrophile (e.g., shepherd's-purse, prostrate knotweed, and common chickweed). Some nutrition is essential for plant growth, but most weed species are valueless as indicators of soil reaction or fertility. Luxuriant weed growth does not indicate a potentially highly productive agricultural soil. Weed growth is determined by many factors in addition to a soil's physical and chemical properties. These include field cropping history, proximity of sources of infestation, the weed seed population present or supplied to a field, water supply, and growing season conditions. The effects of soil structure, water-holding capacity, and nutrient level are more important than soil type.

Flooding is a method of weed control. Some water is required for seed germination and plant growth. Too much water changes soil ecology and can control some weeds, as it has in rice for centuries. Several species are adapted to flooding and rice is not free of weeds. No crop plants and few weeds do well in water-logged soil or compact soil with poor aeration.

Warm, moist soil conditions are best for germination of weed seed and seedling growth. Seed dormancy, in temperate regions, is usually associated with cold, freezing conditions.

C. Weeds and Biota

Association of weeds and crops is determined largely by the degree of competition offered by a particular crop and weed. It is also determined by cultural operations and rotational practices associated with each crop. The factors contributing to association include:

Similarity of Seed Size

If a weed's seed is similar in size to a crop's seed, it can be a common, unnoticed companion when planting. It will also be more difficult to clean or separate the weed's seed from the crop's seed (see Chapter 5). Weeds have a long record of adapting to agricultural practice. A striking example of seed size mimicry is that of lentil seeds by common vetch (Gould, 1991). Lentil seed is lens shaped, and vetch seed is usually more rounded. In Europe, vetch seed evolved to mimic the shape of lentil seed and made separation nearly impossible.

Time of Seed Germination and Formation

If a weed's seed germinates just before or only slightly after a crop's seed, the weed's chances of successful competition are enhanced. If weeds flower and set seed before the crop is harvested that may ensure presence in the next crop.

These things do not guarantee successful competition but they are not deterrents to it. A weed whose life cycle is similar to that of the crop will usually be a more successful competitor than one whose life cycle is much shorter or longer than the crop with which it associates.

Tillage, Rotation, and Harvest Practices

Dandelions are common weeds in turf, as are several species of spurge and common chickweed. These are weeds of turf because they are adapted to turf's cultural practices and withstand mowing. The perennial grass quackgrass grows well in the perennial crop alfalfa. The association of wild oats and green foxtail with small grain crops and wild proso millet with corn is related to all of the preceding factors. They have a similar seed size, their time of germination and ripening is nearly identical, and they easily withstand the tillage and harvest practices of the crops. It is unlikely that a weed adapted to survive in plowed fields will do equally well in no- or minimum-till fields (Gould, 1991).

Some weeds germinate after a crop is laid by (after the last tillage has occurred). These include johnsongrass, some of the foxtails, and barnyardgrass. They often germinate later than broadleaved species and elongate rapidly to compete in row crops. Downy brome competes effectively in winter wheat because it germinates in the fall after wheat has been planted, survives over the winter, and develops and sheds seed the next spring, before wheat has completed its life cycle. It is also an effective competitor during the fallow year in a wheat-fallow rotation because it is shallow-rooted, not affected by many cultural operations, and competes for water before the crop has been planted.

Other plants and animals modify the environment; grazing animals determine weed survival in pastures. Knowledge of crop competition and the relationship of weeds and biota is required to develop better control techniques and management strategies.

Plant environments, and especially cropped fields, are very heterogeneous. A height difference between the top of a furrow and the bottom of only 5 cm may represent a factor of 250 for the smallest weed seeds (Aldrich, 1984). When fields are irrigated, fertilized, or cultivated, we perceive uniformity, but across a large or even a small area, weed seeds experience a nonuniform environment. Nonuniform (random) seed distribution in soil is the rule, not the exception. We also know that our management techniques, including herbicides, are not applied uniformly.

There are significant differences in soil temperatures determined by small amounts of litter cover or shading of soil. There are even greater influences on soil moisture and relative humidity of air just above the soil surface, determined by litter and shading. These small environmental differences explain why several different plant species occupy a single environment.

Differences in growth form are often unobserved ecological interactions. These external expressions of a plant's ability to sample its environment are illustrated in Figures 6.3 to 6.8. The differences enable plants to occupy different ecological niches. Weeds create and occupy ecological niches and change the environment through their germination, growth, and death. They affect moisture, temperature, nutrient supply and ultimately organic matter in soil. Weeds are active, not passive, participants in the agricultural environment.

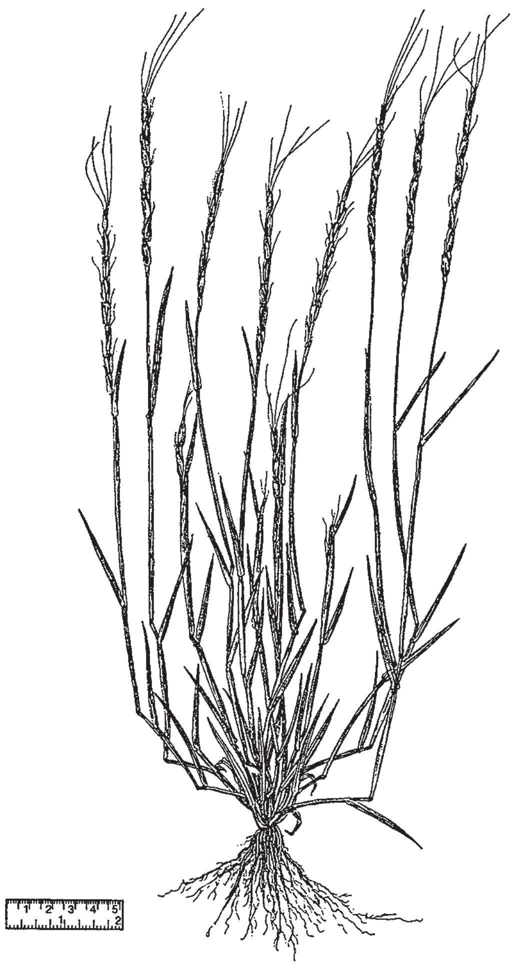

FIGURE 6.3. The upright, narrow, unbranched leaves of jointed goatgrass.

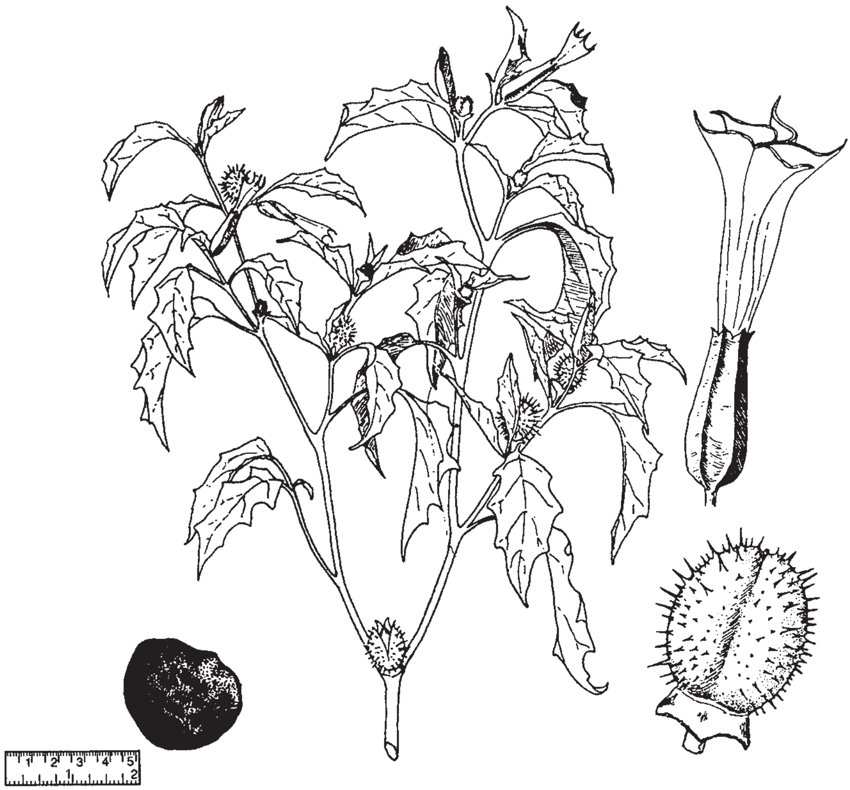

FIGURE 6.4. The upright, branching, broad leaves of jimsonweed.

IV. FUNDAMENTAL ECOLOGICAL CONCEPTS

A. Species

Species is the fundamental biological classification. It is a subdivision of genus, and each is composed of a number of individuals with a high degree of physical similarity that can generally interbreed only among themselves, and show persistent differences from other species. The species *retroflexus* (redroot pigweed) of the genus *Amaranthus* is consistently different from the species *spinosus* (spiny amaranth), and they do not interbreed. Species are products of natural selection and genetic manipulation that create new gene pools. That is *what* happens, but the more important, and more interesting, question is *why* does it happen? Organisms are controlled in nature by the total quantity

FIGURE 6.5. The climbing, twining growth of field bindweed.

and variability of the supply of things essential for growth. All plants have a minimum requirement for various growth factors and interact with their physical and chemical environment to obtain them. Plants also have a limit of tolerance to various environmental components. The *why* question is usually answered in terms of rate and amount. Plant presence and growth are

FIGURE 6.6. The prostrate growth of prostrate knotweed.

controlled by too little or too much of the things needed for growth and by the conditions under which they are available.

Weeds have been continually exposed to conditions that encourage speciation. The major models of speciation are the allopatric and sympatric models. In allopatric speciation, parent species become physically separated into daughter populations by geographic separation that restricts or eliminates gene

FIGURE 6.7. The taproot of redroot pigweed.

flow between the populations. This occurs because of continual movement of people and plants from continent to continent or to different regions within a continent. When weeds are introduced between continents, species development is a long-term process. Allopatric speciation is the primary mechanism for development of new species. Darwin's Galapagos Islands finches are an example of allopatric speciation. Although many weeds may have originated from allopatric speciation there are no good examples. Weeds have been

FIGURE 6.8. The fibrous roots of downy brome.

imported to many places (see Chapters 5 and 7) but there has been little to no study of allopatric speciation of weeds. We assume that is what has happened.

In sympatric speciation, a parent species differentiates in the absence of physical restriction on gene flow. Sympatric speciation is a local, short-term process. The continual disturbance of land and changing agricultural practices provide numerous opportunities for hybridization, selection, and response to imposed and shifting environmental conditions. Species development has not stopped, and weeds in a crop are different today from what they were several years ago and they will continue to evolve. However, once again, there are few examples of weeds that have evolved due to sympatric speciation. One is species of the genus *Passiflora* or passionflower (Harper, 1977). There are about 350 species and The Weed Sci. Soc. of America (Patterson, 1989) lists three as weeds. Nearly every species is unique from others. Leaf shape varies enormously, as do leaf surface characteristics. They are distinguished by feeding habits of the monophagous butterflies of the genus *Heliconius*.

The ready development of ecotypes, or physiological races adapted to various climatic conditions around the world, has occurred in common chickweed and is responsible for its worldwide distribution (Figure 6.9).

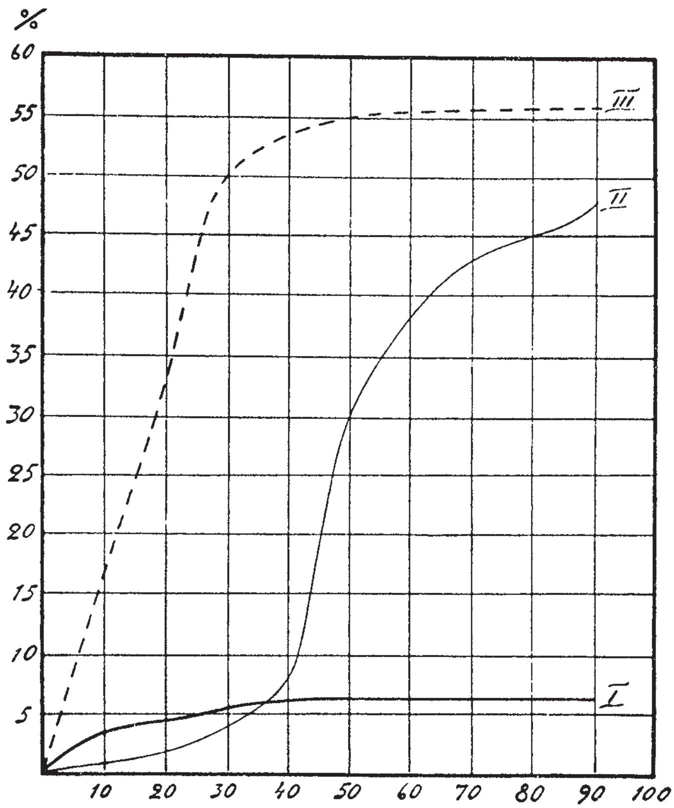

FIGURE 6.9. The average germination obtained over 100 days for lots of seed from three ecotypes of common chickweed: I, arctic, alpine latitudes; II, oceanic latitudes; III, maritime regions in northern latitudes (Peterson, 1936, cited in King, 1966).

Ecotypes exist in dandelion and in members of many other genera. Their development has implications for weed management. Control techniques that work in one place may not work for the same weed in another place because it isn't the same weed, it's an ecotype. Ecotype development is sympatric speciation as locally adapted populations are changed. Aldrich (1984) summarized examples of the development of ecotypes for a wide variety of weed species, including johnsongrass (Burt, 1974; McWhorter, 1971; McWhorter and Jordan, 1976; Wedderspoon and Burt, 1974), Canada thistle (Hodgson, 1964), common ragweed (Dickerson and Sweet, 1971), yellow nutsedge (Yip, 1978), purslane (Gorske et al., 1979), annual bluegrass (Warwick and Briggs, 1978), and medusahead (Young et al., 1970).

Weeds and other plants have two survival strategies called K and r that define a population's response to disturbance. Both terms are derived from terms in the logistic growth equation, where K = environmental carrying capacity and r = the intrinsic rate of population increase. The so-called r reproductive strategy is characterized by production of a large number of seeds (or vegetative reproductive units) and high dispersability. It is the potential rate of increase of a population for a given set of environmental conditions where there is no shortage of resources or any other constraints on growth. The r strategy dominates among annual weeds and is expressed in competitive ability, seed germination, seed dormancy, and seed longevity.

Plants adopting the K reproductive strategy depend on exploitation. They have fewer reproductive units, relatively low dispersability, and strong exploitative ability. K measures an upper size limit beyond which populations cannot go. The limit is determined by available resources and other constraints on population growth. Large-seeded annual weeds (some authors consider sunflower to be a good example, but others disagree) and many perennial weeds generally utilize K reproductive strategy. Plants with K strategy are usually not first colonizers.

Some species combine K and r strategies. Canada thistle, for example, is r for vegetative growth because it produces a large number of vegetative buds, and its creeping roots disperse plants. At the same time, Canada thistle is K for seed production. It is a dioecious plant and usually produces few seeds that have high dispersability but are not strongly exploitative.

It is important to point out that survival strategy as depicted by K and r reproduction is not equivalent to, and should not be confused with, competitive ability, which is controlled by other factors.

Undisturbed plant communities generally have a large number of a few species and a few individuals of many different species. Undisturbed communities are more complex than disturbed communities. Farmers in developed countries want fields to be dominated by a single species—they plant and disturb (plow, cultivate, control weeds, etc.) fields to achieve that goal. Crop dominance is favored by weed control. Weed management systems that rely on single control techniques stabilize weed populations, one hopes at a low population level, and encourage emergence of weeds that are not affected by the control technique.

B. The Community

The crop-weed community is important to weed management because it's the organizational level where change occurs. Change can occur within a species through mutation and ecotype development or by replacement of one species with another. There are at least four reasons (Harper, 1977) why two or more species coexist:

1. Different nutritional requirements as illustrated by legumes and grass coexisting in pasture and hay fields.
2. Different causes of mortality observed in pastures where animals selectively graze.
3. Different sensitivity to environmental toxins (allelochemicals) and human applied toxins (herbicides).
4. A different time demand for growth factors. Many plants require the same things to grow, but they don't demand them at the same time. This may be the most common reason for coexistence.

Plant communities are assembled in logical, predictable ways that can be studied. Community assembly is a branch of ecology that studies how plant communities are assembled over time. Booth and Swanton (2002) propose that assembly theory should be applied to weed management because it has the potential to change the approach to weed management. The present approach emphasizes control of individual or a series of co-occurring weeds (a population) in a crop (that is a series of weeds in a crop at a site). This approach has been very successful given its aim to manage the weeds that occur. The broader approach advocated by Booth and Swanton (2002) asks why weeds occur where they do and how they interact in communities. The population approach inevitably leads to instability because as the present population is controlled successfully, as sure as night follows day, another weed or weed complex will appear. A community assembly approach leads to understanding and balancing the crop-weed community rather than destroying one weed community so another can arise. It demands knowledge of environmental (climatic extremes such as flood or drought, and variation) and weed dispersal (identity of arriving species, arrival sequence, and rate and frequency of invasion) constraints that control the species that can enter an ecological pool. Booth and Swanton (2002) cite the work of Derksen et al. (1993, 1994, 1995) and several others, not included herein, to illustrate the effect of what Booth and Swanton call filters (biotic and abiotic constraints) on the trajectory of community development. Derksen et al. found that no-till, minimum-till, and conventional-tillage systems had different weed communities and that the weed associations varied among years and sites. Tillage filtered community composition but herbicides acted as an additional, strong filter that directed composition back to the original pretillage condition. Booth and Swanton (2002) used the work of Derksen et al. (1993, 1994, 1995) to illustrate how "the multivariate approach of community analysis may bring out patterns not evident when each weed species is analyzed separately."

C. Ecological Succession

Ecological succession is a natural, continuous process. In agriculture, it occurs in continually disturbed areas from which the natural community has been removed. Agricultural ecosystems have a desired, predetermined structure and function, and management success is based on crop yield (Booth and Swanton, 2002). Environmental modification is a driving force for succession and agriculture is conducted by modifying and controlling (managing via fertility, irrigation, community structure) the environment. Dominance is found in agricultural plant communities, and usually a few (rarely only one) weeds dominate cropped fields in modern agriculture. As just mentioned, their removal creates open niches and different species will move in, but usually not immediately. Therefore, weed control, especially successful weed control with present techniques, is a never-ending process. Weed management may be designed best when it achieves less than 100% control and is thus not as successful at opening niches and creating an endless process of succession. It will manage communities not simply the present population. The best weed management systems may combine techniques to gain the desired level of control but not a completely open environment that encourages arrival of new weeds that are not controlled by present techniques and thus, may be more difficult to control.

D. Interactions Between Weeds and Other Crop Pests

A fundamental although not a scientifically based rule of ecology is that in the natural world, it is impossible to do just one thing. Any action creates other actions and reactions. In the natural world actions interact. The rules of ecology that describe the interactions and the interconnection in the natural world can be expressed in simple, nonscientific words that make them easy to understand:

1. Everything is connected to everything else.
2. Nature knows best.
3. Everything must go somewhere.
4. There is no such thing as a free lunch.

Weed management and weed scientists are obliged to know and follow these simple rules. To ignore them is to court disaster and weed management failures.

Weeds live in communities and they are compelled to interact with crops and other pest organisms. In ecological terms weeds are producer organisms, whereas other pest organisms are consumers (Norris, 2005). Norris and Kogan (2000) reviewed the many interactions between weeds, arthropod pests, and natural enemies in managed (agricultural) ecosystems. Their review considered three mechanisms for interactions. The first is direct ecosystem energy/resource flow (trophic) interactions that occur when pests or beneficial arthropods feed directly on weeds, which may lead to allelopathic interactions. The second is alteration of the physical habitat by the presence of weeds (e.g., temperature within a plant canopy, water consumption). The final mechanism is driven by the control tactics employed to manage weeds and other pests (e.g., tillage, herbicides and other pesticides).

In addition to their productive activity, weeds also support beneficial and harmful organisms. Altieri (1994, p. 195) identified more than 70 families of arthropod pests known to be potential crop pests that are primarily associated with weeds. Table 1 in Norris and Kogan's (2000) paper identified more than 94 insect pests that attack 45 different crops via resource and habitat-driven interactions, each of which is facilitated by or dependent on weed presence.

A few examples, each documented by Norris and Kogan (2000), illustrate the interactions. Buffalobur is a native host of the Colorado potato beetle (*Leptinotarsa decemlineata*). The weed's presence, and the presence of other members of the *Solanaceae*, in or adjacent to a potato crop can worsen damage from the potato beetle. The Russian wheat aphid (*Diuraphis noxia*), a major pest of wheat in arid areas, uses jointed goatgrass and downy brome as alternate hosts. The insect can live in summer when wheat is not present and thus the weeds enhance insect damage even when they may not be present in the crop. The tobacco bud worm and the cotton bollworm (aka corn earworm) live on several weeds, whose uncontrolled presence worsens the insect problem in the crop. Similarly, several grass weeds that remain uncontrolled serve as alternate hosts for the European corn borer (*Ostrinia nubilalis*), thus potentially increasing populations that become major problems in field and sweet corn. The opposite of this situation is that weed control may worsen an insect problem by eliminating the plants the insects have been living on and compelling migration to the crop. It is always good to remember that in the natural world one cannot do just one thing—all things are related.

Norris and Kogan (2000) also identify (their Table 2) more than 52 beneficial insects where resource and habitat-driven influences provide benefits to crops. Many of these are insect predators or parasites that live on weeds. Schroeder et al. (2005) suggest three levels of interaction between polyphagous (eat many things) crop pests, including insects, pathogens, and nematodes and weeds. They acknowledge that except for work on biological control of weeds, the literature on the effects of pests on weeds, and, the effect of pests harbored by weeds on crops, is limited. Pests hosted by susceptible weeds may have severe negative effects on insect growth and fecundity. These are of limited concern because they serve to control the weed, which then does not compete for resources. Tolerant weeds host crop pests but without severe effects on the insect's growth and fecundity but possibly important effects on susceptible crops. This results in a larger pest population and effective crop competition. Finally, there are resistant weeds that do not host pests but do compete effectively with crops. Schroeder et al. (2005) suggest that weed communities in most crops are dominated by weeds that are tolerant of or resistant to the onslaught of polyphagous pests because of constant evolutionary pressure from the pests. This suggests, in contrast to Norris (2005) and Norris and Kogan (2000) that because reduction of existing weed populations often dominates crop management, manipulation of weed populations to benefit management of other pests is perhaps a faint hope. Capinera (2005), however, identifies the dynamic interactions between insects and weeds and the importance of weeds as a resource for insects. Weeds that are closely related to crops are especially important as reservoirs for insects that attack the crop. Wisler and Norris (2005) show the same relationships for plant pathogens and weeds.

When understood, weed populations can be manipulated to alter weed-insect interactions to benefit crops. Norris and Kogan (2000) note that the potential benefits of weed management to manage arthropod pests are much greater in perennial than in annual crops. That is because the populations of weed and insect can be observed over time and thus managed, which is much more difficult in annual crops that are in the field only for a few months.

V. PLANT COMPETITION

Plant competition is part of plant ecology. To compete comes from the Latin *competere*, which means to ask or sue for the same thing another does. I reviewed the literature of weed-crop competition twice (Zimdahl, 1980, 2004). Each of the reviews provides a more complete review and discussion of the topic than can or should be presented herein. The three conclusions of the second review (2004) are important. First, the review affirms the central hypothesis of weed science: that weeds compete with crops and reduce crop yield and quality. The second major conclusion is that weed science will benefit from closer integration with plant ecology and a consequent greater emphasis on study and understanding of the coexistence of plants rather than continued major emphasis on weed control. Another way of saying this is that weed scientists must change their primary questions. The questions have been "What is the identity of the problem weed, and how can it be controlled?" These are important questions, but the new questions should be "What is the identity of the problem weed, and why is the weed where it is?" (Zimdahl, 1999). The right question is a systemic, holistic one that accepts the transformation of nature as a necessary prerequisite to food production but rejects domination of nature (Zimdahl, 1999). The final conclusion of the review of weed-crop competition is that modeling (see Section XI) has become an important aspect of modern weed management systems, and it is likely to become more important to future weed management systems.

Imagine yourself having the good fortune to receive free tickets to your favorite football team's next home game. Your tickets are a little way up on the 50-yard line or, if you are very fortunate, in someone's private sky-box. You know you'll see vigorous competition as the two teams charge up and down the field competing for the ball, for scores, for glory, and perhaps, if it's a professional football game, for money.

The next time you drive around in the spring or summer, a careful look at most agricultural fields will reveal competition just as vigorous, but not as obvious, as that you expect to see at the football game. You won't see the plants leaping up and running around and into each other, but they will be competing vigorously for environmental resources. There is no glory and there is no financial reward for the plants. But the competition is real; it is for life.

Competition is what weed control is about. Competition between crops and weeds is why weeds are controlled. If weeds were just there and benign, we wouldn't care as much about them. Because they cause harm to crops by competing with them we are compelled to care and attempt to control or manage them.

Among the references to weeds, some of the earliest and frequently quoted ones are in the Bible.

> Cursed is the ground for thy sake; in sorrow shalt thou eat of it all the days of thy life; thorns and thistles shall it bring forth to thee; and thou shalt eat the herb of the field.
>
> *Genesis III:17–18*

And some fell among the thorns and the thorns sprang up and choked them.
Matthew XIII:7

The Reverend T. R. Malthus, in his 1798 essay on the principle of population, said, "The cause to which I allude is the constant tendency in all animated life to increase beyond the nourishment prepared for it." Malthus's concern was the increasing human population and consequent poverty and misery he saw in his town, Liverpool, England. The Malthusian apocalypse, when the human population is greater than the ability of the earth to produce food, has been avoided because of developments in food production technology. The apocalyptic possibility, especially in the world's developing countries, still concerns many.

A. Plant Competition Defined

Clements et al. (1929) said competition is a question of the reaction of a plant to the physical factors that encompass it and the effect of these on adjacent plants. For them, competition was a purely physical process. "In the exact sense, two plants—no matter how close, do not compete with each other so long as the water content, the nutrient material, the light and heat are in excess of the needs of both.

"Competition occurs when each of two or more organisms seeks the measure they want of any particular factor or things and when the immediate supply of the factor or things is below the combined demand of the organisms" (Clements et al., 1929). In agriculture, competition is not regarded as simply interaction without any effect on either individual. Competition in agricultural communities has results that are usually negative. The subject is discussed well by Booth et al. (2003). The definition according to Clements et al. (1929) makes *competition* different from the broader term *interference*, which includes competition and allelopathy (see Chapter 8). The dictionary defines *competition* as "being for something in limited supply or between agents, as in a rivalry." For physiologists, competition is usually for things. For agronomists and weed scientists, competition is often for things and between individuals (Donald, 1963).

B. Factors That Control the Degree of Competition

Figure 6.10 illustrates the factors that determine the degree of competition encountered by an individual plant. For weeds, density, distribution, and

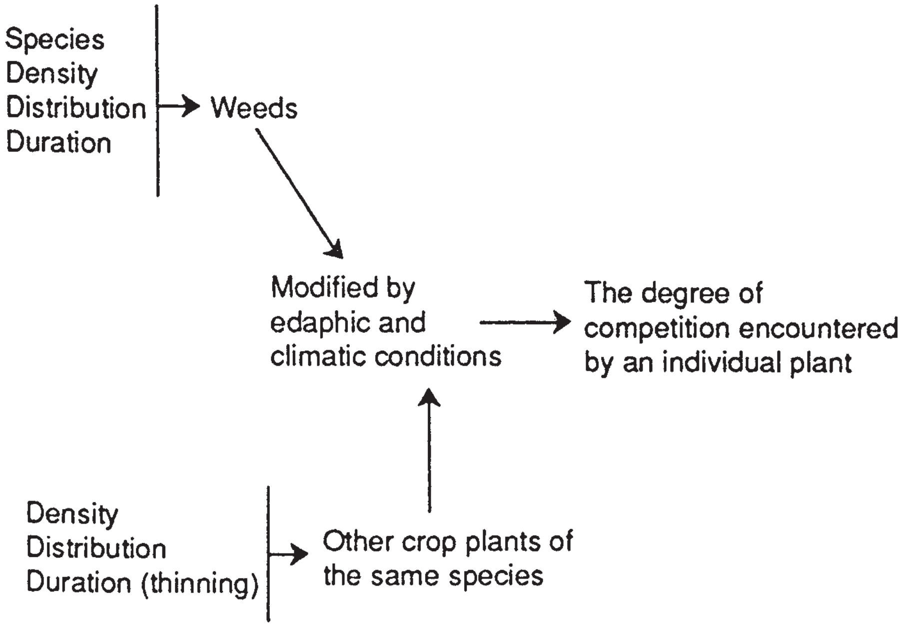

FIGURE 6.10. Schematic diagram of the competition encountered by a plant (Bleasdale, 1960).

duration or how long weeds are present are important. For crops, density, distribution (including spacing between rows and spacing in the row), and duration (whether or not thinning is required) are important. These factors, modified by soil (edaphic) and climatic conditions, determine the degree of competition encountered by each plant. The primary things plants compete for are nutrients, light, and water. When any one is lessened, others cannot be used as effectively. Plants may compete for heat, but it is difficult to conceptualize how they do so. However, it is well known that accumulation of degree days enhances plant growth:

$$\text{Degree day} = \text{Daily maximum} - \text{Daily minimum temperature} - \text{Threshold temperature}/2$$

The threshold temperature differs between species and is the temperature below which the plant doesn't grow. Because they do not grow well at high temperatures, there is a maximum cutoff temperature, in the range of 30°C, for many plants. Plants grow better when it is warm, but no studies have reported competition for heat, perhaps because it is not a resource that exists in a finite reservoir.

Yield reductions are generally in proportion to the amount of light, water, or nutrients that weeds use at the expense of a crop. A very general rule is for every unit of weeds grown, there will be one less unit of crop grown. Inconsistent results between weed management experiments in one year or between years are regularly attributed to environmental (i.e., light, water, nutrient, or climatic) variation. In most cases the data are insufficient to define cause and effect.

It is simple and neat to separate the elements of competition (nutrients, light, and water). H. L. Mencken (1880–1956) reminded us that "for every human problem, there is a solution that is simple, neat, and wrong." It is not wrong to separate the elements of competition experimentally, but it is wrong to assume that plants do so and it is nearly impossible to separate the elements of competition in nature. deWit (1960) was among the first to point out the futility of separating the elements of competition. His work changed the approach to the study of competition. He derived mathematical expressions for competition and advocated consideration of space and what it contained rather than studies that separated the components of competition. For example, competition for light affects growth, which in turn affects a plant's ability to compete for nutrients and water. Competition will be greatest among similar species that demand the same things from the environment. Those species that best use (grow rapidly) or first capture environmental factors will succeed.

Only in recent years has research progressed to consider the spatial distribution or where weeds are in a field. Weed scientists have long been concerned with what weeds (what species) and how many weeds (their density) are present in a field. Control has been directed at the dominant weed or weeds. Studies of weed biology have emphasized seed production, seed dormancy and survival, and seedling growth, establishment, and survival. Results of these good studies have been translated into areas (acres or hectares) without considering the patchiness or nonuniformity of weeds in all fields. Control included the usually unstated assumption that weed distribution and density were uniform over the field. Thus, tillage for weed control and herbicides are nearly always applied uniformly over the field even though most farmers know and weed scientists agree the weeds are not distributed uniformly. Farmers and others who try to manage weeds have long recognized that weed distribution in a field is not uniform and control practices are unnecessary in some places. Weed distribution is heterogeneous, not homogenous (see Chapter 19 on the importance of mapping weed populations). The technology for weed and crop recognition systems that control weeds when they are present in parts of fields rather than whole fields is developing. Biological knowledge to define how the seedbank, seed dispersal, plant demography, and habitat interact to determine the stability of weed or weed seed distribution across fields and across time is not as developed (see Cousens and Mortimer, 1995, Chapter 7). There is also a poor understanding of how control techniques affect weed and weed seed distribution over time. As this knowledge develops weed managers will be able to manage weeds on less than a whole field basis and that will lead to reduced need for tillage and herbicides (Mortensen, et al. 1998; Johnson et al., 1995). The dynamics of patches defined as how inherent weed biology interacts spatially with landscape characteristics (Cousens and Mortimer, 1995) is an important area of weed management research. Weed scientists want to understand *why* weeds are where they are rather than know only what species are present and use the spatial information as another tool to predict and manage weed populations.

C. Competition for Nutrients

Nitrogen, phosphorus, and potassium are primary plant nutrients. One mustard plant needs twice as much nitrogen and phosphorus, four times as much potassium, and four times as much water as an oat plant. Success in gaining nutrients may lead to more rapid growth and successful competition for light and water. Fertilization is used to improve crop growth but may worsen the weed problem.

Table 6.2 shows the pounds of nutrients required to produce equal amounts of dry matter for three crops and five weeds that frequently compete with the crops. The important point about these data is not that weeds require greater amounts of nitrogen and phosphorus than crops. Consumption of nitrogen and phosphorus for weeds and crops is very similar. The point is weeds require the same nutrients, at the same time, and are often, because of early emergence, more successful in obtaining them. Remember, competition occurs when two

TABLE 6.2. Kilograms of Nutrients Required to Produce Equal Amounts of Dry Matter.

Plant	Nitrogen	Phosphorus
Wheat	5.5	1.2
Oats	4.9	1.7
Barley	8.4	2.6
Common lambsquarters	7.6	1.6
Common ragweed	6.6	1.4
Redroot pigweed	5.1	1.4
Common purslane	3.1	0.8
Mustards	9.8	2.7

or more organisms seek what they want or need and the supply falls below the combined demand.

Table 6.3 compares the nutrient content of weed-free corn, corn-free redroot pigweed, and corn grown with redroot pigweed (Vengris et al., 1955). When weed-free corn was set at a nutrient content of 100, in all cases except phosphorus, redroot pigweed grown alone contained more of each of the nutrients than corn. The more interesting data are those in the center row, where the nutrient content of corn infested with redroot pigweed is shown. In every case, nutrient content was reduced. In another study (Vengris et al., 1953), corn was compared with six annual broadleaved weeds and one annual grass (Table 6.4). Weeds contained 1.6 to 7.6 times more of each nutrient. In this study, application of supplemental phosphorus made several weeds more competitive. High fertility did not reduce the detrimental effects of weeds on corn.

A similar study in Poland with wheat, barley, sugarbeets, and rape (Malicki and Berbeciowa, 1986; see Table 6.5) showed that the mineral content of most

TABLE 6.3. Comparison of Nutrient Content of Weed-Free Corn, Corn and Redroot Pigweed, and Redroot Pigweed Alone (Vengris et al., 1955).

	Relative nutrient content				
Species	N	P_2O_5	K_2O	Ca	Mg
Weed-free corn			—100—		
Corn infested with redroot pigweed	58	63	46	67	77
Redroot pigweed	102	80	124	275	234

TABLE 6.4. Mineral Composition of Corn and Weeds (Vengris et al., 1953).

	Mean percent composition				
Species	N	P	K	Ca	Mg
Common lambsquarters	2.6	0.4	4.3	1.5	0.5
Common purslane	2.4	0.3	7.3	1.5	0.6
Corn	1.2	0.2	1.2	0.2	0.2
Crabgrasses	2.0	0.4	3.5	0.3	0.5
Galinsoga	2.7	0.3	4.8	2.4	0.5
Pigweeds	2.6	0.4	3.9	1.6	0.4
Ragweeds	2.4	0.3	3.1	1.4	0.3
Smartweeds	1.8	0.3	2.8	0.9	0.6

TABLE 6.5. Nitrogen, Phosphorus, and Potassium Content of Wheat and Barley (Grain, Straw, and Roots) and Selected Annual Weeds (Malicki and Berbeciowa, 1986).

	Percent dry matter		
Species	N	P	K
Barley	1.5	0.2	1.4
Canada thistle	1.6	0.3	2.0
Common chickweed	2.1	0.6	3.8
Common hempnettle	2.0	0.4	2.3
Common lambsquarters	2.7	0.4	4.1
Corn speedwell	1.5	0.3	1.7
Field bindweed	2.7	0.3	2.7
Hairy vetch	3.0	0.2	1.1
Perennial sowthistle	2.3	0.5	4.0
Shepherd's-purse	1.6	0.3	2.0
Wheat	1.2	0.3	0.8
Wild buckwheat	2.7	0.4	2.5

weeds is higher than that of wheat or barley. The authors proposed that common lambsquarters, Canada thistle, field bindweed, wild buckwheat, perennial sowthistle, and common chickweed are dangerous in wheat because of their high nutrient requirement. Rapeseed responded like the grain crops. The percentage of nutrients in roots and leaves of sugarbeets was high and few weeds exceeded it. This is explained by the high nutrient concentration in the large sugarbeet root.

In a crop heavily infested with weeds, it seems logical that more fertilizer should reduce nutrient competition. If competition does not occur until the immediate supply falls below combined demand, when supply increases, competition should decrease. Actually, although this seems logical, it is wrong. Fertilizer usually stimulates weed growth to the crop's detriment. With low fertility, competition is primarily for nutrients however, with high fertility, competition is just as vigorous, and primarily for light. Yields in unweeded, fertilized plots are usually equal to those in weeded, unfertilized plots. Table 6.6 shows that increasing nitrogen reduced flax yield and tended to increase wild oat density and number of seed-bearing stems (Sexsmith and Pittman, 1963). The opposite situation is more common, nitrogen raises crop yield and then, when in excess, crop yield decreases (see Table 6.7; Okafor and DeDatta, 1976).

TABLE 6.6. Effect of Form and Timing of Nitrogen Fertilizer on Wild Oats and Flax[a] (Sexsmith and Pittman, 1963).

Fertilizer	Wild oats Density (No/m^2)	Stems	Yield (kg/ha)	Flax seed-bearing
None	96 a	124 a	7.0 a	
Ammonium nitrate April 12 (early)	215 ab	254 a	4.2 ab	
Ammonium sulphate April 12 (early)	435 bc	444 b	2.4 bc	
Ammonium nitrate June 1 (seeding)	476 c	530 b	1.9 c	

[a]Means in a column followed by different letters are significantly different at P = 0.05.

TABLE 6.7. Effect of Nitrogen Fertilizer on Rice Yield and Purple Nutsedge Competition (Okafor and DeDatta, 1976).

Nitrogen (kg/ha)	Purple nutsedge (no/m^2)	Rice yield (t/ha)
0	0	1.6
0	750	1.2
60	0	4.4
60	750	2.8
120	0	4.0
120	750	2.4

Table 6.8 shows similar data on competition of barnyardgrass, and barnyardgrass plus the annual broadleaved weed monochoria in rice. It is apparent that increasing nitrogen fertilizer increased yield and that with just barnyardgrass, increasing nitrogen fertilizer from 0 to 60 kg/ha decreased yield. Only after a further doubling of nitrogen did yield increase. Even then, yield was lower than the same amount of fertilizer with no weeds. With both weeds, neither level of nitrogen fertilizer increased yield, and both yielded less than the check plot with no fertilizer and no weeds. These data are confirmed by those in Table 6.9, which show nitrogen uptake of rice and barnyardgrass in two trials in Australia (Boerema, 1963).

The influence of fertility treatments for 47 years on weed types and populations was evaluated in Oklahoma (Banks et al., 1976). Plots with the lowest weed density were those that had received no fertilizer for 47 years. Highest weed density occurred on plots that received complete fertilizer (N, P, K) and lime ($CaCO_3$). Grass weeds were most abundant with complete fertility while broadleaved species declined.

TABLE 6.8. Weed Competition for Nitrogen in Rice (Moody, 1981).

Weed(s)	Tons/ha of rice grain with nitrogen fertilizer applied at (kg/ha) 0	60	120
	(tons/ha)		
None	4.5	5.3	6.6
Barnyardgrass	4.4	4.0	5.5
Barnyardgrass + Monochoria	4.1	3.1	3.5

TABLE 6.9. Nitrogen Uptake of Weeds and Rice in Two Trials (Boerema, 1963).

	Trial 1		Trial 2	
Species	Weeds present	Weeds absent	Weeds present	Weeds few
Barnyardgrass	56.3	0	94.1	1.6
Rice	36.8	99.7	15.5	111.8
Total	93.1	99.7	109.6	113.6

Interactions of soil moisture and fertility on competition between wheat and wild buckwheat are studied in N. Dakota (Fabricus and Nalewaja, 1968). Biomass of wheat growing alone increased with increasing fertility. Wheat biomass declined 30 to 37% regardless of soil moisture or fertility when wheat grew with wild buckwheat. The weed also reduced flax growth 47 to 57% when they grew together for 90 days (Gruenhagen and Nalewaja, 1969). There was proportionately greater flax seed loss with higher fertility.

Table 6.10 shows five densities of wild oats with three levels of nitrogen. It is clear that as wild oat density increases, it is less and less profitable to add nitrogen. Wild oats' advantage is due to their higher nitrogen use efficiency (Carlson and Hill, 1986). Increasing fertilizer application rate is not an economic, agronomic, or energy efficient way to avoid or reduce crop losses due to weed competition.

In general, weeds have a large nutrient requirement and will absorb as much or more than crops. Nitrogen is the first nutrient to become limiting in most instances of weed-crop competition. The nitrate ion is not held strongly in soil and is highly mobile. Nitrogen depletion zones are likely to be quite large and similar to those for water. Therefore, rooting depth and root area of plants

TABLE 6.10. Yield of Wheat Grown in Competition with Wild Oat at Three Levels of Fertilization (Carlson and Hill, 1986).

	Wheat yield with preplant nitrogen			
Wild oat density	0	67	134	Avg.
(plants/m^2)		(kg/ha)		
0	6,990	7,520	7,650	7,390
4	6,430	6,660	6,640	6,580
8	6,460	6,100	6,140	5,230
16	5,940	5,200	5,470	5,540
32	5,400	4,120	3,450	
Avg.	6,240	5,920	5,870	

determine the ability to obtain resources and relative competitiveness for nitrogen is largely determined by the soil volume occupied by roots of competing species. The amount of nitrogen taken up by plants in any combination is about equal (Table 6.9).

Movement of phosphorus and potassium is slow compared to nitrogen, and they move over shorter distances. Smaller depletion zones minimize interplant competition. Competition for phosphorus and potassium is therefore most likely to occur after plants are mature and have extensive, overlapping root development. It is reasonable to assume that competition for phosphorus will be more apparent in perennial crops. Competitiveness of barley cultivars with wild oats varied in response to potassium (Siddiqi et al., 1985) or phosphorus (Konesky et al., 1989) supply. There are few studies of weed-crop competition for phosphorus or potassium.

While competition for nitrogen can sometimes be overcome by nitrogen fertilization, this is rarely true for phosphorus and potassium. It may be possible to prevent or delay weed invasion of perennial crops by maintaining a vigorous crop with fertilizer.

D. Competition for Water

Water, or its lack, is often the primary environmental factor limiting crop production, and it is probably the most critical of all plant growth requirements (King, 1966). Without irrigation, rainfall determines the geographic limit of crops. The water-use efficiency of nine weeds and nine crops is shown in Table 6.11.

TABLE 6.11. Water Use Efficiency (Dillman, 1931; Shantz et al., 1927).

Plant	Water use efficiency[a]	Transpiration coefficient[b]
Weeds		
Common cocklebur	2.41	415
Common lambsquarters	1.52–2.30	435–658
Common purslane	3.47–3.56	281–288
Foxtail millet	3.65–3.98	251–274
Prostrate knotweed	1.47	678
Redroot pigweed	3.28–3.83	261–305
Russian thistle	3.18–4.46	224–314
Sunflower	1.73	577
Witchgrass	3.94	254
Crops		
Alfalfa	1.15–1.25	798–870
Corn	2.77	361
Cotton	1.76	568
Oats	1.65–1.87 m	536–605
Smooth bromegrass	1.02–1.28	784–977
Sorghum	3.51–3.73	268–285
Soybean	1.55	646
Sugarbeets	2.65–3.29	304–377
Rape, oilseed	1.40	714

[a]Water use efficiency = mg of dry weight produced per ml of water consumed.
[b]Transpiration coefficient = ml of water transpired per g plant dry weight.

The point of Table 6.11 is not that weeds use a great deal more water or use water more efficiently than crops. They use about the same amount used by crops with which they compete. Weeds effectively explore soil to obtain water (Table 6.12).

Comparison of rooting depth, uptake diameter, and the volume of soil from which resources can be consumed by one sorghum plant and five weeds makes the reason for weed competitiveness clear. Of the five weeds shown, all have a greater rooting depth, and all but redroot pigweed have a larger feeding diameter and volume affected per plant than grain sorghum. All except redroot pigweed have a greater capacity to consume water than grain sorghum does.

The classic work on water requirements of plants was done in Akron, Colorado, in the early 20th century (Briggs and Shantz, 1914; Dillman, 1931; Shantz et al., 1927). Individual crop and weed plants were grown in separate

TABLE 6.12. Soil Water Uptake Patterns of Common Weeds and Grain Sorghum in Summer Fallow (Personal Communication, Adapted from Davis et al., 1965, 1967).

Weed species	Rooting depth (m)	Feeding diameter (m)	Volume of soil/plant (sq m)	Plants to consume water/ha (number)
Common cocklebur	2.9	8.5	17.9	704
Grain Sorghum	1.7	4.3	6.5	2,841
Kochia	2.2	6.7	9.5	1,136
Pigweed	2.4	3.6	5.2	3,853
Puncturevine	2.6	6.6	10.8	1,136
Russian thistle	1.8	5.0	6.5	2,149

TABLE 6.13. Water Required to Produce One Pound of Dry Matter (Dillman, 1931; Shantz et al., 1927).

Plant	Kilograms of water
Alfalfa	377
Barley, grain	431
Barley, whole plant	237
Bursage	535
Common lambsquarters	300
Common purslane	128
Common sunflower	338
Corn	159
Mustard	1,091
Potato, tuber	430
Potato, vine	150
Redroot pigweed	132–139
Russian thistle	143
Sorghum	283
Wheat	227

pots, and the grams of water required to produce a gram of plant dry matter were determined. Some of the data are shown in Table 6.13.

Weeds compete for water, reduce water availability, and contribute to crop water stress. They require just as much, and often more, water than crops and are often more successful in acquiring it. Weedy sunflowers require approximately twice as much water as corn. It takes more water to produce a potato tuber than to produce a common lambsquarters plant. Therefore, if, as is commonly found, common lambsquarters infests potato fields and water is limiting, fewer and smaller tubers will be produced. About 80 gallons of water are required to produce one pound of dry matter in barnyardgrass, more than the 60 gallons to produce a pound of wheat. Crabgrass requires 83 gallons of water per pound of dry matter.

Many field, laboratory, and greenhouse studies have examined the role of water in weed-crop competition. One of the early studies (Wiese and Vandiver, 1970) compared growth of corn and sorghum with three grass and five broad-leaved weeds at three soil moisture levels in the greenhouse. Corn produced the most biomass at all moisture levels. Common cocklebur, barnyardgrass, and large crabgrass normally grow well in humid regions and in irrigated crops and were the most competitive with wet soil conditions. Kochia and Russian thistle, weeds of dry areas, were more competitive with dry soil conditions and grew poorly when soil was wet. Russian thistle produced twice as much growth in dry as in wet soil.

In field experiments in Texas (Stuart et al., 1984), water competition from smooth pigweed reduced leaf water potential and turgor pressure in cotton. Smooth pigweed was affected less by low soil water because it transpires less water and its larger root system draws water from deeper in soil. Smooth pigweed illustrated what may be called water wasting by weeds. In fact water use is wasteful only from a human perspective or in comparison to another plant, a crop, that uses less water. Each plant uses the water it requires. Stomata in some weeds are less sensitive to declining leaf water potential than those of crops with which they compete (Patterson, 1995a). When this is combined with a larger root system (Table 6.12) or better drought tolerance, weeds are formidable competitors for water. High water use by weeds may be ecologically advantageous to weeds in weed-crop competition, especially when soil moisture is limiting (Patterson, 1995a).

When soybean and velvetleaf competed in Texas, rooting depths were similar early. After 10 weeks, soybean was able to draw water from greater soil depths, and velvetleaf had little effect on soybean's water status (Munger et al., 1987). When the same species competed in Indiana, a wetter, more humid area, velvetleaf reduced soybean growth more in dry than wet years (Hagood, 1980).

In Arkansas, soybean had higher leaf water potential than common cocklebur because of stomatal regulation of transpiration. Common cocklebur had lower stomatal resistance and higher transpiration. It is a high water user and exhausts soil water resources rapidly, to soybean's disadvantage (Geddes et al., 1979; Scott and Geddes, 1979).

Patterson (1995a) surveyed weed-crop competition studies that included water as a variable and found a slight tendency for decreased water availability to favor crops by reducing weed competition. This reasonable generalization may not always be true because it will be affected by each crop-weed combination and the cultural and environmental conditions in each crop season or over several seasons.

For example, the influence of season is shown by competition from any one of three broadleaved weeds that reduced soybean yield more when soil moisture was adequate early followed by a drought than when a drought was early (Eaton et al., 1973, 1976).

Scientists in arid areas have developed fallow cropping systems. Many arid areas have sufficient rainfall to support crop growth only every other year. Often wheat is grown one year, the land is fallowed (no crop) the next year, and it is rotated back to wheat in the third year. The primary purpose of this rotation is water conservation. Natural rainfall is not sufficient to grow wheat each year and extensive dryland cannot be irrigated. Therefore, minimum or no-tillage systems have been developed to conserve water. The data in Table 6.14 show the increase in water stored in the soil profile for a minimum tillage system compared to a tilled, spring fallow system. The minimum-till system increased soil nitrate, grain protein, and wheat yield. Water is the least reliable resource for plant growth because we don't know precisely when it will arrive or how much will be received. This is a major reason why arid areas are irrigated. Because roots grow more rapidly than shoots early in a plant's life, competition for water and nutrients usually begins before competition for light. Competition for water is determined by the relative root volume occupied by competing plants and will be greatest when roots closely intermingle and crops and weeds try to obtain water from the same volume of soil. Less competition occurs if roots of crops and weeds are concentrated in different soil areas. More competitive plants have faster-growing, large root systems so they are able to exploit a large volume of soil quickly. If plants have similar root length, those with more widely spreading and less branched root systems will have a comparative advantage in competition for water.

TABLE 6.14. Conventional Tillage Versus Ecofallow (Greb and Zimdahl, 1980).

	Treatment		
	Spring tillage		
Measurement	Fallow	Ecofallow	Increase
Gain in soil water during fallow (cm)	3.9	5.4	1.5
Gain in soil nitrate during fallow (cm)	51.6	77.4	25.8
Percent gain protein	11.0	11.8	0.8
Wheat yield (bu/A)	34.4	41.8	7.4

E. Competition for Light

The total supply of light is the most reliable of the several environmental resources required for plant growth. But in contrast to water and nutrients, light cannot be stored for later use; it must be used when received, or it is lost forever (Donald, 1963).

Although it varies in duration, intensity, and quality, light regulates many aspects of plant growth and development. Neighboring plants may reduce light supply by direct interception: shading. Leaves are the site of light competition. Leaves that first intercept light may reflect it, absorb it, convert it to photosynthetic products, convert it to heat, or transmit it. If transmitted, the light is filtered so that it reaches lower leaves dimmer and spectrally altered. Whenever a leaf is shaded by another, there is competition for light.

Light competition is most severe when there is high fertility and adequate moisture because plants grow vigorously and have larger foliar areas. Plants with large leaf area indices (LAI) have a competitive advantage with plants with smaller leaf areas. Leaf area index, a measure of the photosynthetic surface over a given area, is correlated with potential light interception. Successful competitors do not necessarily have more foliage, but have their foliage in the most advantageous position for light interception. Thus, a plant's ability to intercept light is influenced by its angle of leaf inclination and leaf arrangement. Plants with leaves disposed horizontal to the earth's surface are more competitive for light than those with upright leaves disposed more or less perpendicular to the earth's surface. Plants with opposite leaves are probably less competitive than those with alternate leaves. Plants that are tall or erect have a competitive advantage for light over short, prostrate plants. A heavily shaded plant suffers reduced photosynthesis, leading to poor growth, a smaller root system, and a reduced capacity for water or mineral uptake. The effect of shading is independent of direct competition for water or nutrients and entirely under the influence of light (Donald, 1963). Current cropping practices used, at least partially, to manage weeds, such as smother crops and narrow row spacing (see Chapter 9) exploit plant responses to light (Holt, 1995). Most weeds and crops respond to shading in similar ways via morphological and physiological adaptations (Patterson, 1995a). This is not surprising because these plants evolved in disturbed habitats where shade adaptation has few selective advantages (Patterson, 1995a).

Reports that crops are physiologically and genetically capable of higher productivity and photosynthetic efficiency than obtainable in the field confirm that intercepted light is a limiting factor in crop canopies (Holt, 1995). Reduced production in low-light acclimated crop plants is undesirable. Several reviews of responses of weeds and crops to light are available (Holt, 1995; Patterson, 1982, 1985, 1995a; Radosevich and Holt, 1984).

Crops and weeds differ in shade tolerance. Soybean and several of its associated weeds (e.g., eastern black nightshade, tumble pigweed, and common cocklebur) were most photosynthetically efficient under low growth irradiance (Regnier et al., 1988; Stoller and Myers, 1989). Many other weeds acclimate to low growth irradiance by plastic responses that reduce the growth-limiting effects of shading and allow restoration of high rates of photosynthesis when the plant is exposed to high irradiance (Dall'Armellina and Zimdahl, 1988; Patterson, 1979).

Bazzaz and Carlson (1982) generated photosynthetic response curves for 14 early, mid, and late successional species grown in full sunlight and 1% of full sunlight. Early successional species, all common annual weeds, had the highest difference in response between sun- and shade-grown plants. The magnitude of photosynthetic flexibility decreased in plants from later successional stages. All species studied were able to change their photosynthetic output in response to light, but the change was larger for early successional annuals (Bazzaz and Carlson, 1982). These findings suggest that weeds are not only adapted to high light but are more capable of adapting to extreme variation in light, particularly deep shade. Thus, managing the light environment in a crop field to deter weed growth is difficult and not likely to be effective (Holt, 1995).

Available light is a major factor in yellow nutsedge competition with corn. More yellow nutsedge grows between corn rows than within the row because less light reaches the soil under plants. Yellow nutsedge density decreases as corn density increases (Ghafar and Watson, 1993); therefore, an acceptable yellow nutsedge management technique is increasing corn population. Increasing corn population density from 66,700 to 133,000 plants per hectare reduced yellow nutsedge tuber production 71%. Reducing corn population from 66,700 to 33,300 plants per hectare increased tuber production 41% (Ghafar and Watson, 1983). Field studies of the effect of artificial shade on yellow nutsedge concluded that rapidly developing crops (e.g., corn or potato) suppressed the weed through competition for light (Keeley and Thullen, 1978). Shading greatly reduced shoot and biomass production and reduced, but did not eliminate, tuber production. Stoller and Woolley (1985) estimated that competition for light caused almost all soybean yield loss in competition with velvetleaf or jimsonweed and half of the yield reduction in soybean competing with cocklebur.

Many studies have quantified the effects of light competition between weeds and crops. Cudney et al. (1991) showed that wild oats reduced light penetration and growth of wheat by growing taller. When wild oats were clipped to the height of wheat, light penetration in a mixed canopy was similar to that in monoculture wheat. Interference from wild oats planted at low densities reduced light penetration to wheat at later growth stages (Cudney et al., 1991).

Similar height effects were observed in studies of competition between velvetleaf and soybean. Greater light interception by velvetleaf was due to greater height and dry weight allocation to more upper branches (Akey et al., 1990). Reductions in tomato yield were greater when it grew in competition with eastern black nightshade compared to black nightshade because eastern black nightshade is taller (McGiffen et al., 1992). These studies show that plant architecture, especially height, location of branches, and height of maximum leaf area, determine competition for light and influence crop yield (Holt, 1995).

Interaction of light and water is illustrated in a study of how yield of quackgrass infested soybeans was increased by irrigation when soil moisture was limiting. Soybeans infested with quackgrass yielded less than quackgrass-free soybeans. Quackgrass was nearly the same height or taller than soybeans at all stages of soybean development and competed for light throughout the growing period. Adequate moisture reduced quackgrass competition in soybeans but did not eliminate it because quackgrass continued to compete with soybeans for light (Young et al., 1983).

Studies in India (Shetty et al., 1982) showed that dicots are less shade-sensitive than monocots and help explain why monocots are often important tropical weeds. Broadleaved weeds usually do not appear until after tropical crops are well established. It seems that manipulation of tropical crop canopies could suppress weeds via shading. The height of the dicot weeds, celosia, and coat buttons was reduced by 90% shade but that shade level had no effect on height of southern crabgrass. Ninety percent shade reduced height of bristly starbur 50% and purple nutsedge 30%. The effects were most pronounced early in the growing season, and similar reductions in leaf area index and plant dry matter were observed. Slender amaranth's height was not affected by shade, but as light decreased, seed production decreased. For most annuals, 90% shade reduced seed production up to 90% and 40% shade reduced seed production 45%. Shading reduced purple nutsedge tuber production 89%.

F. Factors for Which Plants Do Not Compete

Plants that emerge at the same time rarely compete for space, even though plant density may be high. When plants emerge at different times, the first plant that occupies an area will tend to exclude all others and have a competitive advantage and, in this sense, plants compete for space by occupying space first. Occupancy or competitive exclusion can be, and among plants should be, regarded as competition for the resources in a space.

In general, plants that emerge at the same time and plants that grow together do not compete for space but rather for what space contains. This may not be true in root crops that are planted closely, but in most cases it is the light, nutrients, and water that space contains for which plants compete. They do not compete for the space itself. Booth et al. (2003) agree with this assertion but caution that plants whose roots are restricted generally have reduced shoot biomass, height, or growth. Others (Schenk et al., 1999, cited by Booth et al., 2003) argue the still controversial hypothesis that plants may be regarded as territorial because they defend their space against invasion by others. In other words, a plant may effectively defend its territory by preventing others from using it. Consistent with the argument above, plants may do this by using or preventing the use of an area's resources by other plants.

Plants may compete for oxygen. Although there are no studies to document this, it is theoretically possible. In most soils, diffusion of oxygen is rapid enough so that adequate supplies are available for all roots. Oxygen can be limiting in very wet soils. Similarly, in most circumstances, carbon dioxide concentrations are always higher than the carbon dioxide compensation point (the light intensity at which there is a balance between carbon dioxide given off by respiration and required by photosynthesis). Competition for carbon dioxide is unlikely to occur under field conditions, but crop yields can be increased by supplemental carbon dioxide. (See earlier comments in this chapter on climate change.) More efficient utilization of carbon dioxide by weeds with high photosynthetic capacities may contribute to their rapid growth and provide a competitive advantage. Therefore, a plant's competitive ability could depend on its capacity to assimilate carbon dioxide and use the photosynthate to extend foliage or increase size. Plants that fix carbon dioxide at high rates are potentially more competitive.

There is no evidence that plants compete for environmental factors such as heat energy or agents of pollination.

VI. PLANT CHARACTERISTICS AND COMPETITIVENESS

In general, it is true that plants possessing one or more of the following characteristics are more competitive than plants that lack them. This list is not in rank order, and it cannot be said that a plant with a certain characteristic will always win over a plant with another. Most competitive plants have the following traits:

1. Rapid expansion of a tall, foliar canopy
2. Horizontal leaves under overcast conditions and obliquely slanting leaves (plagiotropic) under sunny conditions
3. Large leaves
4. A C_4 photosynthetic pathway and low leaf transmissivity of light
5. Leaves that form a mosaic leaf arrangement for best light interception
6. A climbing habit
7. A high allocation of dry matter to build a tall stem
8. Rapid stem extension in response to shading

The most obvious competition among plants is what we see: foliar competition. Competition for nutrients and water takes place beneath soil, where it can't be seen. The most competitive plants also share some of the following root characteristics:

1. Early and fast root penetration of a large soil area
2. High root density/soil volume
3. High root-shoot ratio
4. High root length per root weight
5. High proportion of actively growing roots
6. Long and abundant root hairs
7. High uptake potential for nutrients and water

VII. THE RELATIONSHIP BETWEEN WEED DENSITY AND CROP YIELD

Early weed science literature assumed that the relationship shown in Figure 6.11 described the effects of weeds on crop yield. That assumption was wrong. Figure 6.11 says that with no weeds, crop yield will be maximized, and at some large weed density, crop yield will be zero. The real relationship is curvilinear, not linear. Such a relationship is supported by data (Figure 6.12) showing the effect of kochia, an annual broadleaved weed, on sugarbeet root yield.

Other data show the curvilinear relationship depicted schematically in Figure 6.13, which is intuitively logical, is also wrong. Some of the data in Table 6.15 show that the relationship is neither linear nor curvilinear. Doubling of weed density does not double crop loss in any of these studies and even when weed density is increased by a factor of 25, crop loss does not go to zero. Therefore while the curvilinear relationship is not entirely incorrect, it is not correct and can be misleading.

Smith (1968) studied the interaction of rice and barnyardgrass density, and his data show the appropriate relationship is neither linear nor curvilinear.

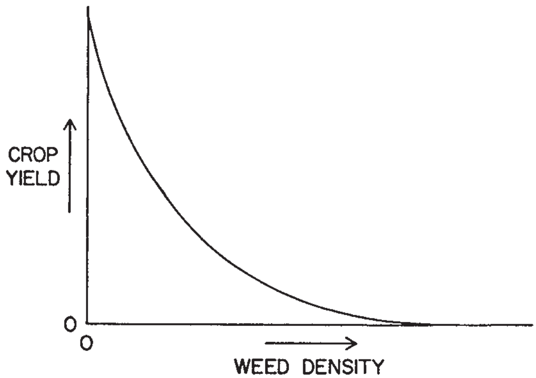

FIGURE 6.11. A schematic curvilinear relationship depicting the effect of increasing weed density on crop yield (Zimdahl, 1980).

The curvilinear relationship fails because it predicts that a high weed density will reduce crop yield to zero, and that does not happen. Some crop plants always survive, even though they may be very small and the yield is unprofitable. Smith's data show the interaction of crop density and how, as it increases, the effect of weed density decreases (Table 6.16).

An interpretation of the relationship between crop yield and weed density has been described by the sigmoidal curve in Figure 6.13 (Zimdahl, 1980). At very low weed densities, there is no effect on crop yield, and as weed density increases, while there may be an effect, it is barely discernible. As weed density continues to increase, crop yield drops quickly but never goes completely to zero. Even very high weed densities do not eliminate all crop plants. This represents most weed-crop competition data and provides a picture of what happens but it is still not correct. Its appeal is that it is very difficult to measure the effect of a few weeds in a large area. It may not even be wise to attempt to do so. For practical purposes, the effect of 1 weed/acre is zero and that weed has no immediate, measurable economic effect. However, that one weed does affect nearby crop plants and produces seed and can, thereby, affect future crops.

There are many places in the literature of weed science that state, or the data clearly imply that, the relationship between yield loss and weed density is sigmoidal (Figure 6.13) with little or no loss at low weed density, or nearly none. Cousens et al. 1987 state unequivocally that the data do not support this. When yields are plotted over a range of weed densities, there is no evidence to support a sigmoidal response. The most accurate representation of crop-weed interactions is that created by regression analysis of crop yield and

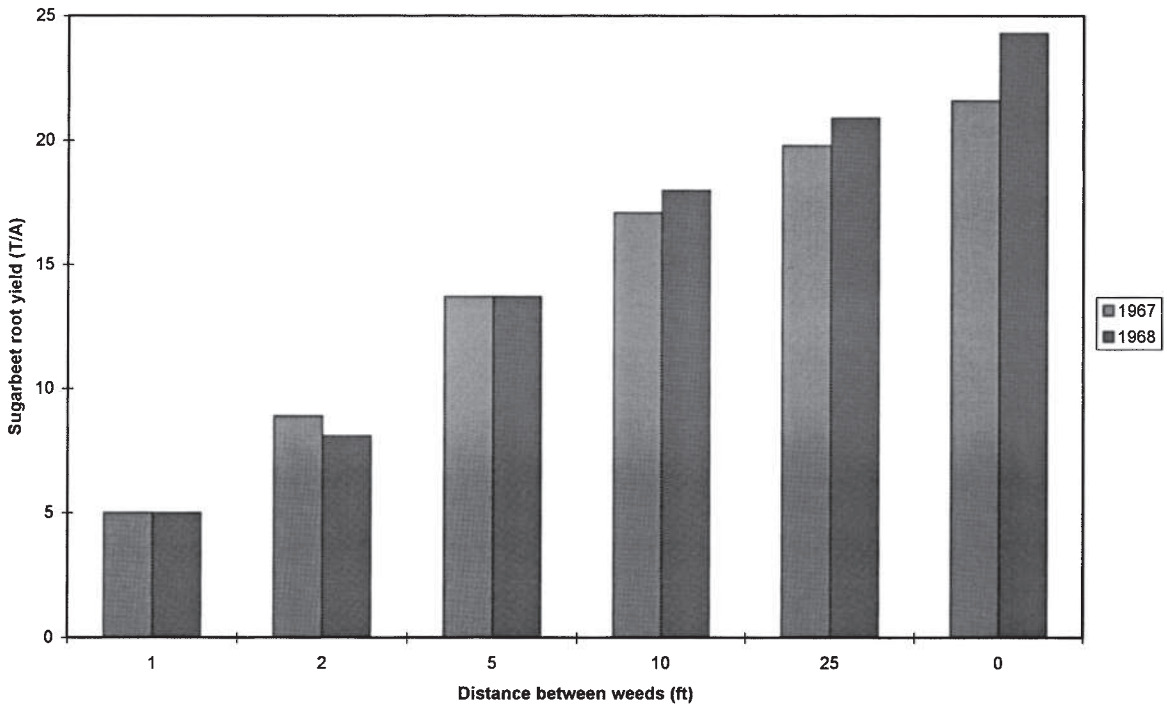

FIGURE 6.12. Effect of kochia on sugarbeet yield (Weatherspoon and Schweizer, 1971). Each yield bar in each year (not between years) is significantly different than every other bar (yield) for that year.

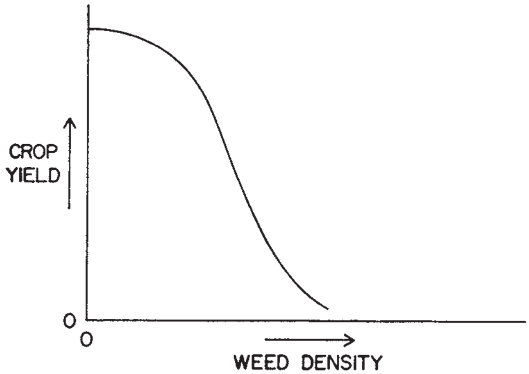

FIGURE 6.13. A schematic sigmoidal relationship depicting the effect of increasing weed density on crop yield (see Zimdahl, 1980, 2004).

TABLE 6.15. The Effect of Weed Density on Crop Yield.

Crop	Weed	Weed density	Yield reduction from control (%)	Source
Wheat	Wild oats	58.5/m^2	22.1	Bell and Nalewaja, 1968
		134/m^2	39.1	
Wheat	Green foxtail	721/m^2	20	Alex, 1967
		1,575/m^2	35	
Cotton	Prickly sida	2/5 cm of row	27	Ivy and Baker, 1972
		4/5 cm of row	40	
		12/cm of row		
Rice	Barnyardgrass	1/0.09 m^2	57	Smith, 1968
		5/0.09 m^2	80	
		25/0.09 m^2	95	
Soybean	Common cocklebur	3,297/ha	10	Barrentine, 1974
		6,597/ha	28	
		12,295/ha	43	
		25,989/ha	52	
Corn	Giant foxtail	½/5 cm of row	4	Knake and Slife, 1962
		1/5 cm of row	7	
		3/5 cm of row	9	
		6/5 cm of row	12	
		12/5 cm of row	16	
		54/5 cm of row	24	

TABLE 6.16. Interaction of Rice and Barnyardgrass (Smith, 1968).

Rice plants/0.09 m^2	Barnyardgrass	% Yield reduction
3	0	0
3	1	57
3	5	80
3	25	95
10	0	0
10	1	40
10	5	66
10	25	89
31	0	0
31	1	25
31	5	59
31	25	79

weed density. This is because densities observed in the field and those used in experiments cannot represent the whole range of possible weed densities depicted in Figure 6.13. Multiple regression models must be chosen carefully so they reflect biological reality and not just mathematical convenience. For a more complete discussion of the role of modeling in studies of weed-crop competition, see Chapter 10 in Zimdahl (2004).

VIII. MAGNITUDE OF COMPETITIVE LOSS

Tables 6.17a and b, 6.18a and b, and 6.19 show the magnitude of loss in a few studies of weed competition in corn, soybeans, and small grains. This small set of data provides evidence that weeds decrease crop yield, often a great deal. The data also show that the effect of weeds is not entirely predictable, nor is the effect of a particular density consistent. The tabular data are shown as they appeared in the original publication because it makes an important point about many studies—the lack of precision of the data. There is no uniform definition of a heavy stand, a small infestation, or a natural stand (Table 6.17a) and therefore the work is not repeatable. The data also illustrate the inevitable effect of year and place. In competition studies, it is important to define precisely the number of weeds and crop plants per unit area (the density).

TABLE 6.17a. Weed Competition in Corn (See Zimdahl, 1980, for Complete Citations).

Location	Density	Yield reduction
Illinois	Heavy stand	55%
Illinois	54 foxtail/ft of row in 4″ band over row	25%
Iowa	Handweeded	50% greater than unweeded
Iowa	Small infestations of foxtail	6–8 bu/A

TABLE 6.17b. Weed Competition in Corn (See Zimdahl, 2004, for Complete Citations).

Weed species	Density	Yield reduction
Barnyardgrass	100 m^2	18%
	200 m^2 concurrent emergence	26–35%
	Emergence when corn had 4 leaves	6%
Common milkweed	11,000 to 45,000 plants per m^2	10%
Giant ragweed	1.7, 6.9, or 13.8 plants per m^2	13.6–90%
Giant foxtail	10 per meter of row	13–14%
Green foxtail	0, 29, 56, or 89 per m^2	20–56%
	129 per m^2	5.8–17.6%
Hemp dogbane	Natural stand	0–10%
Itchgrass	2, 4, up to 14 weeks	125 kg per ha per week of presence
	Season-long	33%
Quackgrass	65 to 390 shoots per m^2	12–16%
	745 shoots per m^2	37%
Palmer amaranth	0.5 to 8 per m^2	11–74%
Redroot pigweed	0.5 per meter of row with concurrent planting at corn's 3 to 5 leaf stage	5%
Wild proso millet	10 per m^2	13–22%
Yellow nutsedge	100 shoots per m^2	8% per 100 shoots
	300 tubers per m^2	17%
	700 tubers per m^2	41%

TABLE 6.18a. Weed Competition in Soybeans (See Zimdahl, 1980, for Complete Citations).

Location	Density	Yield reduction
Nebraska	86 lbs/A	l bu/A
Iowa	10–12 weeds/ft of row	7.5–17.1%
Illinois	54 foxtail/ft of row in 4″ band over row	28%

TABLE 6.18b. Weed Competition in Soybeans (See Zimdahl, 2004, for Complete Citations).

Weed species	Density	Yield reduction
Common cocklebur	One per 1.8 m of row	7%
	One per 0.9 m of row	14%
	One per 0.3 m of row	30%
Hemp sesbania	Full season	28 to 41%
Jerusalem artichoke	16 per m^2—full season	43%
Full season	1 tuber per m of row	31%
	2 tubers per m of row	59%
	4 tubers per m of row	71%
4 weeks after planting	4 tubers per m of row	9%
6 weeks after planting	4 tubers per m of row	10%
8 weeks after planting	4 tubers per m of row	38%
20 weeks after planting	4 tubers per m of row	82%
Jimsonweed	0.3 per m of row—full season	8%
	1.6 per m of row	
	2 weeks	7%
	4 weeks	14%
	Full season	41%
Johnsongrass	Full season	59 to 88%
Johnsongrass with early maturing cultivar	1 week after maturity	32%
	2 weeks afer maturity	35%
	3 weeks after maturity	36%
Johnsongrass with late maturing cultivar	1 week after maturity	27%
	2 weeks after maturity	29%
	3 weeks after maturity	29%
Ivyleaf morningglory	1 per 15 cm of row—full season	13 to 36%
Quackgrass	Natural stand for	
	6 weeks	11%
	8 weeks	23%
	Full season	33%
Velvetleaf		
Mid May planting	1 per 30 cm of row—full season	27%
Late June planting	1 per 30 cm of row—full season	14%

TABLE 6.19. Weed Competition in Small Grains (See Zimdahl, 1980, 2004).

Location	Crop	Density	Yield reduction
Montana	Spring wheat	Canada thistle/sq. ft.	
		3–5	4.2 bu/A
		20–25	9.0 bu/A
		40–45	15.3 bu/A
Oregon	Winter wheat	1 fiddleneck/sq ft	10.0 bu/A
New York	Oats	15 mustard/sq ft	11.0 bu/A
Nebraska	Sorghum	15 lbs of weeds/A	1.0 bu/A

IX. DURATION OF COMPETITION

It is obvious that a weed present for one day in the life of a crop will probably have no measurable effect on final yield. But what if the weed is present for 2, 20, or 200 days? The question of duration of competition has been asked in two ways. The first kind of study asks what is the effect when weeds emerge with the crop and are allowed to grow for defined periods of time? After each of these times, the crop is then kept weed-free for the rest of its growing period. These studies define what many call the critical duration of weed competition. The second kind of study asks what is the effect when the crop is kept weed-free from emergence for certain periods of time and then weeds are allowed to grow for the rest of the growing season? These define what many call the critical weed-free period. Vega et al. (1967) studied the effect of duration of weed control on rice. Weeds grew in no time at all or in intervals of 10 days up to 50 days after rice was planted. They also allowed weeds to compete for 10, 20, 30, 40, or 50 days after planting and then kept the crop weed-free thereafter (Table 6.20).

The data show that yield is reduced when rice is weeded for a short time after planting. When it was weeded for 40 days, yield reached a maximum, and there was no benefit from weeding an additional 10 days. In the same way, if weeds were allowed to grow up to 20 days after planting and then removed, there was no effect on yield. Therefore, rice (and many other crops) can withstand weed competition early in the growing season and do not have to be weeded immediately. Weeds in rice cannot be present more than about 30 days, or yield will go down.

Corn must be kept weed-free for three to five weeks after emergence or nine weeks after seeding, depending on the location and the weeds (Table 6.21). The opposite study (Table 6.22) shows the length of early weed competition

TABLE 6.20. The Effect of Duration of Weed Control and Weed Competition on Rice Yield (Vega et al., 1967).

Weed control duration (Days after planting)	Yield (kg/ha)
0	46
10	269
20	1,544
30	2,478
40	3,010
50	2,756
Weed competition duration (Days after planting)	
10	2,944
20	3,067
30	2,752
40	2,040
50	1,098
Unweeded	55

TABLE 6.21. Weed-Free Period Required to Prevent Yield Reduction in Corn (See Zimdahl, 1980, 2004).

Weed-free weeks required after seeding emergence	Competing weeds	Location	Source
9	Mixed annuals	Mexico City	Alemàn and Nieto, 1968
5	Mixed annuals	Vera Cruz, Mexico	Nieto, 1970
3	Giant foxtail	Illinois	Knake and Slife, 1969
After 7-leaf stage	Redroot pigweed	Ontario, Canada	Knezevic et al., 1994
3 to 14 leaves	Natural stand	Ontario, Canada	Hall et al., 1992
6 leaves	Natural stand	Ontario, Canada	Halford et al., 2001

tolerated by corn. If provided with a weed-free period for three weeks after emergence, corn will compete effectively with weeds emerging afterward. Conversely, corn can withstand weed competition for up to six weeks if it is then weeded and kept weed-free.

When barnyardgrass and a mixture of redroot pigweed and Palmer amaranth was planted with alfalfa and removed by 36 days after planting, there

TABLE 6.22. Length of Early Weed Competition Tolerated Without Yield Loss in Corn = the Critical Duration (See Zimdahl, 1980, 2004).

Weeks of competition tolerated after seeding emergence	Competing weeds	Location	Source
3	Mixed annuals	Vera Cruz, Mexico	Nieto, 1970
4	Mixed annuals	Mexico City	Alemàn and Nieto, 1968
4	Mixed annuals	Chapingo, Mexico	Nieto et al., 1968
2–4	Halberdleaf orach and Persian speedwell	England	Bunting and Ludwig, 1964
4	Green foxtail	Ontario, Canada	Sibuga and Bandeen, 1978
6	Giant foxtail	Illinois	Knake and Slife, 1969
6	Redroot pigweed	Oregon	Williams, 1971
2–3	Mixed annuals	New Jersey	Li, 1960
8	Itchgrass	Zimbabwe	Thomas and Allison, 1975
4	Longspine sandbur	Colorado	Anderson, 1997
9 to 13 leaves	Natural stand	Ontario, Canada	Halford et al., 2001
14 leaves	Natural stand	Ontario, Canada	Hall et al., 1992

was no effect on alfalfa yield (Fischer et al., 1988). Thereafter, yield decreased in direct proportion to the length of weed interference. If the same weeds were seeded 65 or more days after alfalfa emergence, there was no effect on alfalfa yield, but weed biomass reduced first-cutting hay quality.

These kinds of data have been used to derive the critical period for weed competition that has been defined as apparent (Table 6.23a) for a few crops and over a range of time for several crops (Table 6.23b). It is clear from Table 6.23b that weeds behave differently in different crops (e.g., compare johnson-grass in soybean and cotton or common cocklebur in bean and peanut). A critical period is not equal to the critical weed-free period just mentioned. The critical period—the period after seeding when weed competition does not reduce yield but after which weed presence does not reduce yield—has been found for several crops. It is the time between the early weed-free period required and the length of competition tolerated (Figure 6.14). It is not a fixed period for a crop because it varies with season, soil, weeds, and location. The critical period is a useful measure because it gives guidance on when to weed. For example, potatoes, if kept weed-free for six weeks, will survive the rest of the season without yield reduction, even if weeds grow. If potatoes are weeded nine weeks after seeding, yield will not be reduced if they are subsequently

TABLE 6.23a. Crops with an Apparent Critical Period for Weed Competition (See Zimdahl, 1980, 2004, for Complete Citations).

Crop	Weed-free weeks required	Weeks of weed competition tolerated
Corn	3–5	3–6
Potato	4–6	4–9
Rice, paddy	4–6	4–9
Soybean	2–4 after planting	4–8 after planting

TABLE 6.23b. Crops with an identified critical period for weed competition (See Zimdahl, 2004, for Complete Citations).

Crop	Critical period
Barley infested with wild oat	2-node stage to maturity
Bean, snap infested with common cocklebur	Emergence to full bloom of snap bean Note: This is too long to be a critical period.
Bean, dry infested with hairy nightshade	3 to 9 weeks after emergence
Cotton infested with hemp sesbania	=>62 days after planting
Cotton infested with johnsongrass	4–6 weeks after emergence
Cotton infested with barnyardgrass	3–6 weeks after emergence
Cotton infested with bermudagrass	4–7 weeks after emergence
Peanut infested with common cocklebur	2–12 weeks after peanut emergence
Peanut infested with bristly starbur	2– weeks after emergence for tolerated loss of 3–4%
Peanut infested with horsenettle	2–6 or 8 weeks after emergence
Rice infested with bearded sprangletop	21–56 days after emergence
Soybean	9–38 days after emergence = 2nd node (V-2) to beginning pod formation (R-3) stage
Soybean infested with giant ragweed	4–6 weeks after emergence in one year and 2–4 weeks in a second year
Soybean infested with johnsongrass	4–5 weeks after emergence
Tomato, transplants	24–36 days after transplanting
Watermelon infested with large crabgrass	0–6 weeks after emergence

kept weed-free. Therefore, weeding of potatoes must be done sometime between six and nine weeks after seeding, or yield will decrease. Critical period analyses show that preemergence weed control is not essential, nor is weed control immediately after emergence. The method of weed control dictates when it must be applied, but the lesson of critical period studies is that weed control does not have to be done in the first few weeks after crop emergence.

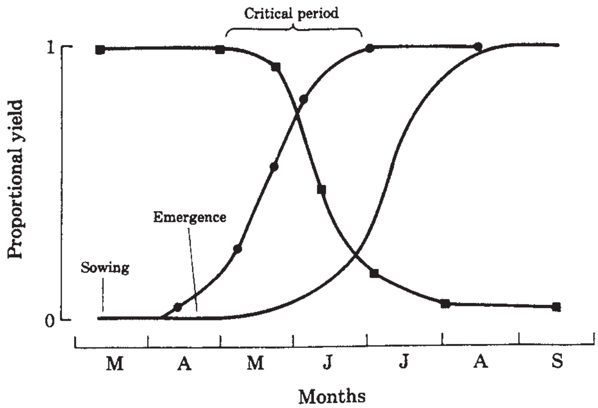

FIGURE 6.14. The "critical period of competition" illustrated for onions. —, changes in crop dry weight from sowing to harvest; ■, yield response from delaying the start of continuous weed removal; ●, yield response from delaying the termination of weed removal, as adapted by Mortimer, 1984.

Critical periods have practical weed management value, but Mortimer (1984) points out their limitation: All weeds are considered equally injurious, and no distinction is made between the kinds of competition that can occur. Most humans would be injured in a fistfight but will be injured less if they get to pick their opponent (that little fellow) than if the opponent is the heavyweight boxing champion.

X. ECONOMIC ANALYSES

More economic analyses of weed control are being done. Farmers know weeds reduce yield, and the question they ask is not whether weeds will reduce yield but how many weeds reduce yield how much. Their question is "Should I control weeds and, if so, what method(s) is best? The farmer's definition of *best* usually means the method that offers the highest profit potential. The farmer knows a few weeds are not of consequence and asks how many weeds *are* of consequence? The data in Table 6.24 illustrate how the answer might be provided.

The study showed that for three potential wheat yields, what the profit or loss would be for spraying, given a certain value of wheat and a defined spraying cost. For example, if a farmer has ½ weed per square foot, the estimated yield loss is 5%. If the wheat yield is estimated to be 15 or 20 bushels per acre, the cost of controlling the weeds will exceed the benefit to be gained. If, on

TABLE 6.24. Potential Profit or Loss from 2,4-d Application to Control Pinnate Tansymustard in Winter Wheat (Wiese, 1965).

		Potential wheat yield, bu/A		
	Percent estimated	15	20	30
Weeds per square foot	yield loss		Profit or loss, $[a]	
1/4	2.5	−1.03	−0.87	−0.56
½	5	−0.56	−0.25	0.38
1	10	0.38	1.00	2.25
1	20	2.25	3.50	6.00
4	40	6.00	8.50	13.50

[a]Profit or loss, value of yield loss if weeds are uncontrolled—spray cost; wheat, $1.25/bu; spray cost, $1.50/A.

TABLE 6.25. Yield Loss Caused by Wild Oats in Barley, Wheat, and Flax (Bell and Nalewaja, 1967).

	Yield reduction in bu/A		
Wild oat seedlings/m^2	Barley	Wheat	Flax
10	1.6	1.5	2.0
40	2.7	3.5	5.0
70	4.9	5.2	6.3
100	6.0	5.4	6.9
130	6.2	7.3	7.4
160	7.1	8.7	7.5

the other hand, yield will be 30 bushels, then the gain will exceed the cost and the weeds should be controlled. The values in Table 6.24 are out of date, but the table is provided to illustrate the principle, which remains valid. A similar set of data assist with decisions on controlling wild oats in barley, wheat, or flax. These data (Table 6.25) show the potential yield loss for each crop from a wild oats density that a farmer could determine.

A farmer could calculate control costs and value of yield lost to determine whether control should be done. Other studies of decision models have been done (King et al., 1986; Lybecker, 1984), but most decisions about what to do are still made by growers with incomplete information. Weed science needs more information on the efficacy of various weed control techniques and weed management systems in different soils and cropping systems. This information must be combined with information on percent emergence of the weed species in the soil seed bank, expected crop yield, weed control cost, and the farm's current economic situation to make wise weed management decisions.

XI. MATHEMATICAL MODELS OF COMPETITION

A large number of experiments have been done to demonstrate that weeds reduce crop yield (Zimdahl, 1980, 2004). This work has demonstrated that some weeds are more detrimental to one crop than another and the effect is always modified by environmental interactions. Weed scientists don't need more experiments to establish that weeds are detrimental. In fact, the important questions in weed control and weed management cannot be answered by experiments to determine yield loss as a function of weed density.

Mortimer (1987) cited four primary issues in weed management:

1. For a given crop management, what is the likelihood of invasion by weeds?
2. Given the presence of weed infestation, how rapidly will the weeds spread and what crop losses will be suffered?
3. How much of any proposed control measure is required to contain the infestation or lead to total eradication?
4. What are the comparative costs of different weed control measures and what risks are involved in switching weed management strategies?

It is possible but not desirable to answer these questions with standard field experiments because there is not enough time, money, or weed scientists to do so. Therefore, weed scientists are working to develop models to test experimental hypotheses and complement experimentation. Cousens et al. (1987) described four ways models can enhance research:

A. As the framework to integrate available information. Critical gaps in research can be pinpointed; incompatibilities and erroneous or abnormal results may become apparent.
B. Mathematics is a formal, rigorous language in which theories and intuition can be expressed. Models can reduce ambiguity and describe complex systems.
C. When used with an experimental program, models can increase the speed with which understanding develops. They can be used to identify critical experiments, thereby making the most economical use of resources.
D. Models can be used to forecast and predict what might be observed under conditions not previously included in experiments.

Models can be empirical and describe data or a response to imposed management options. They can also be mechanistic and attempt to incorporate knowledge of processes that determine response (Cousens et al., 1987). Much modeling effort has been expended to develop computerized decision-aid software to answer the third and fourth questions posed by Mortimer (1987). Decision-aid models are based on the knowledge that weed effects are population dependent and all models attempt to predict the biological (weed density) and economic consequences of management decisions (Coble and Mortensen, 1992). Models incorporate the concept of thresholds or beginning points for weed effects. There are at least four kinds of thresholds used in decision-aid models (Coble and Mortensen, 1992):

1. *Damage*—the weed population at which a negative crop yield response is detected.
2. *Economic*—the weed population at which the cost of control is equal to the crop value increase from control.
3. *Period*—time or times during the crop's life when weeds are most detrimental.
4. *Action*—the point when a control measure should be initiated.

Mathematical, computer-based models are not widespread in weed science. Cousens et al. (1987) proposed that the slow development of modeling in weed science was due the early lack of scientists familiar with mathematical modeling and its capabilities. There was also a limited demand for model development and a high demand for problem solving. Herbicide evaluation provided quick solutions to weed management challenges. Simulation models have been used primarily to predict crop yield losses from weeds. Weaver (1996) recommended linking crop-weed simulation models with biological models of population dynamics. Modeling and experimentation should proceed in tandem, not separately. Given the increasing public acceptance of environmental objections to expanding herbicide use and herbicide resistance, it is time to move toward models that permit weed management with other than broad-scale herbicide application. As models are developed, perfected, and tested against biological knowledge, they will be used more and more. Models are increasingly able to fulfill the basic requirements for a good weed-crop competition model (Cousens, 1985):

A. Without weeds there is no yield reduction.
B. At low weed densities, the effect of increasing weed density will be additive.
C. Yield loss can never exceed 100%.
D. At high weed densities there is a nonlinear response of crop yield to weed density.

It is beyond the scope or intent of this book to present a detailed discussion of crop-weed interference modeling in weed science (see Zimdahl, 2004, for a more complete review). Readers are directed to the references cited herein and to current literature for more information on this expanding research area.

THINGS TO THINK ABOUT

1. Why do plants compete?
2. What do plants compete for?
3. Do plants compete for space?
4. What factors determine weed-crop associations?
5. What makes a plant competitive?
6. How is the critical period of competition determined and what is it used for?
7. What is the most appropriate description of the relationship between crop yield and weed density?
8. How much yield is lost due to weeds?
9. What must be known about crop-weed competition to make good weed management decisions?
10. How do economic analyses help make weed management decisions?
11. What is the role of mathematical models in weed science?
12. What kinds of thresholds are used in crop-weed interference models?
13. How can models aid research and weed management?

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CHAPTER 7

Invasive Plants

FUNDAMENTAL CONCEPTS

- Invasive plant species can seriously damage native plant and animal communities, increase soil erosion, cause ecological changes, and interfere with human activities.
- The arrival of an invasive species is usually silent and unnoticed, whereas its effects can endure.
- Invasive plants can affect all aspects of life.
- Invasive plants are not just agricultural problems; they are ecological problems.
- Not all non-native plant invasions are inevitably harmful or undesirable.

LEARNING OBJECTIVES

- To know what invasive species are.
- To understand the extent of invasive species invasions.
- To understand the consequences of invasive species.
- To understand why plant invasions occur.
- To know some management options.

I. THE DEFINITION OF INVASIVE SPECIES

As is true for many areas of study, one must first determine *what* must be studied. Therefore, the first question is "What is an invasive plant species?" When study of invasion biology began, most researchers used neutral terms such as *introduced*, *non-native,* or *founding populations* to describe the species being studied (Burdick, 2005). Soon, scientists began using *alien, exotic*, and *invader*, which emphasized the danger posed (Burdick, 2005).

More than 50,000 exotic species (not just plants) have arrived in the United States over the past 200 years. About 5,000 of them were plants, but only about 14% (perhaps as many as 675 species) of all introductions are regarded as invasive (Chafe, 2005; Pimentel et al., 2000). Of the 5,000 exotic plant species that were intentionally introduced, beneficial species (e.g., corn, wheat, rice, plus cattle and poultry) accounted for 98% of the productive crops grown in the US food system in 1998 (Chafe, 2005). In the United Kingdom, 71 of 75 non-native crops are naturalized species (Williamson and Fitter, 1996). Crop plants are almost always considered to be beneficial, but as Williamson and Fitter point out, because they are strongly selected to grow where they are cultivated, they may also be adapted to grow well outside cultivation. Plants with the greatest potential to become invaders are those that are primarily aquatic or semi-aquatic, grasses, nitrogen fixers, climbers, and clonal trees (Daehler, 1998). Clearly, no plant possesses all of these characteristics (i.e., grasses are not clonal trees), but good invaders commonly have one or more. Natural area invaders are from ecologically diverse plant families and are frequently from largely woody families (Daehler, 1998). But one must remember that all non-native species are not threats; some are beneficial. Only 25% of non-native natural area invaders have been serious agricultural weeds (Daehler, 1998). To return to the opening question, what are these invasive species? How can one recognize an invading plant?

If an invader is simply a species that comes from somewhere else, then the definition is purely geographic (Burdick, 2005), and that is an inadequate definition. If invading plants are defined as weeds, then a human attitude determines if an invader is a threat or just a kindly new neighbor. In this case, the question about definition becomes "Who cares?" (Burdick, 2005). The International Union for Conservation of Nature and Natural Resources (IUCN) (aka World Conservation Union) provides a three-part definition of *invasive species* (McNeely, 2001):

> An alien species that becomes established in natural or seminatural ecosystems or habitats, is an agent of change, and threatens native biological diversity.

Weber (2003, p. 1) suggests that this definition differentiates between common weedy species and most plant arrivals that become naturalized in a new place, do not expand their range, and remain confined to disturbed habitats. Weeds grow primarily in agroecosystems and other highly disturbed, human-created habitats. The plants that weed scientists have been concerned with are dominantly (not exclusively) herbaceous species that occur in highly artificial, species-poor habitats (cropped fields) that are environmentally homogeneous and have predictable disturbance patterns (Weber, 2003). Invasive species, what Weber (2003) suggests might be called environmental weeds, occur in species-rich, natural habitats that are environmentally heterogeneous with unpredictable, or no unnatural, disturbance patterns.

It is clear that there is confusion in the literature about exactly what invasive and naturalized plants are. Richardson et al. (2000) define the necessary terms carefully. Plant introduction occurs when a plant or its propagule(s) has been transported intentionally or accidentally by human action across a major geographical barrier. They are aliens (i.e., non-natives) and may be simply casual introductions, which do not form self-replacing populations. They may become naturalized, which means they sustain populations over many life cycles without or often, in spite of, direct human intervention. However, these non-native populations may not become invasive. Invasive species produce numerous offspring that reside away from the parent population. Richardson et al. (2000) suggest a scale of movement >100 m; in <50 years for those that spread by seed, and >6 m/3 years for taxa that spread vegetatively. As mentioned, not all naturalized plants become invasive, and not all are weeds. Common weeds are those plants that may or may not be aliens that grow where they are not wanted (in a human disturbed habitat—a cropped field, garden, landscaped area, etc.) and whose presence leads to undesirable economic or environmental effects. Environmental weeds (see Weber, 2003, p. 1) are alien plants that invade natural areas, usually with adverse effects on biodiversity or ecosystem functioning. For more discussion of terminology, interested readers are referred to Davis and Thompson (2000) and Sagoff (2005).

The US government's Executive Order 13112 (1999) defined *alien, invasive*, and *native species* as follows:

> An *alien species* is defined with respect to a particular ecosystem as any species including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to that ecosystem.
>
> An *invasive species* is an alien (a non-native) whose introduction causes or is likely to cause economic or environmental harm or harm to human health.
>
> A *native species* is one that as a result of introduction, historically occurs or currently occurs in a particular ecosystem.

NOTE: In spite of the precision of the preceding definition of *invasive species*, there is disagreement about what species are truly *invasive*. All plant invasions are harmful if the economic or environmental harms outweigh the benefits. However, benefits and risks are commonly debatable, subjective determinations. For example, some claim that smooth brome is invasive, but others argue that its forage value for wildlife and domestic livestock far outweighs its invasive risk, and therefore it is not an invasive species.

President Clinton's executive order has been controversial because it also included the directive that Executive Branch agencies "work to prevent the introduction and control the spread of invasive species and eliminate or minimize their associated economic, ecological, and human health impacts." Much of the controversy is because not all agree on the definitions and therefore on what should and should not be imported. The definition problem and the inevitable conflicts are discussed well in a 2006 white paper from the National Invasive Species Council.

Given the IUCN definition (McNeely, 2001), some weeds may be invasive species, but most are not. One must also conclude that because of the great public and environmental interest in all kinds of invasive species, the awareness of many weed scientists may shift their research focus from the weeds of agroecosystems to alien plants (of foreign origin, i.e., they traversed a dispersal barrier) that become established (they create self-sustaining populations) in natural or seminatural ecosystems or habitats, are agents of ecological change, and threaten native biological diversity. The latter point is important because transformation of the biological environment is what creates concern. It is highly likely that because of the concern about environmental transformation, the scope of concern of weed science must expand to include invasive species.

II. THE IDENTITY OF INVASIVE PLANT SPECIES

In general, no one knows enough about plant invasion biology to be able to predict if an introduced species will become invasive and a threat to something or someplace (Weber, 2003). A reasonable, but not a perfect, predictor of behavior in a new place is behavior in the place of origin (the home range). Plants that behave badly in their place of origin are likely, but not surely, to behave badly in a new place. Most non-native invaders, however, do not become problems. They become naturalized and fit in their new place as they did in their place of origin.

Westbrooks (1998) claims that there are about 8,000 plant species, 3% of all known plants, that are considered invasive. Of those, only 200 to 250 (less than 0.3%) are major world weeds (Holm, 1978), and the most troubling weedy species are in 80 taxa (Holm et al., 1977). A few plant species have invaded widely separated places on the planet, which Mack et al. (2000) equate to being "the ecological equivalent of winning repeatedly in a high-stakes lottery." Troubling weedy species span 80 taxa, but the world's worst invasive species belong to only a few families and genera: Acacia, Asteraceae, Cyperaceae, Poaceae, and Mimosa (Mack et al., 2000).

A few plants that become invasive are natives; most are not. For example, the common reed, native to central Europe, is invasive within its native range (Weber, 2003). Historically, common reed was restricted to its place of origin in the United States—brackish wetlands, high marsh habitats with low salinity and high soil oxygen content (Amsberry et al., 2000). It seems to have invaded low marsh habitats by first invading high marshes and then expanding to the lower, less favorable areas via clonal integration. This expansion, in the view of Amsberry et al. (2000), is due to a variety of human-induced changes in coastal habitats rather than to a single cause. In the United States, the native common reed has been displaced by an invading, similar species from the same genus (Saltonstall, 2002). Junipers, native to the western and southwestern United States, have expanded beyond their historical range (Ansley et al., 1995).

A third example of a native becoming invasive is the US weed common waterhemp. It is native to North America and has become a weed of agricultural fields, stream banks, and flooded areas in many states. Weed scientists seem to agree that nearly all weedy species of *Amaranthaceae* (examples include Palmer amaranth, redroot pigweed, and smooth pigweed) are native to the United States and have become invasive in agricultural habitats. Another example of a native weedy species that has become invasive is the presence of feral (wild, or red rice) rice in rice fields. It has been present in rice fields for a long time but has only become an important weed problem as planting has shifted from transplanting to direct seeding (see Baki et al., 2000, for a complete discussion of the current problem).

Highly specific classifications or lists of characteristics are of little help in identifying potential invasive organisms (Noble, 1989). Reed's (1977) large study included 1,200 foreign plants from 101 families that were weeds in their native place and might become serious weeds if they invaded the United States where different "environmental and biological restraints no longer controlled their development." Reed's work was a warning, not a prediction. Invading species with ecological and physiological traits similar to native species have been identified (e.g., members of the *Linaria* genus and some perennial grasses). Noble (1989) points out that absence of special long-distance dispersal mechanisms (e.g., wind transported seed) is not a hindrance to invasion because humans are the primary vectors of transport. In contrast, short distance dispersal mechanisms may enhance the "probability and rate of invasion." Plants that produce many reproductive propagules have enhanced invasion potential, but the characteristics of the new area are perhaps the most critical determinant of invasion success. It is the interaction of a particular invader's characteristics with the invaded environment that determines success. Pheloung et al. (1999) developed a weed risk assessment model for use in evaluating plant introductions to Australia and New Zealand. The model was based primarily on a taxon's weed status in other parts of the world, its climate and environmental preferences, and certain biological attributes (e.g., method of dispersal and seed survival). All taxa classified as serious weeds and most minor weeds were rejected (excluded) by the model, which they recommend as a screening tool.

Concern about invasive species is not just a passing fancy that will fade as we understand them better. The concern is related to the fact that globalization of so many aspects of life and the consequent speed of movement have created more opportunities for invasive species to become agents of change and threats to native biological diversity. McGrath (2005) estimates that more than 40% of all presently imperiled native US plants and animals are at risk of extinction because of invasive species. The Brooklyn Botanic Garden published one of the first reports of invasive weeds (Randall and Marinelli, 1996). Weber's (2003) book includes 1,462 references on more than 400 invasive plant species. Westbrooks's (1998) report on how invasive plants are changing the face of the United States included 198 species, 95 of which are not included in Weber's book. Given the problems of definition and the fact that Westbrooks's book was published by a federal committee concerned with weeds, it is not surprising that 48 of the species included in Westbrooks's book are clearly weedy plants. Weber's book does not exclude weeds but it emphasizes alien species that "establish in natural or seminatural ecosystems or habitats."

Many, perhaps most, invaders have been intentionally introduced, and most introductions have been ornamentals (e.g., purple loosestrife; Reichard and White, 2001). Horticulture has been what Bright (1998, p. 147) calls "a gargantuan engine of biotic mixing that has helped unleash some of the world's worst plant invasions." A few examples are shown in Table 7.1. In the United States, 82% of woody species that have colonized areas outside their area of cultivation (they have become invasive) have been introduced for landscape purposes (Reichard and Hamilton, 1997). A survey of 1,060 woody plant invasions found that in 624 cases, where origin could be determined, 59% came from botanical gardens (Bright, 1998). Many invasive species have been introduced accidentally as crop seed contaminants (e.g., leafy spurge, spotted knapweed, yellow starthistle) or simply as free riders in a shipment of unrelated things (e.g., cheatgrass). Some of the worst plant invaders have been intentionally introduced, including English ivy, johnsongrass, kudzu, tamarisk, and waterhyacinth (Westbrooks, 1998).

TABLE 7.1. Plant Invaders with a Horticultural Origin (Bright, 1998, pp. 148–149).

Plant	Source	Location of problem invasion
Rubber vine	Madagascar	Northern Australia
Travelersjoy clematis	Northern Europe	New Zealand
Waterhyacinth	South America	Southern United States, Africa, South Asia
Purple loosestrife	Europe	Northern United States
Japanese knotweed	East Asia	Europe and North America
Tamarisk/salt cedar	Central and East Asia	Most of the United States

A weedy invader of current concern is camelthorn, which was imported to the United States as a wrapping for date tree cuttings and in alfalfa seed in about 1900 (Brock, 2006). It is now abundant in nine states, especially in northwestern Arizona. It rapidly displaces native vegetation (Brock, 2006).

Many plant introductions are the result of deliberate, flawed forethought (Mack et al., 2000). But not all have resulted in disaster. Camellia and azalea, originally from Asia and India, are planted widely. Both stay where they are planted. Neither escapes by vegetative fragmentation or bird dispersal of seed, and both behave well (Burks, 2002).

But the problem of invasive plant species cannot be attributed only to the desire of horticulturalists to identify and import new ornamentals. Globalization of commerce leading to rapid, often unchecked, movement of species is much more important. The world is becoming smaller in the sense that the speed and frequency of travel have increased. Lovelock (1979), a mathematician, was the first to argue that the earth was a single, planet-sized organism. He named it Gaia after the Greek earth goddess. His arguments seemed less than scientific, perhaps mystical, and they were not greeted with enthusiasm by the scientific community. While there has always been movement among the earth's communities, it was slow and controlled by natural forces. Real, ecologically relevant geographic and climatic barriers are no longer as great as they once were. Lovelock (1979) proposed three reasons for their decline in importance (Bright, 1998, p. 20). First, the frequency of movement has increased. Planes and ships move thousands of people daily across vast distances. Each plane and ship carries known and unknown organisms in addition to the people who bring known and unknown organisms on and in their bodies, clothing, and personal possessions. For centuries, natural movement across geologic barriers was slow, and human travel was slow. Natural movement is still slow, but the rapidity of human movement has vastly increased the speed of arrival of all kinds of organisms. Second, movement can now occur almost anywhere on almost any day. Intense biotic mixing has changed from "an occasional regional event to a chronic global occurrence" (Bright, 1998). Finally, what was an impossible migration is now possible and common. Miles of salt water or desert used to be effective, impenetrable barriers to organism movement. Such barriers provided the isolation that allowed unique species and ecosystems to evolve (McNeely, 2004). Now, with modern rapid transportation, such barriers are crossed with ease. In fact, they are not barriers to movement of any organism.

In the classic view of ecosystem invasion, first proposed by Elton (1958), ecosystems lived on a knife's edge (Burdick, 2005). Elton proposed that a community's resistance to invasion increased in direct proportion to the number of species in the community—the species richness hypothesis. The essence of the hypothesis is that a community's species richness (the greater the number of species) indicates reduced resource availability and, therefore, greater resistance to invasion because resources are being used by the wide variety of species present in the community. Levine and D'Antonio (1999) examined this hypothesis and found it to be based on controversial premises. Experimental results have shown positive and negative effects of diversity. Results that show diverse communities to be more invasible may be attributed to environmental factors rather than to diversity per se (Levine and D'Antonio, 1999). However, work by Dukes (2002) supports the species richness hypothesis. He showed that eight species grown in monoculture differed widely in their ability to suppress yellow starthistle. The ability of yellow starthistle to suppress other species declined with species richness. The work suggests that diversity can limit invasibility and may reduce an invaders effects. Dukes's work also proposes that knowledge of the relative competitive ability of native and invasive plants can lead to effective management techniques. A monoculture of the late-season annual, hayfield tarweed, was the most effective competitor with yellow starthistle. No polyculture was as effective. Hayfield tarweed's success may be due to rapid soil moisture depletion, and the authors hope this knowledge may lead to new techniques for suppression of an invasive species. The palatability of hayfield tarweed is low, and imposed dryness is not a popular solution among ranchers.

Second, Dukes (2002) proposes that all ecosystems are carefully structured, and unless they are disturbed, there is little room for invaders because all resources are being used by the residents. Especially in species-rich communities, all live on the knife's edge competing for limited resources—the resource availability hypothesis. In contrast, what study of invasions has shown is that all ecosystems have plenty of resources that are available to new species and that diverse systems use resources more completely (Tilman et al., 1996). The hypothesis is that there are vacant niches to be occupied, but there may be fewer such niches in diverse communities.[1] Stohlgren et al. (1999) showed in the Colorado Rocky Mountains and in the central grasslands of Colorado, Wyoming, South Dakota, and Minnesota that exotic species primarily invaded areas of high species richness. They concluded that sites high in herbaceous foliar cover, soil fertility, and plant diversity are invasible. Invasibility was more a function of resource availability than species richness. Other work confirmed the susceptibility of species rich areas to invasion (Stohlgren et al., 2003). See Ricciardi (2001) for confirmation of the hypothesis in an aquatic habitat.

[1]*Niche* is used to describe a species place in the community, including when it is present, what place (space) it occupies, and what function(s) it fulfills in the community. The ecological concept of niche includes a species specialization—its special or unique function in the community.

One must conclude the following:

1. The threats of invasion are real and well documented.
2. Several invading species have been identified.
3. Diverse plant communities are susceptible to invasion.

Given these facts, can we identify the traits of an invader? How can we know one when we see one?

Rejmánek (1989) compiled a list of 54 invaders of natural communities in several parts of the world. His list included species from 40 families that represented all major plant growth forms. He suggests that the list is a "bizarre collection of extremely diverse adaptations that have been necessary for invasions into a variety of more or less natural communities in different environments." Rejmánek (1989) suggests it is difficult, if not impossible, to quantify invasive potential of a particular species or the invasibility of a community. There is abundant evidence that disturbance (see section III) of many kinds makes invasions more likely (Forcella and Harvey, 1983). Successful invasion depends on the extent and type of disturbance, the number of non-native species propagules available in a community per year, and how long the community is exposed to invading propagules (Rejmánek, 1989). Therefore, communities that experience intensive and frequent disturbance, a rapid, enduring spread of highly competitive invasive propagules that have a lower overlap of resource requirements compared to the natives, can be invaded more easily. For example, Zedler and Kercher (2004) point out that wetlands are especially vulnerable to invasions. Only 6% of the earth's land is wetland, but 24% of the world's most invasive species are wetland species. Wetlands are what Zedler and Kercher call *landscape sinks*, "which accumulate debris, sediments, water, and nutrients, all of which facilitate invasions by creating canopy gaps or accelerating the growth of opportunistic plant species." That is to say that consistent with Rejmánek's (1989) hypothesis, a wetland is frequently disturbed and may have a high rate of spread of invading propagules that have different resource requirements compared to the natives. The invasion of alligator weed from Brazil to Australia is a good example. It established itself as a noxious weed throughout Australia within 60 years.

In contrast to Rejmánek (1989), Westbrooks (1998) lists 12 characteristics of invasive species that permit them to invade new areas and outcompete native vegetation. The characteristics Westbrooks includes are those of successful weeds:

1. Early maturity
2. Profuse reproduction by seeds and/or vegetative structures
3. Long life in soil (of seeds and vegetative parts)
4. Seed dormancy to assure dispersal in time

5. Adaptation for dispersal as contaminants of crop seeds
6. Allelopathy (see Callaway and Aschehoug, 2000)
7. Spines and thorns that cause physical injury and repel grazing animals
8. Ability to parasitize other species
9. Seeds that are the size and shape of crop seeds, so separation by standard cleaning techniques is not effective
10. Vegetative structures with large food storage
11. Survival and seed production under adverse growing conditions
12. High photosynthetic capacity

These characteristics are included in the now classic list of characteristics of weeds (Baker, 1965; see Chapter 2). But not all introduced plants are or become weeds and contrary to the accepted definition of invading species, most non-natives do no harm. No one knows which plants may become successful invaders because no common characteristics are known (Bright 1998, p. 25). Finhoff and Tschirhart (2005) proposed that all species have a rich array of traits that make them suited for some environments and not for others. Identification of invasive species that are successful under some environmental conditions is linked to four physiological parameters: specific leaf area that defines its solar energy intake, the ideal level of environmental resource(s), and two respiration parameters. Their model integrates ecological and economic considerations and is a step toward defining the specific characteristics of invasive species.

Some of the worst invaders are highly adaptable generalists—that is, they have the characteristics of good weeds. Others are not, and attempts to develop a uniform list of characteristics of invaders have failed. While many invaders are from plant families that have several weedy members, not all invade cropped fields; they are not agricultural weeds. It is also true that many invasive species have few or no aggressive relatives. For example, what Holm et al. (1977) call the world's worst weed, waterhyacinth, is the only member of the *Eichornia* genus that is invasive (Mack et al., 2000). That could be due to the lack of opportunity to invade offered to relatives or to a lack of the right characteristics for invasion (Mack et al., 2000).

Fifty years of research on invasion biology has failed to identify a clear difference between an ecosystem rich in native species and one full of aliens (Burdick, 2005). The best conclusion seems to be that invasions don't weaken ecosystems. When successful (and most are not), they transform them into different systems that may be of greater or less economic or aesthetic value to humans (Burdick, 2005). This reality brings us back to definitions. As just stated, a human attitude may determine whether an invader is a threat or just a kindly new neighbor. The question still becomes "Who cares?" (Burdick, 2005).

III. WHY DO INVASIONS OCCUR?

Those who study invasion biology agree that many invasive plant species were introduced by humans for horticultural or ornamental purposes. For example, Reichard and Campbell (1996) showed that 85% of 253 invasive woody species in the United States were introduced as ornamentals and another 14% were introduced as agricultural plants. Many invaders are sold regularly in nurseries. These plants were introduced and are sold because they possess positive traits that are highly desirable to gardeners, landscapers, and the nursery industry (Li et al., 2004). For example, they are usually easy to establish and grow with little care, often under diverse environmental conditions. The homeowner goes to the nursery wanting a plant that will grow easily, with little care, in a bad place (shady, dry, etc.), and there it is. What it may become in 10 years is neither asked nor revealed, if it is even known.

Those who study invasion biology and weed scientists have not found a set of words that adequately define an invasive species. Those who sell them often don't know about invasion potential, at least partially because there is no agreement on what it is that ensures success of an invader. Lonsdale (1999) proposed that the invasion of any environment by a new species is influenced by three things: the number of propagules entering the environment (propagule pressure), the characteristics of the new species, and the environment's susceptibility to invasion (invasibility). There is general agreement that Lonsdale is correct, but there is lack of specific agreement on how the three things interact and their relative importance. Lonsdale's three things are necessary components of a satisfactory definition, but they are not sufficient to define the characteristics of plant communities that are susceptible to invasion.

A related question is whether an invader is the driver or simply a free rider in degraded ecosystems (MacDougall and Turkington, 2005). The driver model predicts that competition is vigorous in invaded plant communities, and native species are simply outcompeted by the invader. Over time, they are excluded by the superior competitive success of the alien invader. If the invader is a free rider or a passenger, as MacDougall and Turkington (2005) call them, then the community is structured mainly by noncompetitive forces such as environmental factors or dispersal limitation that are frequently less constraining on the invader, which begins to dominate. MacDougal and Turkington tested these hypotheses in an invaded, fire-suppressed oak savanna community. They found that relative abundance was most determined by environmental trade-offs (e.g., long-term fire suppression), rather than resource capture. In the environment studied, the free rider model best explained the dominance of invasive species, but it may not be applicable to all environments or to all invaders.

For agricultural and horticultural crops, the characteristics of invasive species seem to be obvious because the concern is about weedy invaders. The way agriculture and horticulture are practiced creates open niches in which weeds thrive. Weeds are the inevitable result of the environmental disturbance that is a central trait of crop culture in the developed world. Thus, for invasive plants that are weeds (a category of invasive plants), the way crops are grown provides adequate opportunity for invasion. Cropping systems in developed country agriculture succeed in creating monocultures of a single desired plant, and all other plants are declared weeds. The system creates open niches ready for invasion—the vacant niche hypothesis (Elton, 1958). Plant communities with vacant niches (a cropped field with open rows or spacing between crop plants) are relatively impoverished (species poor) and have little biological resistance to invaders. However, other than in cropped fields, demonstration of vacant niches has proven difficult.

A variant of the vacant niche hypothesis is the community richness hypothesis of Elton (1958), mentioned previously. A plant community that is rich in species was in Elton's view capable of resisting invaders. The theory is that communities tend to be more stable if they are rich in species because they have fewer or no vacant niches. All niches are occupied by one or more of the community's diverse species. It is true that there is often reduced resource availability in communities with high species richness. But in some cases the hypothesis does not hold. All communities have resources that are not being used, and study of invasions has verified this. In fact, invasions often increase the species richness and therefore the biodiversity of a plant community (Burdick, 2005), although there are notable exceptions that will be discussed. *Biodiversity* is a common, frequently undefined, term in discussions of invasive species. It is the variability among living organisms of all kinds in a community. It includes diversity within species, between species, and of plant (and other species) communities within ecosystems (UNEP, 1992). Tilman (1999), in a comprehensive review of the ecological consequences of biodiversity, suggests it is one of several factors that control population and ecosystem dynamics. Others that must be considered include disturbance, nutrient supply, and climate. Once again, it is certain that in biology and ecology the quest for certainty leads to definition of a multiplicity of factors that must be considered and the difficulty of creating sweeping generalizations that answer all questions.

Invading species may thrive because they have escaped from the biotic constraints of their previous home: the enemy release hypothesis (Mack et al., 2000). Independent of how they reached a new place, they made the journey without their previous associates, such as other competing plant species, predators, grazers, or parasites. Such journeys are often made in the dormant or resting state as a seed or vegetative structure. The hypothesis is that the invading species does not necessarily possess any special invasive traits. It does well because it left its old enemies behind and is not readily attacked by new natural enemies. It has not encountered new enemies that are anywhere near as effective. Stastny et al. (2005) suggested that the competitive ability of an invader may be associated with "changes in resistance as well as tolerance to herbivory." That is the former natural enemies (the herbivores) are not present, and the new ones are not as effective. Release from herbivory may be an important key to success of highly aggressive invaders (Carpenter and Cappuccino, 2005). In a test of 39 exotic plants and 30 natives in natural areas near Ottawa, Canada, exotics suffered less from herbivory than natives. Reduced or lack of herbivory may also indicate evolution of defensive chemicals in the exotics that confer resistance to herbivory. Mitchell and Power (2003) tested 473 naturalized plant species in the United States. On average, 84% had fewer fungal and 24% fewer viral enemies than each had in its native range, which is strong support for the enemy release hypothesis. Colautti et al. (2004) argued against the simple relationship the enemy release hypothesis establishes between enemy release and the vigor, abundance, or effects of nonindigenous species. Clearly, ecologists are vigorously debating the merits of these competing hypotheses.

Especially with weeds, one of the best hypotheses about the reasons for invasion is that disturbance before or at the time of invasion is the primary cause (Mack et al., 2000). When sudden or regular changes in a particular environment occur as an invader arrives, successful invasion is more likely. One of the best examples of disturbance is the intentional or accidental use of fire. It has played a significant role in several biotic invasions (Mack et al., 2000). Invasions of non-native species on the arid, temperate grasslands of Australia and North and South America were facilitated by fire (Mack et al., 2000). D'Antonio and Vitousek (1992) provide one of the few studies that illustrate the change wrought by invading grasses (from Africa in this case) on previously forested areas of the Amazon basin. Land clearing, nutrient loss, altered microclimate, prevention of succession, and fire are significant on a local scale and are becoming significant on regional and global scales. The success of alien grasses is aided by fire and they prevent succession of native species, thereby creating an environment conducive to success of the aliens at the expense of native species. Once the grasses become established, their continued success is ensured because of their rapid annual reproduction and highly flammable litter. Regular fire, in an ecosystem not adapted to fire, denies establishment to the natives but does not harm and, in fact, encourages invading grasses.

The regular disturbance of grazing and subsequent overgrazing often favors invaders over native species. Many of the world's presently dominant rangeland plants owe some of their success to grazing pressures (Bright, 1998,

p. 41). The success of cheatgrass (weed scientists know it as downy brome) on western US rangelands was caused by continued overgrazing. Downy brome has been called the most devastating ecological problem in the western United States (Devine, 1993). It is a native of Eurasia, which began to invade the western United States and Canada between 1889 and 1894 and had shown up in most areas where it is today by 1928 (Mack, 1981). It may have been introduced intentionally as a forage, but it is more likely that it arrived in several locations as a contaminant in seed (Mack, 1981). It now dominates more than 100 million western US acres. Its presence would not have mattered much if cattlemen had not weakened the range's natural resilience by overgrazing. Native plants are often easily damaged by livestock (cattle) grazing. This is because some evolved without being regularly grazed by large herbivores (Devine, 1993). In contrast, downy brome evolved in Eurasia, in a grazing adapted ecosystem, under regular grazing from camels, horses, and other grazing animals and is not affected detrimentally by intense grazing as long as it can set seed, which it does quickly and abundantly early in the spring. Overgrazing thus tends to eliminate native species and create opportunities for downy brome to thrive. Downy brome can but often does not enter native plant communities in the western United States and cohabit without dominating. Downy brome's invasion of the West is a clear demonstration of how successful an invader can be when "preadaptation, habitat alteration simultaneous with entry, unwitting conformation of agricultural practices to the plant's ecology and apparent susceptibility of the native flora to invasion, are all in phase" (Mack, 1981). Overgrazing and changes in the fire regime have been the key disturbances that allowed downy brome to invade aggressively. In spite of the weed's well-known invasive ability, ranchers do not completely despise it because it provides abundant, early spring grazing.

Davis et al. (2000) proposed that fluctuation in resource availability is a key factor that controls invasibility of plant communities. Disturbance, a major factor in invasion, usually increases resource availability. Research (Davis and Pelsor, 2001) has demonstrated that changes in resource availability affect competition intensity, which affects community invasibility. Short-term (a few weeks) increases in resource availability can "temporarily reduce or suspend competition from resident vegetation," thereby increasing an environment's invasibility for as long as 12 months (Davis and Pelsor, 2001).This is consistent with Mack's (1981) hypothesis that habitat alteration at entry has a major affect on success. The importance of resources is also illustrated by the work of Meekins and McCarthy (2001), who demonstrated that growth and reproduction of the nonindigenous forest herb, garlic mustard, was not dependent on disturbance. Its invasive success was determined by adequate soil moisture and available light. Similarly, more effective competition for light because of stem elongation and canopy formation enabled western elodea to invade and become established in the presence of common elodea (Barrat-Segretain and Elger, 2004).

Goldberg (1990) argued that "effect on and response to a resource is positively correlated only to the extent that both are a function of uptake rates." Uptake may be a relatively unimportant determinant of the magnitude of the effect on and response to a resource. Research needs to be done to compare effect on and response to a required resource. Goldberg also proposes that species that make heavy demands on a resource will dominate in "communities where success is determined by size-symmetric competition." Good examples include cropped agricultural fields, early succession areas, or gaps in existing vegetation. In contrast, plants that tolerate and grow well with low resource levels often dominate when size-asymmetric competition occurs, as it does when seedlings germinate in mature vegetation (Goldberg, 1990). Fargione et al. (2003) showed that in a prairie grassland, resident species inhibited establishment of species with similar resource use patterns by early resource consumption. The success of invaders decreased as diversity increased, and this is explained by the simple mechanism of competitive inhibition of invaders that are similar to established and abundant species in seed size–symmetric competitive situations.

Brown and Rice (1998) showed that the early-season, shallow-rooted invader of prairie plant communities, soft brome, was least successful in mixtures of species with similar resource use patterns. The mixtures were composed of species that were resource incompatible—that is, all needed the same things at the same times. The late-season invader yellow starthistle was least successful in compatible mixtures of species with varied resource use patterns some of which were similar to yellow starthistle. Invaders in this work were not as successful in plant communities of species with similar resource use patterns. Both invaders were less successful in more diverse (greater species rich) communities and their success was reduced by existing vegetation independent of the resource use pattern of the invading species (Brown and Rice, 1998).

Contrary to the implicit assumption of concern about invasive plants, the evidence is that invasive plants usually do not outperform co-occurring native plants (Daehler, 2003). Alien invaders are not more likely to have higher growth rates, competitive ability, or fecundity. Their relative performance (success) depends much more on growing conditions (Daehler, 2003). In Daehler's work in Hawaii, invaders were more likely to have greater phenotypic plasticity, which is particularly advantageous in disturbed environments. Daehler concludes that there are no super-invaders that have universal performance advantages over natives. That is, no one has identified universal characteristics of all successful invasive plants (Daehler, 1998). Success is more often associated with disturbance—often human (see preceding discussion of downy brome).

Hallett (2006) supports this by concluding that "no overarching conceptual framework for the mechanism of plant invasion has emerged." He identifies the common theme in all invasions that the invading plant "in the process of geographic displacement, has been dislocated from its coevolved biota and relocated with a less familiar biota." This observation leads to the conclusion that a plant's invasive potential is not determined by its life history or the nature of the invaded ecosystem. Invasiveness is primarily a result of the process of invasion. Plants dislocated from their co-evolved relationships are inevitably confronted with new relationships that must be dealt with. Some succeed, many fail. In human terms it is similar to moving from the town you grew up in, where everything is familiar and you knew who was friendly and who was not. Suddenly you are compelled to move to a new place, and you don't know who is nice and who is not, where things are located, or how you can meet people. Humans often become unsettled by such moves, and plants do, too. When confronted with new relationships, they undergo ecological transformation, after which some succeed and others do not. It is the transformation, in Hallett's (2006) view, that affects the ability of a plant "to become established, invasive, and naturalized in a new environment."

Hybridization can also stimulate the evolution of plant invasiveness (Ellstrand and Schierenbeck, 2000). Many invasive species that achieve success do so only after a long time. That is, they have succeeded in surviving in a new environment but have not become invasive. Ellstrand and Schierenbeck (2000) propose an evolutionary mechanism to account for the lag and later invasive success. Hybridization between the potential invader and "disparate source populations may serve as one stimulus for the evolution of invasiveness." They found 28 examples from 12 plant families where invasive success was preceded by hybridization. Several of the examples were weedy species. For example, they attributed the invasive success of the *texanus* subspecies of common sunflower and sorghum almum to intertaxon hybridization. A few of the other weedy species that evolved after intertaxon hybridization include purple loosestrife, Scotch thistle, wild radish (after interbreeding with common radish), and a perennial rye that resulted from hybridization between common rye (a grain crop) and a weedy rye (*Secale montanum*). Only a few hybrids become invasive. Success is conditioned by opportunity (a suitable open niche, competitive success, or ecological release). Hybridization is one mechanism that can catalyze the evolution of invasiveness. The success of hybridization has been demonstrated with Eurasian watermilfoil populations in the United States (Moody and Les, 2002). It is present in 45 states and 3 Canadian provinces (Natural Res. Conservation Serv., 2001). Its invasive success has "resulted from hybridization between non-indigenous and native species, . . . resulting in heterosis maintained by vegetative propagation" (Moody and Les, 2002).

In contrast, the invasive success of spotted knapweed among grass species and against native knapweeds may be due to an entirely different mechanism. Success may be due to root exudates (allelopathy) and how the root exudates affect competition for resources (Callaway and Aschehoug, 2000; Callaway and Ridenour, 2004). Success of diffuse and spotted knapweed in North America may be due to the adaptation of its Eurasian neighbors to the allelopathic chemicals produced by the knapweeds and the lack of evolved adaptation among new North American neighbors. The primary allelochemical in spotted knapweed [(+)-catechin] has been suggested in work by Bais et al. (2002, 2003) and Thelen et al. (2005). That work has been questioned by Blair et al. (2005, 2006), who strongly suggested that much more research is required before the role of allelopathy in general or the specific role of catechin in knapweeds as a novel mechanism that explains its invasive success can be confirmed.

IV. THE CONSEQUENCES OF PLANT INVASIONS

Invasive plants now dominate more than 100 million acres in the United States and are increasing at an estimated 3 million acres each year (Nat. Invasive Species Council, 2001). Myers and Bazely (2003, pp. 18–19) compiled data for several world regions to show the percent of all plants that have been introduced. The following data clearly show that the problem is shared by all world areas.

World region	Number of areas	Average percent of introduced plants
Oceania	7	35
Canada	7	26
United States	12	16.5
Caribbean	4	25
Europe and United Kingdom	9	11.8

All introduced invasive species cost the United States about $125 billion annually (Baker, 2001). Introduced invasive weedy species alone reduce US crop yields by $23.4 billion each year (Pimentel et al., 2000). The US Department of Agriculture estimated the costs of lost production due to invasive or noxious weed species in 64 crops to be $7.4 billion annually. Control may cost in excess of $35 million each year (Hall, 2000; Pimentel et al., 1999). Control costs do not include the unknown costs of loss of ecosystem function, affects on human health, habitat loss among native species, and reductions in biodiversity (Li et al., 2004).

Downy brome (sometimes called cheat or cheatgrass) may be the most devastating ecological problem in the western United States (Devine, 1993). Duncan and Clark (2005) estimated its annual rate of spread in the United States to be 14%. But it is not the only, and may not be the worst, plant invader. There are many competitors for the title. For example the National Wildlife Refuge Assoc. (2002) lists its Dirty Dozen invaders that include nine plants (garlic mustard, Chinese tallow, purple loosestrife, giant salvinia, leafy spurge, melaleuca, phragmites, spotted knapweed, and yellow star thistle). In 2001, the Nature Conservancy also had its Dirty Dozen list of invasive species that included six plants (Chinese tallow, hydrilla, leafy spurge, miconia, purple loosestrife, and tamarisk). More recently, the Nature Conservancy lists 25 plants that gardeners should avoid buying (five for each of five US regions) on its website (http://nature.org/initiatives/invasivespecies/files/inv_wallet_card.pdf; accessed January 2006). They include the Frightening Five (giant salvinia, kudzu, purple loosestrife, multiflora rose, and tree of heaven) on a separate list. West Virginia has its list of the Dirty Dozen invasive plants:[2] African mile-a-minute, garlic mustard, Japanese knotweed, Japanese stiltgrass, kudzu, multiflora rose, purple loosestrife, reed canarygrass, trailing crown vetch, tree of heaven, water shield, and yellowflag iris. All are recognized as weeds by the Weed Science Society of America. It is interesting to note that the groups do not choose the same plants and that the plants chosen change with time and, perhaps, with who is doing the choosing. It is also interesting that many of the plants on these lists are available for sale. Around the world organizations with names like Weed Warriors and Weedbusters[3] have been created to monitor, document, and aid in management of invasive plants.

It is not the purpose of this chapter to present and discuss the real or potential consequences of all of them. The literature cited will lead interested readers to more information on many invasive species. A few prominent weedy examples are described following.

Plant invasions seem to be a permanent feature of modern, large-scale, dominantly monocultural agriculture (Bright, 1998, pp. 47–53). Modern

[2]Source: http://wvgardengate.homestead.com/files/WV_Dirty_Dozen.htm. Accessed January 29, 2006.

[3]Both are public and educational programs to train volunteers to aid in management of invasive plants. Weed Warriors is primarily an Australian program (see http://www.weeds.crc.org.au/for_schools/weed_warriors.html). Weedbuster programs can be found in Australia, New Zealand, Maryland/Washington, DC—A Nature Conservancy program, Massachusetts, and Montana.

agriculture and environmental manipulation in our increasingly globalized world create situations that make invasion likely, if not ensured. Bright describes four aspects of agriculture's instability that create its susceptibility to invasion.

1. The boundary between crops and weeds is porous. Some crops and weeds are closely related species (e.g., domestic and wild oats, wheat and jointed goatgrass, and potatoes and nightshades). They can and do occupy similar habitats and can interbreed. Gene flow between cultivated and wild sunflower has been well documented in the United States (Burke et al., 2002). It has become of special concern with the advent of genetically modified sunflower throughout the range of sunflower cultivation in the United States. The same phenomenon has been reported for cucurbits (Spencer and Snow, 2001) and canola and its wild Brassicaceae relatives (Snow et al., 1999). Weeds closely related to crops can also serve as hosts for crop pathogens (see Chapter 2). This porous boundary is more related to why invasions occur than it is to their consequences.

2. Related plants may act together to create mutual advantage from the new association. Agriculture regularly sorts and resorts the residents of its crop lands and new relationships occur that may be beneficial. A disease may find a new vector or a new mutualism may develop that benefits crop and weed.

3. Movement of species between the agricultural and surrounding landscape can damage both environments. There are numerous examples of plants imported for some purpose, especially as ornamentals, that have become major weed species. Table 7.2 includes several examples, as do the books by Westbrooks (1998) and Weber (2003).

4. Agricultural pests change. In agriculture, as in natural landscapes, natural selection is continuous. Bright (1998, p. 51) points out that a crop field with its pest population is a "relentless genetic machine, performing millions of tiny evolutionary experiments simultaneously." Weeds change naturally and often rapidly in response to herbicide pressure. Resistance and cross-resistance develop, and the weed populations evolve. Nearly perfect herbicidal weed control is a fine achievement, but it is also a huge advantage to the small percentage of the population that survives the chemical pressure.

It is important to recognize that plant invasion is not just a US or developed world problem. China has a long history, as does the United States, of introducing plants that someone deems to be potentially beneficial. With its fairly recent and expanding international trade, intentional introductions are now joined by unintentional introductions that because they are unknown and unexpected, may not be beneficial. Diamond (2005, p. 367) notes that in Shanghai Harbor, one of many international Chinese harbors, "between 1986 and 1990, examination of imported materials carried by 349 ships from 30 countries revealed as contaminants almost 200 species of foreign weeds."

TABLE 7.2. Purposeful Plant Introductions That Have Become Important US Weeds (Williams, 1980, and Other Miscellaneous Sources).

Weedy species	Origin	Purpose of introduction
Autumn olive	Asia	Wildlife attractant/erosion control
Birdsrape mustard	Eurasia	Cultivated crop
Bermudagrass	Europe	Forage crop
Bouncing bet	Europe	Ornamental
Cogongrass	Asia	As packing material
Corncockle	Europe	Ornamental
Dalmatian toadflax	Europe	Ornamental
Hydrilla	South America	Use in aquaria
Japanese knotweed	East Asia	Ornamental
Jimsonweed	Tropics	Ornamental
Johnsongrass	Africa/Asia	Forage
Kochia	Europe	Forage/ornamental
Kudzu	East Asia	Ornamental/forage/erosion control
Lantana	Europe/Asia	Ornamental
Melaleuca	Australia	As a tropical forest species
Multiflora rose	East Asia	Windbreaks/cover
Musk thistle	Europe	Ornamental
Reed canarygrass	Eurasia	Forage
Salt cedar/tamarisk	Europe	Ornamental
Tansy	Europe	Herbal plant
Tree of heaven	China	Ornamental
Tropical soda apple	Argentina	Unknown
Waterhyacinth	Tropics	Ornamental
Yellow toadflax	Europe	Ornamental

Source: Williams, 1980.

"Weeds and poisonous grass species have spread at the expense of high-quality grass species" over as much as 90% of China's grasslands (Diamond, 2005, p. 366).

Over 3,000 plants are weeds in Australia and cause losses of at least US $2 billion each year (Diamond, 2005, p. 400). Catclaw mimosa is a nitrogen fixing shrub that has invaded a World Heritage national forest (the Kakadu Forest) in Australia (Diamond, 2005). It establishes quickly after disturbance; forms thorny, impenetrable thickets; and can double the area occupied in a year. All other species (not just plants) are excluded (Weber, 2003, p. 271).

An interesting plant phenomenon reported by Leslie and Spotila (2001) recounts how the invasive alien bitterbush in South Africa shades the nests of Nile crocodiles. This seems to be a trivial effect, but shading lowered soil temperatures enough to change the sex ratio of crocodile hatchlings. The story illustrates the complexity of what may appear to be subtle effects of any invasive species.

Introduced weeds are Montana's most expensive problem (Diamond, 2005, p. 55). Most are of Eurasian origin, and 30 are quite troublesome. Leafy spurge and spotted knapweed are widespread throughout Montana. Spotted knapweed infests 566,000 acres in the Bitterroot valley and 5 millon acres in the state (Diamond, 2005, p. 55). Leafy spurge may cause as much as $144 million in livestock damage in Montana, South Dakota, and Wyoming. Both weeds are so widespread and such good survivors that eradication is impossible. Management is the only feasible option, but management options are limited. A management clue is provided by the work of Marler et al. (1999), who showed that arbuscular mycorrhizal fungi strongly enhance the ability of spotted knapweed to invade native grasslands of western North America and compete effectively against natives such as Idaho fescue.

Invasive plants are present in all 50 states, and it is highly likely they will be found in any country where someone looks. As many as 100 million US acres (the area of California) now are home to one or more invasive plants, and they are spreading at a rate of 14 million acres a year. Duncan and Clark (2005) estimated the average annual rate of spread for 15 weedy species in all continental US states was 11 to 17%. A few examples of plant invaders that decrease species richness and biodiversity of the plant and general ecological community are described following. Two of these and several others are reviewed thoroughly in Duncan and Clark (2005).

A. Tamarisk/Salt Cedar

Tamarisk or salt cedar was introduced to New Jersey as an ornamental nursery plant in 1837 (Myers and Bazely, 2003, p. 25). It was introduced to the arid western United States from central Asia in the early 1800s (Westbrooks, 1998) as an ornamental, for use in windbreaks, or to stabilize eroding stream and riverbanks. Now it has invaded nearly every watershed throughout the arid west. It consumes up to 4 million acre-feet of water annually across 17 western US states. It is also invasive in Australia and Southern Africa (Weber, 2003). Three species are present in several world areas but not invasive (e.g., Europe, Northern Africa, Canada, southeastern United States, Pacific Islands; Weber, 2003). One mature tamarisk plant can consume as much as 200 gallons of water a day in an area known as the arid west, where water is the primary limitation to continued economic growth. Each year, tamarisk alone consumes three times more water than is used by all of the households in Los Angeles (Millar, 2004). The three introduced species are all small deciduous trees or large shrubs. They invade desert areas and streambanks but grow best in damp, saline, and alkaline soils. Dense, impenetrable thickets form and lower water tables due to the plant's high water consumption. Salt, secreted by the plant on its leaves, is washed off or drips down to increase soil salinity to which tamarisk is more resistant than native species. It may be the US poster plant to illustrate that invasive plants are one of the preeminent environmental problems of the 21st century. The habitat destruction, its dense thickets, and dense plant residue on the soil surface lead to displacement of native plant, animal, insect, and microbial species and to their eventual elimination from the habitat.

Tamarisk worked very well for all three purposes for which it was introduced (ornamental, windbreak, erosion control), but its invasive potential soon became the dominant feature. Mature plants can survive immersion in water for more than one year. The capability of a single tree to produce up to 250,000 minute seeds each year enables colonization because the seeds quickly exploit suitable germinating conditions. The seeds survive about seven weeks but are spread easily and widely by birds and small mammals (Weber, 2003). Deeply penetrating roots enable exploitation of deep water resources unavailable to native species. It has invaded every major river system in the southwestern United States (Millar, 2004). It can be removed by arduous hand labor (a weed wrench) or herbicides. However, herbicides are not always fully effective and often may not be used along waterways (should not be unless approved for use along waterways or in water). Its deep root system and vegetative reproductive capability permit it to survive flooding and burning, both of which are detrimental to native plants. It comes close to being a perfect weed because it is resistant to available control measures and lacks natural enemies. Successful control has been achieved with the imidazolinone herbicide imazapyr (Duncan and McDaniel, 1998). Imazapyr applied in August or September alone at 1 pound per acre or in combination with glyphosate (0.5 pounds per acre) achieved 90% or greater control. Control was less successful in dense stands and older stands.

The value of lost ecosystems services just due to tamarisk in western US states is estimated to be between $7 and 16 billion over 55 years (Zavaleta, 2000).

B. Kudzu

Kudzu is a good example of what Mack et al. (2000) called the result of deliberate but flawed forethought. Kudzu first arrived in the United States when the Japanese Pavilion exhibited it as an ornamental vine at the US Centennial Exposition in 1876 in Philadelphia. It is a climbing, perennial vine, the planting of which was encouraged in the United States between 1935 and 1942 by the US Soil Conservation Service (SCS), which propagated 85 million kudzu seedlings, “flinging them about the country like wedding rice” (Williams, 1994). Encouragement of its planting followed passage of the Federal Soil Conservation Act in 1935. The US government actually paid farmers as much as $8 per acre to plant kudzu, kudzu clubs were formed, and the plant was proclaimed to be the “miracle vine” (Williams, 1994). Its foliage dies each year in cold weather, but the roots survive the mild winters of the southern United States and resprout vigorously each spring (Westbrooks, 1998). When it was being promoted widely, there were some skeptics who suspected that its lack of presence in the United States was not due to what Williams (1994) called “divine error.” But it grew so well, nearly everywhere, and it helped manage the problem it was imported to solve: soil erosion. The characteristics that made it successful for erosion control also made it succeed as an invader. Soon after its introduction, many noticed that it was growing *everywhere*. Its 90-foot-long older stems and ground-covering mats that could be up to 6 feet thick grew over telephone poles and trees and covered gardens, fences, and forest understories. It became “the vine that ate the South.” Now it may infest as much as 7 million acres in the southeastern United States. In 1993 the Congressional Office of Technology Assessment estimated kudzu was costing the US economy $50 million annually in lost yields and control efforts.

C. Waterhyacinth

At least one garden shop in my town sells small waterhyacinth plants for placement in bubbling little ponds with pumps that circulate water and make pleasant sounds. They are regarded as, and are, pretty ornamentals. I suspect some people may tire of them and discard them. So far, waterhyacinth has not been seen growing in Colorado waters. (So far!) Our winters are cold, although they do not seem to be as cold or as long as they used to be, and cold temperatures kill waterhyacinth, a native of South America’s Amazon basin that was introduced to the southern United States, southern Asia, and Africa in the 19th century (Bright, 1998, p. 148). It has infested Florida’s and many tropical waterways ever since. It is regarded as invasive in Australia, southern Europe, tropical and southern Africa, southeastern and western United States, and tropical Asia (Weber, 2003).

Waterhyacinth is a perennial, free-floating aquatic herb. It has attractive lilac to bluish-purple, erect flowers that produce long-lived seed soon after self-pollination. The primary means of reproduction is vegetative by rhizomes and stolons. Vegetative offshoots are bound to the parent by strong stolons. Offshoots separate from the parent as a result of the action on wind and water. Stolons weaken with time, and this also separates offshoots into independent plants. It rapidly colonizes large areas by forming free-floating large mats that can completely cover lakes and rivers. Holm et al. (1977, p. 74) estimated that under good growing conditions, 25 plants can produce enough offshoots to cover a hectare in one growing season. A mat of medium-sized plants may contain 2 million plants per hectare and weigh between 270 and 400 metric tons per hectare (Holm et al., 1977, pp. 73–74). The dense mats change ecological relationships, crowd out native plants, kill fish, and other aquatic species, change water temperature, and lead to eutrophication. The plant can root on land with sufficient moisture, but it is primarily an aquatic not a terrestrial agricultural problem.

Lake Victoria (aka Victoria Nyanza), the largest lake in Africa (26,920 square miles), is the primary reservoir of the Nile River, which flows out of the northern end of the lake. Parts of the lake lie within the boundaries of Kenya, Tanzania, and Uganda. The Lake Victoria basin is home to at least 30 million people, and the population has one of the fastest growth rates in the world (Bright, 1998, p. 90). In Uganda, fish accounts for half the nation's protein. Waterhyacinth is closing down the fisheries by blocking shorelines where fish spawn, blocking access to open water because boats cannot penetrate the large floating mats, lowering the lake's water level, and killing fish. By 1996 it was blocking 90% of the lake's shoreline (Bright, 1998, p. 90). It is interesting to note that waterhyacinth's presence in Lake Victoria has actually increased the lake's biodiversity (McNeely, 2001; Sagoff, 2005). Waterhyacinth has blocked dams in Zimbabwe, often backing up enough water to burst a dam. It threatens Uganda's main electric power plant by blocking the flow of water to the generators (Bright, 1998, p. 182).

It has been estimated that waterhyacinth costs seven African countries US $20 to $50 million per year (Joffe and Cook, 1997). World costs are much larger.

D. Purple Loosestrife

When Ohio's legislature attempted to restrict growth and importation of purple loosestrife, the Ohio nurserymen's association won an exemption for its hybrid cultivars because they were presumed to be sterile (Williams, 1994). Subsequently, it was found that they interbred easily with wild loosestrife plants and the invasion continued. It was another example of deliberate, flawed forethought (Mack et al., 2000) and has left us with a plant that literally flaunts the power of invasive species.

Purple loosestrife is native in most of Europe; the United Kingdom; northern, tropical, and temperate Asia; and southern Africa. It was introduced to the United States in the early 19th century as a contaminant in the ballast of ships from Europe and as an ornamental (Malecki et al., 1993), which in the view of some, it is. It has been valued as a medicinal plant for treatment of diarrhea, dysentery, bleeding wounds, ulcers, and sores (Stuckey, 1980). Since its introduction to the United States in the 1800s, it has spread rapidly (Thompson et al., 1987). From 1940 to 1980 its rate of spread has been about 1.5 latitude-longitude blocks per year (Westbrooks, 1998). In 1998, Westbrooks reported that it was invasive in 42 of the 50 US states. The distribution Westbrooks presents (p. 42) shows a few states without purple loosestrife, each surrounded by states with it. Therefore, it is likely that it is now in all 48 continental US states. Its cost in loss of forage and the cost of control is estimated to be $45 million per year (Hall, 2000; Pimentel et al., 1999). Thompson et al. (1987) reported it was spreading to 115,000 hectares each year. In 2004, Li et al. reported the same rate of spread of 285,000 acres (1 hectare equals 2.47 acres) each year.

It grows best in freshwater marshes, on stream banks, and on alluvial flood plains. When it invades it forms extensive, persistent, monotypic stands in wetlands, where it replaces native plants and excludes associated insects, small mammals, and other wetland inhabitants. It is noted and often prized for the beauty of its late summer inflorescence, which provides a nectar and pollen source for bees (Malecki et al., 1993). In spite of its invasive characteristics, nurseries in many states continue to sell it as an ornamental. Several states include it on the state noxious weed list, which precludes its sale and importation.

These few cases illustrate, without belaboring the point made in Westbrooks (1998) and Weber (2003), that invasive plant species are major ecological problems—indeed they can be ecological threats. Invaded ecosystems tend to be (but are not always) biologically impoverished and differ in many ways from adjacent noninvaded areas. Williams and Baruch (2000) showed the effects of pasture creation and invasion by African C_4 grasses (e.g., guineagrass, johnsongrass, kikuyugrass, pangolagrass, paragrass, signalgrass) on ecosystem processes in subtropical regions of North and South America and the Caribbean. They suggest that as global warming progresses, the same grasses may negatively influence North American pasture and rangeland. The primary effects were loss of woody species and changes in the fire regime. The success of African grasses is encouraged by fire, and they respond more favorably to fire disturbance than native grasses. The large amount of dead plant material left at the end of each season encourages fires and increases their intensity.

Cronin and Haynes (2004) first showed that when the tall-grass prairies of North America become dominated by smooth brome (which some do not consider invasive because its benefits outweigh its risks), the spatial and temporal dynamics of a native natural herbivore became about 50% lower within three generations. The smooth brome–dominated areas showed extinction rates of the natural herbivore were four to five times greater than in native plant habitats. Japanese honeysuckle was imported to the United States as an ornamental vine more than 150 years ago. The US Department of Agriculture promoted it as a garden and wildlife plant in the 1880s. It invades native woodlands throughout the eastern United States and is a common part of the flora in the Northeast (Westbrooks, 1998). It is also invasive in the United Kingdom, Australia, New Zealand, Hawaii, and many parts of the continental United States. Several cultivars have become naturalized in the United States. It grows as a ground shrub on forest floors or as a twining or trailing shrub that quickly climbs into forest canopies where light is increased in tree gaps (Weber, 2003). It forms a dense curtain on forest edges and displaces understory shrubs. It is a competent and common invader of forests. But it has been discovered that Japanese honeysuckle has actually created a new species (Cowen, 2005). Tephritid fruit flies are specifically adapted to berry-producing plants. Japanese honeysuckle has its own specially adapted fruit fly, but the fly did not originate or arrive with the plant. Schwarz et al. (2005) showed that the fly is a hybrid resulting from flies that live on blueberry and snowberry. Normally such a hybrid would die, but Japanese honeysuckle offered an environmental niche that was not inhabited (a residence without inhabitants, an open niche) and for which there was no competition. A subtle, but perhaps important, change wrought by an invasive species.

Subtle changes created by a local invasive species may combine in ways that affect the earth's (Gaia's) interrelated web of organic life. For example, increasing atmospheric carbon dioxide levels could favor the growth of an invasive species (a new weed) over native species. Weed scientists properly are concerned about the effects of any invasive weed on crop production, but its effects may go well beyond those on yield. Invasive plants could power unknown ecological changes whose consequences are equally unknown. It is interesting to note in this regard that Ziska (2006) reported that the average increase in biomass of six invasive weedy species (Canada thistle, field bindweed, leafy spurge, perennial sowthistle, spotted knapweed, and yellow starthistle) was 46% when they were grown from seed with 719 μmol mol^{-1} (the predicted atmospheric concentration of CO_2 level in by the end of this century) instead of 380 μmol mol^{-1} (the current atmospheric level). The largest response (73% increase in biomass) was from Canada thistle a widespread invasive weed.

As mentioned at the beginning of this chapter, intentionally introduced exotic plants have had major benefits (e.g., corn, wheat). One must remember that all invaders are not threats; some are beneficial. In fact, when all exotic species are considered, the benefits exceed the costs. Perhaps an intensive battle against introduction of future exotic species is not warranted. Even kudzu, “the plant that ate the South,” has benefits. It is a legume that fixes nitrogen and grows fast enough to cover potentially erodible soil. It makes a high-quality fodder for cattle and other livestock. Baled kudzu is actually sold. It is also used by cooks because of its nutritious leaves and roots. However, more is available than interested cooks can possibly use. Sagoff (2000) notes that biologists, weed scientists among them, “attribute to immigrant species some of the same characteristics that nativists and xenophobes have ascribed to immigrant humans: sexual robustness, excessive breeding, low parental involvement with the young, a preference for degraded conditions, and so on.” In short, they are all bad. If we return to the question of definitions raised earlier, none of the traits that Sagoff (2000) lists is sufficient to identify a species as exotic or as a potential invader. They are judgments based on fear, not biological definitions.

Even a casual examination of the invasive plant literature leads to the conclusion that the essence of the scientific and public (if the public thinks about them at all) attitude toward invaders is negative. They are not desirable, ought to be controlled if not eradicated, and no more should be allowed into the United States without prior knowledge and careful control. Sagoff (2005) presents five arguments in asserting that the negative attitude toward all exotics is not easily defended. First of all, the concept of harm to the environment is “nebulous and undefined.” Without a scientific definition of harm to the natural environment, the values in question depend solely on personal preference and that is not sufficient to justify action. For the weed scientist, harm to the agricultural environment as measured by crop yield reduction is a scientific measure that is sufficient to justify action. Second, because harm to the natural environment is not well defined and because invasive species science does not yet know how to predict the behavior of a non-native species, regulatory action is limited to an impossible task or to banning all, which is politically unacceptable. The third point Sagoff (2005) makes is based on Elton’s (1958) species richness hypothesis, which is based on controversial premises. Experimental results have shown positive and negative effects of diversity. A corollary hypothesis is that ecosystems are carefully structured, and unless they are disturbed, there is little room for invaders because all resources are being used by the residents, especially in species-rich communities all live on the knife’s edge competing for limited resources—the resource availability hypothesis. What study of invasions has shown is that all ecosystems have plenty of resources (albeit they may be transient) that are available to new species. Sagoff (2005) questions the species richness hypothesis. Introduced species “generally increase—and only in exceptional cases decrease—species richness in natural ecosystems.” Therefore, the assumption of ecosystem harm is questionable and not supported by the evidence. Fourth, even though the general attitude toward invasive species is that they are harmful because their presence may lead to native species extinction, there is limited evidence that non-native species "are more likely than native species or species in general to be significant factors in extinction."

Sagoff's (2005) final point is that "the belief that non-native species diminish biodiversity and impair ecosystem health or integrity should not rely on stipulative definitions." That is, the definition cannot become simply "Who cares?" (Burdick, 2005). The mere presence of a non-native species cannot be the prime indicator of a lack of environmental health. The concepts of biodiversity and invasion appeal to "political and social values but have no scientific meaning" (Sagoff, 2005). Sagoff appeals for "a scientific or empirical as well as an aesthetic or spiritual basis for the assumption that non-native species are pernicious in their effects on natural areas and environments." Harm and threats to biodiversity must be defined in ways that "do not logically entail that alien species cause harm or diminish biodiversity." His challenge to biologists and weed scientists remains.

V. MANAGEMENT OF INVASIVE PLANT SPECIES

Invasive plants are, as all weeds seem to be, management challenges. Action must often be taken to prevent further invasion before one can be sure of all consequences of the action. The risk of inaction is deemed to be greater. Myers and Bazely's (2003) review of the ecological and control aspects of invasive plants is an essential resource.

The Maui Coastal Land Trust owns a 277-acre refuge on the northern shore of the Hawaiian island of Maui, just outside the town of Waihe'e, known as the Waihe'e Coastal Dunes and Wetlands Refuge. The trust also has about 300 additional acres that are protected by conservation easements. The trust expects to acquire easements on additional land on Moloka'i. The refuge includes a 7,000-foot coastal strand, a 26-acre wetland, and about 150 acres of sand dunes, which enclose the wetland and shore area. The refuge is populated by a large number of weedy species and some particularly troublesome invasive species of *Pluchea*. The species of most concern are *P. carolinensis* and *P. indica*, neither of which is recognized as a common weed by the Weed Science Society of

America (WSSA), nor is either mentioned in Weber (2003) or Westbrooks (1998) as important invasive species. *Pluchea camphorata* (L.) DC., or stinkweed, is recognized as a weed by WSSA. Members of the genus are often known by the common name fleabane. The genus *Pluchea* includes 40 species, all part of the Asteraceae family. Nearly all are tropical herbaceous plants or shrubs, but only a few are weedy. *P. carolinensis* is an aromatic branched shrub that grows up to 10 feet tall. It has been known as *P. symphytifolia* and in older literature as *P. odorat*. It is native to tropical America and was first collected on Oahu in 1931. In the Hawaiian islands, it is common in pastures, forest, roadsides, and uncropped areas. It thrives in both wet and dry areas.

P. indica, a native of south Asia, has up to 10 branching stems but grows only 6 feet tall. The branching stems make it much more difficult to control than *P. carolinensis*. It was first collected on Oahu in 1915. *P. Indica* invades wetlands, whereas *P. carolinensis* does not do so as readily. *P. indica* grows well in saline soil.

If *P. carolinensis* invades wetlands, the Land Trust's management strategy is to do nothing if it is in an area that will be flooded during the wet season because it will die after about six days of submersion in water.

Both species probably arrived with cattle or in their fodder. They have not always been as invasive as they now seem to be. Both have significant environmental effects. They grow large and eliminate native species of plants and destroy endangered bird habitats. They displace native forage species in coastal pastures and native species in coastal marshes and wetlands. Both species are sensitive to some herbicides (e.g., 2,4-D, dicamba, glyphosate, and triclopyr). Land Trust personnel use these sparingly, if at all. The best results have been achieved with mixtures of glyphosate and one of the growth regulator herbicides. The first reason for reluctant herbicide use is that the herbicides are not selective enough. That is, they kill the native as well as the invading species, and return or reestablishment of the native species is a major goal of the refuge. Second, herbicides are expensive for an organization with limited funding. There are two primary control methods: hand pulling of young plants and using a large mattock to pull out the large plants by the roots. Both methods are labor intensive and arduous work. A control method that works well for both species and for their hybrid *P. fosbergii* is flooding by rainwater for at least five days. A third weed management complication is the fact that the Maui coastal land trust property includes 85 listed archaeological sites. Large-scale grubbing or grading requires several bureaucratic layers of approval. Hand tools and herbicides are acceptable because they do not lead to potential destruction of archaeological sites. The manual methods and flooding both protect native species, but they are slow and might be more expensive if quick control of a large area is desired and if labor is expensive or unavailable.

The Maui Coastal Land Trust also has invasive populations of the tropical weeds Brazilian peppertree, largeleaf lantana, and Java plum. Related species of the latter are used in food flavoring, pomanders, and analgesics for toothache. All three are invasive in the right habitat.

Perhaps the first step in development of management plans is not direct action against plants at all but legislative. Clout and De Poorter (2005) recommend international rather then just national action because of the increasing globalization of the world economy. There must be an agreed upon, effective international strategy to deal with invasive species of all kinds. To be effective, this must be combined with fundamental and applied research on all aspects of invasion biology. There must be appropriate economic policies that enable management. This is especially important because the beneficiaries of invasive plant management are often not apparent. Everyone in an area may benefit, but when all benefit, deciding who should pay is not always clear. Agreement on how to establish the risk of the invader and how to balance that against the cost of management must be obtained, and these decisions and the threat of invasive plants have to be communicated to the public in easily comprehended ways (McNeely, 2004). Those charged with assessing risk depend on scientific research to develop and advise on biologically plausible management methods that enable fully informed regulatory decisions (Powell, 2004).

The next logical step in a national management program and the first step recommended by Clout and De Poorter (2005) is prevention. Prevention is usually less costly than postentry control (Mack et al., 2000). A preventive approach advocates changing the current policy of denying entry only to species that are known to be harmful (e.g., known harmful weeds) to one of presuming guilt until innocence can be proven (Mack et al., 2000). This is contrary to the American system of jurisprudence, but it may nevertheless be prudent to adopt the precautionary principle (Clout and De Poorter, 2005) to govern imports. Horticulturalists, the landscape industry, the seed industry, and the pet importers would (do) object, and environmental groups would support the policy. If prevention is not enforced then management devolves to the same methods available to weed managers: mechanical, cultural, biological, and chemical means (see Chapters 10, 11, and 12). There are few other choices.

Because science cannot predict either the common attributes of invaders or locales susceptible to invasion, control within a management system is the only viable option. Control, regardless of technique, will always be more successful when it includes a long-term ecosystem strategy rather than a tactical, local approach (Mack et al., 2000).

South of the Colorado/Wyoming border and about 5 miles west of I-25, the 18,771-acre Soapstone Prairie Natural Area of relatively undisturbed shortgrass and mixed-grass prairie with some wetlands and riparian areas has been preserved through the cooperative efforts of city and county government, the Nature Conservancy, and the Legacy Land trust (see www.fcgov.com/naturalareas). The area includes the Lindenmeier site, a registered national historic landmark and the location of one of the oldest (about 10,000 years) known areas of human habitation (Folsom man) in the United States.

Soapstone, similar to other large natural areas, is valued for its scenic beauty and geological importance, as well as its agricultural use for sheep and cattle grazing. It must be managed, and invasive, primarily weedy, species are part of the management challenge. Soapstone will also be used for recreational purposes by citizens, which is part of the management plan.

State and local laws demand control to diminish populations of invasive noxious weeds. This is designed to maintain the rangeland's health and stop the spread of the invaders. The invasive weeds of concern within Soapstone are Canada thistle, cheatgrass, field bindweed and dalmation toadflax. Canada thistle occurs principally in areas frequented by cattle and especially near the water tanks. Cheatgrass is found in the higher areas, whereas field bindweed and dalamation toadflax are found in disturbed areas, especially along roadways.

Land managers use mowing where the terrain permits, and, in contrast to the Maui Coastal land area, different herbicides (dicamba, imazapic, tordon, or 2,4-D) are employed for control of the different weeds. Prevention of spread is a major goal. The techniques are quite effective and managers claim significant population reduction in three to five years. Citizen concern about the weed management techniques has been minor and infrequent.

The meaning of *long term* is very clear. *Long* is not defined precisely, but one can be fairly certain that it means decades, not just years, and certainly not one crop year. Ecosystem strategies are also a bit vague, but the clear implication is that consideration of one field or small region is not enough. The scope of the existing or anticipated invasion must be considered and that demands a much broader range than weed scientists have used in the past. Weed science has been an active field with many talented practitioners. But their focus has most commonly been on control of individual species in an area (e.g., leafy spurge in the western United States) or groups of species in a crop (e.g., a weed complex in corn or soybeans). There has been too little interaction between weed scientists and ecologists or conservation biologists. The latter have tended to focus on invasion ecology, while the former have tended to focus on the current or potential effects of an invader.

Several people have been concerned that weed scientists and plant ecologists were unaware of each other's activities and, perhaps, did not even care about what the others were doing. Greater cooperation has been advocated (D'Antonio and Jackson, 2004).

Hobbs and Humphries (1995) illustrate the complexity of the management challenge (Figure 7.1). Management has often been limited to control, but they claim it must include three other components: the spatial and temporal dynamics of the population, the structure and dynamics of the ecosystem, and the effects of human activities on all components. Control programs generally are initiated only after the problem has become obvious. Weed scientists are vigorous and have been persistent in their claims that aggressive, large-scale campaigns must be undertaken to prevent further spread and economic losses caused by invasive weeds. A fundamental difference in approach exists between research science and weed control and management (McPherson,

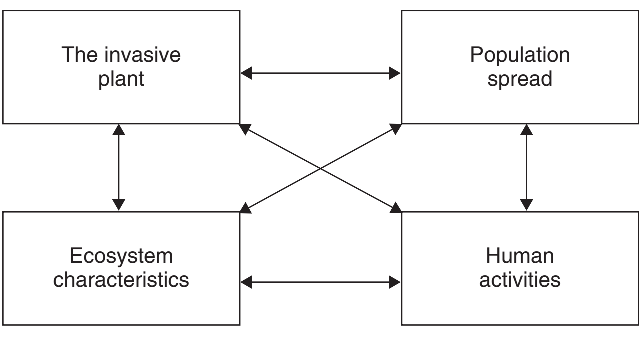

FIGURE 7.1. Components of management strategies for plant invasions (adapted from Hobbs and Humphries, 1995).

2004). The difference often inhibits cooperation. Research science often strives for large-scale generalities with broad application. The weed manager, however, is confronted with a site and the necessity of achieving a specific objective (i.e., eliminate the invasive species and do so quickly). The tendency of the weed manager is to use herbicide(s) to "solve" the invasive problem. The invader is regarded, as all weeds are, as an external problem that exerts only negative effects on the natural system and on human welfare (Timmons, 1970). The thought has been that external problems must be eliminated, and chemical and mechanical methods are the best way to accomplish the goal. This thinking has led to the many problems caused by herbicides because of its focus on solving the problem (eliminating the invader) without ever understanding why the invader invaded. Questions such as the role of disturbance, open niches, and control practices have been regarded as less important or ignored in favor of development of control techniques. The control approach will inevitably lead to the same kinds of problems that now plague weed science.

In many cases, there is little good evidence that aggressive management is the best course of action or is economically optimal (Eiswerth and van Kooten, 2002). For example, attempted eradication of yellow starthistle was not economically optimal, but strategies that attempted to control its spread were (see Dukes, 2002). A framework for identifying weeds that are not yet major invaders but have the potential to become so and then preventing invasion of new territory by eradication in their present location before they invade and become dominant has been advocated by Cunningham et al. (2004).

Ecological niche modeling is a new method that may assist in determining the geographic course of an invader. Peterson et al. (2003) tested the technique and found that it effectively predicted the actual course of invasion of four North American weeds. Ecological niche modeling uses ecological characteristics of known occurrences in the native location of a species to identify areas of potential invasion.

Older management techniques should not be abandoned simply because they are old. Fire is a very effective technique to manage junipers in the western and southwestern United States. Fire always reduces juniper canopy cover and density. It is useful when the management goal is to reduce the presence and effects of junipers in an ecosystem (Ansley and Rasmussen, 2005). Biological control is also available for managing invasive species, but it, like other techniques, must be managed carefully. Rand et al. (2004) showed that using the flowerhead weevil (*Rhinocyllus conicus*) to reduce musk thistle influenced the extent of attack on the native wavyleaf thistle. Using biological control to control an invasive species can have the undesirable result of attack on native species that help "maintain populations of the shared insect herbivore."

Li et al. (2004) propose a management technique that was not even conceivable a decade ago: genetic modification to create sterility. It is one of the few new choices that can now be added to those mentioned previously. The transgenic solution is to create sterile cultivars of non-native ornamental plants that have commercial value, which, it is proposed, would reduce or eliminate their spread. Because prohibiting imports is politically, socially, and economically (in the view of those who sell ornamentals) not feasible, the transgenic solution may be reasonable. Li et al. (2004) suggest the solution is "to neutralize the invasive characteristics of economically important non-native species before they are planted in the landscape." Given that no one knows for sure what "invasive characteristics" are, it is nevertheless an imaginative management approach. Li et al. (2004) cite several advantages and disadvantages of the technique. Introduction of sterility can be broadly applicable to species that spread (invade) by sexual reproduction. It is also quite inapplicable to species that spread vegetatively (e.g., kudzu). The insertion of the gene would not affect overall plant morphology; an ornamental would still be attractive. The method can be quite fast once the technique is perfected for a species, but insertion of a gene for steriity or parthenocarpy into many plants can be technically difficult. Not everyone can do it. Special facilities are required. Clearly, the technique may be useful to eliminate undesirable traits of plants that have been modified, but it will have no effect on plants that are already in the environment. It is a proactive, not a retroactive, management method. Many will object to the technique because of unease about all uses of genetic modification technology (potential for escape and hybridization and dilution of the gene pool of native species). Finally, there is a hint of scientific hubris as opposed to humility in the face of nature's complexity in the proposal. The method could work very well. Some plants might still produce fertile seed when pollinated by a nonsterile relative growing nearby. Even sterile plants may still possess some of the undesirable traits of an invader. Scientists always know what they are doing but may not know what they are undoing. Myers and Bazely (2003, p. 244) criticize the genetic approach to invasive plant management because they see it as a potential time bomb. No one knows precisely what genetic and environmental traits may combine to make any plant invasive. Therefore, it may be scientific hubris to assume that genetic modification, a relatively new management option, is well enough understood so that its effects can be predicted. Genetic modification could increase a species invasion potential rather than decrease it. As Myers and Bazely (2003) clearly point out, "The fundamental assumption underlying the technology of genetic modification is that genes from other organisms, introduced by bacteria to target plant species will direct the production of (useful) proteins that are not normally synthesized by the plant." The assumption is correct. The problem is that there is little peer-reviewed evidence to support the assumption that the effects of such modification will be exclusively beneficial. They also point out that because such products (modified plants) are presently made by organizations interested in patenting and benefitting from their efforts, the questions about all effects often are not asked until after release, if they are asked at all. Then, as experience with plant introductions (kudzu, tamarisk, etc.) shows, it may be too late.

THINGS TO THINK ABOUT

1. Are all invasive species also weeds? Why or why not?
2. Are all weedy species also invasive species? Why or why not?
3. What is the definition of an invasive plant species?
4. What characteristics do invasive plant species share?
5. Are all invasive plant species of foreign origin?
6. What justification can be offered for introduction of a plant species to a new place?
7. Describe the theories used to explain why plant invasions occur.
8. How do disturbance and invasion relate?
9. Are there examples of species that survive in a new place but do not later become invasive? Name a few.
10. What aspects of agricultural instability create susceptibility to invasion?
11. Name some examples of successful plant invasions.
12. Are all plant invasions necessarily harmful?
13. What is the first step in a management plan for all weedy or invasive species?
14. How can genetic modification be incorporated in an invasive species management plan?

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CHAPTER 8

Allelopathy

FUNDAMENTAL CONCEPTS

- Allelopathy is a form of plant interference that occurs when one plant, through living or decaying tissue, interferes with growth of another plant via a chemical inhibitor.
- Allelopathy may be present in many plant communities.
- Allelopathy has a potential but largely unexploited role in weed management.

LEARNING OBJECTIVES

- To know the definition of *allelopathy*.
- To understand the complexity of research to discover true allelopathy.
- To understand the complexity of allelopathic chemistry.
- To understand how allelochemicals enter the environment.
- To know the application of an analogous form of Koch's postulates to allelopathy.
- To know some examples of allelopathic interference.

The Three Princes of Serendip was published in Europe in 1557 by the Venetian author Michele Tramezzino. Horace Walpole, a British statesman, read the story as a child and coined the word *serendipity* in a 1754 letter to Horace Mann, the British envoy to Florence. The story is based on an ancient Persian tale in which the characters make fortunate, unexpected, wonderful discoveries. In the story, the three princes, each vying for the hand of a princess, are assigned impossible tasks by the princess. Each failed to accomplish the assigned tasks, but wonderful, serendipitous things happened to them as they tried to do what they had been asked to do. Serendipity is an apparent aptitude to make fortunate discoveries accidentally; unexpected, good things happen. Serendipity may be available to weed science if the presence of allelopathy can be used to control weeds. Organisms from microbes to mammals find food, seek mates, ward off predators, and defend themselves against disease via chemical interactions. Allelopathic interactions are chemical, and discovery of the cause and mechanism of these interactions may yield a treasure of biological and chemical approaches to control weeds. At least 25% of human medicinal products (see Chapter 4) originated in the natural world or are synthetic derivatives of naturally occurring substances. Many natural interactions are chemical interactions, and some of them could influence the course of weed science.

Interference is the term assigned to adverse effects that plants exert on each other's growth. Competition is part of interference and occurs because of depletion or unavailability of one or more limiting resources. Allelopathy, another form of interference, occurs when one plant, through its living or decaying tissue, interferes with growth of another plant via a chemical inhibitor (Figure 8.1). Allelopathy comes from the Greek *allelo*, meaning "each

Interference = Competition + Allelopathy

FIGURE 8.1. Components of plant interference.

other," which is similar to the Greek *allelon*, meaning "one another." The second root is the Greek *patho* or *pathos*, meaning "suffering, disease, or intense feeling." Allelopathy is therefore the influence, usually detrimental (the pathos), of one plant on another by toxic chemical substances from living plant parts through their release when a plant dies or their production from decaying tissue.

There is a subset of allelochemicals known as *kairomones* (from the Greek *kai*, meaning "new," and *hormaein*, meaning "to set in motion, excite, stimulate") that have favorable adaptive value to organisms that receive them. A natural kairomone from waterhyacinth is a powerful insect attractant for a weevil (*Necochetina eichhorniae*) and the waterhyacinth mite (*Orthogalumna terebrantis*). The kairomone is liberated when waterhyacinth is injured by surface wounding or by the herbicide, 2,4-D. The kairomone enhances control of waterhyacinth by attracting large numbers of weevils and mites to the area of the plant's wound (Messersmith and Adkins, 1995). Thus, the kairomone has favorable value to the insects but not to the waterhyacinth. Control of waterhyacinth is enhanced when insect damage is combined with herbicide stress.

For weed management purposes, allelopathy is considered a strategy of control. Corn cockle and ryegrass seeds fail to germinate in the presence of beet seeds. If tobacco seeds germinate and grow for six days in petri dishes, and then an extract of soil, incubated for 21 days with timothy residue, is added, the root tips of tobacco blacken within one hour, while radicle elongation is unaffected. If an extract of soil that is incubated with rye residue is added, the symptoms are reversed (Patrick and Koch, 1958). Residues of timothy, maize, rye, and tobacco all reduce the respiration rate of tobacco seedlings (Patrick and Koch, 1958).

Kooper (1927), a Dutch ecologist, observed the large agricultural plain of Pasuruan on the island of Java, Indonesia, where sugarcane, rice, and maize grew. After harvest, the fallowed fields developed a dense cover of weeds. Kooper observed that the postharvest floristic composition of each community was stable year after year. He found that floristic composition was determined at the earliest stages of seed germination, not by plant survival rate or a struggle for existence but by differential seed germination. He showed that seeds of other species were present but could not germinate unless removed from their environment. Competition for light, nutrients, or water did not cause the consistent floristic composition. Kooper (1927) concluded that previous vegetation established a soil chemical equilibrium (an allelopathic phenomenon) and determined which seeds could germinate and, subsequently, which plants dominated.

The word *allelopathy* was first used by Molisch (1937), an Austrian botanist. He included toxicity exerted by microorganisms and higher plants, and that usage has continued. The phenomenon, however, had been observed much earlier by several scientists (Putnam, 1985). A classic example of allelopathy is found in the black walnut forests of Central Asia (Stickney and Hoy, 1881). Few other plants survive under the forest plant canopy because of the presence of juglone, a quinone root toxin derived from black walnut trees (Massey, 1925). The effect of juglone couldn't be reproduced in the greenhouse because some plant metabolites, including phenolics, require ultraviolet light for their biosynthesis (Davis, 1928).

Another classic study is the work by Muller and Muller (1964) in California, who observed that California chaparral often occurred near, but not intermixed with, California sagebrush. Neither species grew in the zones of contact between the respective communities; other species grew between the communities. They found terpenes, particularly camphor (a monoterpene ketone) and cineole (a terpene ether) produced by the chaparral, were responsible for the no contact zones. They concluded that plants, in this case the chaparral, are fundamentally leaky systems. Other studies are described by Rice (1974, 1979) and Thompson (1985).

One plant does not consciously set out to affect another, but rather the effect occurs as a normal, perhaps serendipitous, ecological interaction with evolutionary implications. Allelopathic species have been selected by evolutionary pressure because they can outcompete neighbors through energy-expensive biochemical processes that produce allelochemicals. The energy expense is not a waste of resources because no species evolves successfully by wasting resources. Exploration of the phenomena will lead to better understanding of plant evolutionary strategies and, possibly, provide clues for herbicide synthesis and development.

Reviews of allelopathy are found in Putnam (1985, 1994) and the proceedings of the American Chemical Society symposium on the chemistry of allelopathy (Thompson, 1985). Putnam (1985, 1994) lists 50 weeds alleged to interfere with one or more crops (Table 8.1). Allelopathy has also been explored with a number of crops, and there have been attempts to find crop cultivars with a competitive allelopathic edge (Putnam, 1983, 1985; Rice, 1979; Thompson, 1985). Residues of several crops have phytotoxic activity on other plants (Table 8.2).

Laboratory studies have often demonstrated allelopathy, but the evidence produced should not be regarded as conclusive of the existence of allelopathy in the environment until it is confirmed by field studies. Field studies are essential to obtain ecologically relevant data (Foy and Inderjit, 2001; Inderjit

TABLE 8.1. Some Weeds with Alleged Allelopathic Activity in Agroecosystems (Putnam, 1983, 1994; Duke et al., 2002).*

Weed	Susceptible species
Barnyardgrass	rice, wheat
Bermudagrass	barley, coffee, soybean
Bluegrass	tomato
California peppertree	cucumber, wheat
Canada thistle	several
Catnip	peas, wheat
Cogongrass	corn, cucumber, rice, sorghum, tomato
Common chickweed	barley
Common lambsquarters	cabbage, cucumber, corn, sugarbeet, wheat
Common milkweed	sorghum
Common purslane	alfalfa, durum wheat, tomato
Common ragweed	several
Corn cockle	wheat
Crabgrass	cotton, trailing crownvetch
Diffuse knapweed	ryegrass
Dock	corn, pigweed, sorghum
Field bindweed	wheat
Flaxweed	flax

(*Continues*)

TABLE 8.1. (*Continued*)

Weed	Susceptible species
Giant foxtail	corn
Giant ragweed	peas, wheat
Goosegrass	bean, corn, sorghum
Goldenrod	several
Hairy beggarticks	several
Heath	red clover
Italian ryegrass	oats, brome, lettuce, clover
Jimsonweed	several
Johnsongrass	barley, cotton, soybean, trailing crownvetch
Ladysthumb	potato, flax
Large crabgrass	several
Leafy spurge	peas, wheat
Mayweed	barley
Mugwort	cucumber
Mustard	several
Nutsedge, purple	barley, black mustard, broccoli, Brussels sprouts, cabbage, carrot, collards, cotton, cucumber, onion, radish, rice, sorghum, soybean, strawberries, tomato
Nutsedge, yellow	corn
Prince's feather	mustard
Prostrate spurge	several
Quackgrass	several
Redroot pigweed	soybean, wheat
Russian thistle	several
Spiny amaranth	coffee
Sunflower	barley, garden cress, jimsonweed, lettuce, redroot pigweed, tomato, wheat
Syrian sage	wheat
Velvetgrass, common	barley
Velvetleaf	several
Western ragweed	several
Wild cane	wheat
Wild garlic	oats
Wild marigold	several
Wild oats	barley, flax, wheat

*Complete citations for several weeds can be found in Duke et al., 2002.

TABLE 8.2. Some Crops Whose Residues Have Been Reported to Be Phytotoxic (Putnam, 1994; Duke et al., 2002).

Crop	Affected species
Alfalfa	alfalfa
Apple	apple
Asparagus	tomato, asparagus, fescue spp.
Barley	white mustard
Bean	pea, wheat
Black walnut	tomato
Cabbage	mustard, lettuce, spinach, tomato
Clover, red	several
Clover, white	radish
Coffee	several
Corn	several weeds
Crambe	wheat, velvetleaf
Cucumber	several weeds
Jackbean	Brazilian satintail
Lentil	wheat
Oats	several
Pea	several
Rice	barnyardgrass, lettuce, rice
Rye	common lambsquarters
Ryegrass	several
Smooth bromegrass	several
Sorghum	fescue
Sunflower	barley, clover, garden cress, jimsonweed, lettuce, redroot pigweed, tomato, wheat
Wheat	several weeds

et al., 2001). Lab studies provide clues but are not sufficient without field confirmation. For example, Norsworthy (2003) demonstrated the allelopathic potential of aqueous extracts of wild radish in controlled environment studies. The evidence indicated that aqueous extracts of wild radish or incorporated wild radish residues suppressed seed germination, radicle growth, seedling emergence, and seedling growth of “certain crops and weeds,” but subsequent field confirmation is essential to establish the reality of allelopathy as an ecological phenomenon.

I. ALLELOPATHIC CHEMISTRY

Plants produce a myriad of metabolites of no known utility to their growth and development. They are often referred to as secondary plant metabolites and are defined as compounds that have no known essential physiological function. The idea that these compounds may injure other forms of life is not without a logical base. However, proof is questionable because most allelochemical effects occur through soil, a complex chemical matrix. Conclusive studies require extraction and isolation of the active agent from soil. Any allelopathic chemical may be chemically altered prior to or during extraction. That which is extracted, isolated, and studied may not be what the plant produced.

Secondary plant metabolites, also known as natural products, are regarded by many as "a vast repository of materials and compounds with evolved biological activity, including phytotoxicity" (Duke et al., 2002). It is proposed that some of these compounds may be useful directly as herbicides or as templates for herbicide development. According to Duke et al. (2002), they often have unique molecular target sites in plants but have not been developed or used much in agriculture or herbicide development. Several reviews of this area of research are available (Dayan et al., 1999; Duke et al., 1998, 2000a, 2000b, 2002; Hoagland, 2001; Hoagland and Cutler, 2000). Acetic acid, the primary component of vinegar, is a contact, burning herbicide that can be used selectively in some crops (e.g., onion and sweet corn). Martan 2 is a clove oil product that also shows promise as a natural product herbicide (Evans and Bellinder, 2006). In both cases, success depends on the time of application and the growth stage of the crop and weeds. Both require high active ingredient application (acetic acid 34 to 68 gallons per acre), and both are expensive (up to several hundred dollars per acre) (Evans and Bellinder, 2006).

Allelochemicals vary from simple molecules, such as ammonia, to the more complex quinones, juglone, and the terpenes camphor and cineole, to very complex conjugated flavonoids such as phlorizin (isolated from apple roots) or the heterocyclic alkaloid caffeine (isolated from coffee) (Putnam, 1985; Rice, 1974; Thompson, 1985). Putnam (1985) lists several chemical groups from which allelopathic agents come: organic acids and aldehydes, aromatic acids, simple unsaturated lactones, coumarins, quinones, flavonoids, tannins, alkaloids, terpenoids and steroids, a few miscellaneous compounds such as long chain fatty acids, alcohols, polypeptides, nucleosides, and some unknown compounds. Some of the diversity and complexity of allelopathic chemistry are shown in Table 8.3. The diversity suggests several mechanisms of action, a multiplicity of effects, and is one reason for the slow emergence of a theoretical framework. The chemistry of allelopathy is as complex as synthetic herbicide chemistry, but it is a chemistry of discovery as opposed to one of synthesis.

TABLE 8.3. Allelopathic Compounds Isolated from Plants (Putnam, 1983).

Common name	Chemical class	Natural source
Acetic acid	aliphatic acid	decomposing straw
Allylisothiocyanate	thiocyanate	mustard plants
Arbutin	phenolic	manzanita shrubs
Bialaphos	amino acid derivative	microorganisms
Caffeine	alkaloid	coffee plants
Camphor	monoterpene	*Salvia* shrubs
Cinnamic acid	aromatic acid	guayule plants
Dhurrin	cyanogenic glucoside	sorghum plants
Gallic acid	tannin	spurge plants
Juglone	quinone	black walnut trees
Patulin	simple lactone	*Penicillium* fungus on wheat straw
Phlorizin	flavonoid	apple roots
Psoralen	furanocoumarin	*Psoralea* plants

There is little doubt that allelopathy occurs in plant communities, but there are questions about how important allelopathic chemicals are in nature and if they can be exploited in cropped fields. It has been reported for many crop and weed species (Putnam, 1983, 1985, 1994), but proof of its importance in nature is lacking (Foy and Inderjit, 2001). Proof will require something similar to the application of Koch's (1912) postulates that were proposed for plant pathology in 1883 and amended by Smith (1905).

These are the analogous postulates applied to allelopathy (Aldrich, 1984; Putnam, 1985):

1. Observe, describe, and quantify the degree of interference in a natural community.
2. Isolate, characterize, and synthesize the suspected toxin.
3. Reproduce the symptoms by application of the toxin at appropriate rates and times in nature. [Koch's (1912) postulates called for reisolation of the bacterial agent from the experimentally infected plant—an inappropriate criterion for allelopathic research.]
4. Monitor release, movement, and uptake, and show that they are sufficient to cause the observed effect(s).

These four steps describe difficult, expensive, complex scientific research. Rigorous proof has rarely been applied to any ecological interaction, but such proof is vital if allelopathic research is to move from description to causation.

In short, it is insufficient to make an observation and suspect a toxin. It is insufficient to demonstrate the toxin is produced by one plant. Specific cause and effect must be demonstrated through chemical and plant studies. It may not be necessary to prove that plant X is the source of allelochemical Y. If an allelochemical, effective as a natural herbicide, can be isolated and identified, in theory, it might be useful without absolute proof of its plant origin or physiological mode of action. The basic chemistry and biology would remain a scientific challenge, but it might be possible to exploit the activity. Proceeding with partial knowledge is more risky but not impossible. For example, medical science still doesn't know exactly how aspirin relieves pain, and weed science doesn't know exactly how 2,4-D kills a plant, but both can be used productively and safely.

II. PRODUCTION OF ALLELOCHEMICALS

Production of allelochemicals varies with environment and associated environmental stresses. It can occur in any plant organ (Rice, 1974), but roots, seeds, and leaves are the most common sources. Source becomes important for exploitation of allelochemicals for weed control. For example, an allelochemical found in flowers or fruits would have less potential value than if it were concentrated in roots or shoots (Putnam, 1985). (A statement about availability, not allelochemical potency.) For control, soil incorporation of whole plants might create proper distribution regardless of which plant part produced the chemical. The amount is important for control purposes, and if specific effects are to be predicted in the field, total quantity and concentration must be determined (Putnam, 1985).

There is evidence that allelochemical production may be greater when plants suffer from environmental stress (Putnam, 1983, 1985; Rice, 1979). Production is influenced by light intensity, quality, and duration, with a greater quantity produced with high ultraviolet light and long days (Aldrich, 1984). Weeds, commonly understory plants, might be expected to produce lower quantities of allelochemicals because UV light is filtered by overshadowing crop plants. This, of course, assumes that crops provide shade and that shade effectively suppresses allelopathic activity. Quantities of allelochemicals produced are also greater under conditions of mineral deficiency, drought stress, and cool temperatures, as opposed to more optimal growing conditions. In some cases, plants affected by growth regulator herbicides may increase production of allelochemicals. Because stress frequently enhances allelochemical production, it is logical to assume that stress accentuates the involvement of allelopathy in weed-crop interference and that competition for limited resources may increase allelopathic potential or sensitivity of the weed, the

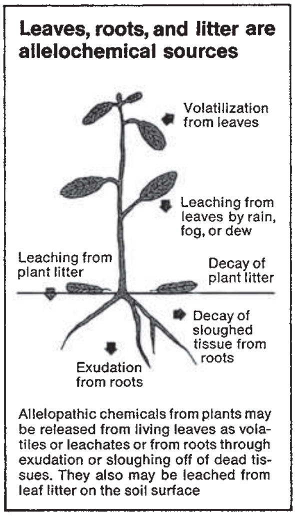

FIGURE 8.2. Sources of allelochemicals (Putnam, 1994).

crop, or both. Thus, weed-crop competition and allelopathy should be regarded as intimately related components of interference in a crop ecosystem.

Allelochemicals enter the environment in a number of ways at different times, and mode and time of entry can alter their effects (Figure 8.2). Although chemicals with allelopathic activity may be present in many species, presence does not mean that allelopathic effects will ensue. Even after a chemical has been isolated and identified, its placement in the environment after plant release or its time of release may preclude expression of potential activity.

Allelochemicals enter the environment through volatilization or root exudation and move through soil by leaching (Figure 8.2). These entry paths are usually regarded as true allelopathy. Toxins also result from decomposition of plant residues, properly regarded as functional allelopathy—that is, environmental release of substances that are toxic as a result of transformation after their release by the plant.

Allelochemicals can be produced by weeds and affect crops, but the reverse is also true, although it has not been as widely studied (Putnam, 1994). It is probably true that some crop cultivars produce allelochemicals. Therefore, it is theoretically possible that such cultivars could be planted to take advantage of their allelochemical potential. It has been suggested that crops with allelopathic potential could be planted as rotational crops or companion plants in annual or perennial cropping systems to exert their allelopathic effect on weeds. Rye and its residues have been shown to provide good weed control in a variety of cropping systems (Barnes and Putnam, 1983). Rye residues reduced emergence of lettuce and proso millet by 58 and 35%, respectively. Rye shoot tissue inhibited lettuce seed germination 52%. It also was phytotoxic to barnyardgrass and cress (Barnes and Putnam, 1986).

III. ALLELOPATHY AND WEED-CROP ECOLOGY

Aldrich (1984) suggested allelopathy was significant for weed-crop ecology in three ways:

1. As a factor affecting changes in weed species composition
2. As an avenue of weed interference with crop growth and yield
3. As a possible weed management tool

Allelopathy should not always be implicated when other explanations do not suffice, but it should not be overlooked because of the difficulty of establishing causality.

A. Effects on Weed Species

Why one species succeeds another is a question that has intrigued ecologists for many years. Weed scientists are interested in the same question but often only for the life-span of an annual crop. Weed scientists accept that plants change the environment and are changed by it. It is generally agreed that many early colonizers succeed by producing large numbers of seeds, whereas late arrivals succeed through greater competitive ability. This is true in old-field succession and in annual crops. Ecologists have shown that successful plants may change the environment to their advantage by subtle means, such as changes in soil nitrogen relationships caused by release of specific inhibitors of nitrogen fixation or nitrification (Putnam, 1985; Thompson, 1985).

B. Weed Interference

Weed seeds survive for long periods in soil, and chemical inhibitors of microbial decay have been implicated in their longevity, but specific identification of inhibitors from weed seeds has not been accomplished. Allelochemicals have been implicated in the inability of some seeds to germinate in the presence of other seeds or in the presence of crop residues in soil. Although neither phenomenon has been exploited for weed management, there is little doubt that both occur. Eventual exploitation may depend on discovery of specific chemicals and their mode(s) of action. Because of the mass of plant residue and its volume compared to the volume of seed (even though the number of seeds may be large), the possibility of effects from plant residues is greater than that of effects from seed.

The problems with replanting the same or different crops in a field have been cited (Putnam, 1985; Rice, 1974) to show the effect of allelochemicals on crop growth. Putnam (1983) showed that the allelopathic potential of sorghum residues has been exploited for weed control in subsequent rotational crops. While there is little doubt that allelochemicals inhibit crop growth, a research challenge still exists to separate allelopathic effects from competition. Most greenhouse studies cannot be directly translated to the field because of different climatic, edaphic, and biological conditions, and possible effects of soil volume. Allelopathy awaits adequate experimental methods for independent but related field and greenhouse studies.

A fundamental assumption of biological control of weed is that damaged plants are less fit and compete poorly and therefore they will fail in the struggle for survival. That assumption, like so many in science, often is not borne out by research. When, as a management strategy, spotted knapweed is intentionally attacked by the larvae of two different root-boring biocontrol insects and a parasitic fungus, its allelopathic potential increases significantly, and it has “more intense effects on native” vegetation (Thelen et al., 2005). The authors conclude that while biological control can be very effective, it can often be less effective or fail. Without a detailed understanding of the basic ecology of the area and the plants, it is not possible to know why success or failure occurred. “An invasive species that inhibits natives via unusually deep shade might be a more appropriate target for biological control than allelopathic invaders.”

C. Weed Management

A living cover crop of spring planted rye reduced early season biomass of common lambsquarters 98%, common ragweed 90%, and large crabgrass 42% compared to control plots with no rye (Barnes and Putnam, 1983). Wheat straw has reduced populations of pitted morningglory and prickly sida in no-tillage culture. It was suggested the wheat produced an allelochemical that inhibited emergence of several broadleaved species (Liebl and Worsham, 1983). Inderjit et al. (2001) studied the allelopathic potential of wheat and perennial ryegrass. They showed in a laboratory study that root length of perennial ryegrass was suppressed by wheat and was dependent on the density of wheat seeds in a petri dish. Ryegrass shoot growth was unaffected by wheat, and ryegrass density had no effect on wheat seedling growth. The allelopathic potential of wheat straw has been demonstrated in the laboratory (Guenzi and McCalla, 1962; Guenzi et al., 1967; Hamidi et al., 2001) but not in the field.

It is reasonable to assume that many plants have allelopathic potential or some susceptibility to allelochemicals when they are presented in the right amount, form, and concentration at the appropriate time. It is equally reasonable to assume that allelopathy may have no role in the interference interactions of many species. However, enough work has been done to conclude that allelopathy could be utilized for development of new weed management strategies. Trials in South Dakota showed that fields planted to sorghum had two to four times fewer weeds the following year than similar fields planted to soybean or corn (Kozlov, 1990). It was proposed, although not proven, that reduced weed seed germination was due to phenolic acids and cyanogenic glucosides given off by sorghum. Suppression of weeds by sorghum has been reported by Guenzi and McCalla (1966) and Hussain and Gadoon (1981). Sunflower has been reported to have an allelopathic effect against grain sorghum (Schon and Einhellig, 1982) and against other weeds (Leather, 1983). Guenzi and McCalla (1966) found allelopathic phenolic acids in oats, wheat, sorghum, and corn residues, and Lodhi et al. (1987) discussed the role of allelopathy from wheat in crop rotations. Other sources are available to describe and summarize the major findings of allelopathy research and their application in weed management (Putnam, 1983, 1985, 1994; Rice, 1974, 1979; Thompson, 1985; and the reviews previously cited). A few examples follow to illustrate the research and its potential.

Walker and Jenkins (1986) were the first to demonstrate that sweet potato residues inhibited growth of sweet potato and cowpea. Decaying residues reduced uptake of calcium, magnesium, and sulfur by other plants (Walker et al., 1989). Additional studies showed that after one growing season, shoot dry weight of yellow nutsedge growing with sweet potatoes was less than 10% of the weight when yellow nutsedge was grown alone. Moreover, remaining yellow nutsedge had no effect on sweet potato growth (Harrison and Peterson, 1991). Allelochemicals were present in the tuber periderm that is continually sloughed off during root growth. Proso millet was susceptible to all extracted fractions but other plants showed differential susceptibility, indicating that several allelochemicals may be present (Peterson and Harrison, 1991).

Plant pathogens and allelochemicals from plant pathogens and other soil microorganisms can be used as bioherbicides. This possibility has been studied for more than three decades (Hoagland, 2001). Numerous pathogens and microbial allelochemicals have been isolated and studied for their bioherbicidal potential. A good example of a microbial product is the herbicide bialophos (active ingredient phosphinothricin). It is manufactured by fermentation as a metabolite of the soil microbe *Streptomyces viridochromogenes* (Auld and

McRae, 1997). It is available in Japan (as Herbiace) but not in the United States. The second example is the ammonium salt of phosphinothricin, glufosinate (see Chapter 13). A gene coding for the enzyme phosphinothricin acetyl transferase was isolated from the nonpathogenic bacteria *Streptomyces hygroscopicus* and cloned into several crops. The enzyme converts the herbicide glufosinate to a nonphytotoxic metabolite and the genetically engineered crop is thus resistant to glufosinate. Another example began with a study of the root parasitic damping of fungus (*Pythium* spp.) in turf. Christians (1991, 1993) wanted to establish the fungus in the soil of a new golf course green at Iowa State University. Pythium was cultured in the laboratory on cornmeal, a standard procedure. The culture was placed on field plots, and other plots were treated with the same amount of fresh cornmeal. The attempt to establish Pythium failed, but seeded cultivars of creeping bentgrass did not germinate well on plots that had received fresh corn gluten meal, a by-product of the wet-milling process of corn grain. This was unexpected. Further study showed potential for selective control of crabgrass in Kentucky bluegrass turf. Liu et al. (1994) demonstrated that enzymatically hydrolyzed corn gluten meal was more herbicidally active than corn gluten. Corn gluten hydrolysate completely inhibited germination of crabgrass and creeping bentgrass seed and root emergence of perennial ryegrass seed. Corn gluten meal is used for preemergence weed management and fertilization (Bingamen and Christians, 1995; Christians, 1993; Gough and Carlstrom 1999).

Pollen can also be allelopathic. Pollen can release toxins that inhibit seed germination, seedling emergence, sporophytic growth, or sexual reproduction (Murphy, 2001). Two crops (timothy and corn) and four weeds (orange hawkweed, ragweed parthenium, yellow hawkweed, and yellow-devil hawkweed) are known to exhibit pollen allelopathy (Murphy, 2001). There may be others. Pollen allelopathy might be useful in biological weed management because the allelochemical is active in very low doses (as little as 10 grains of pollen per mm^2 on stigmas) and pollen is a small, naturally targeted distribution system. Murphy (2001) points out that pollen allelopathy has potential but is not a confirmed weed management technique. Disadvantages include weed adaptation to pollen toxicity and possible threats of toxic pollen to crop plants.

Few researchers recommend that allelopathy is a dominant way plants interact. Many argue that it is present and that nonresource competitive mechanisms should regularly be considered to account for the success of weeds and other invading species (Hierro and Callaway, 2003). Diffuse knapweed is an invasive Eurasian weed in western North America. Research and general observations suggest that diffuse knapweed produces virtual monocultures and that allelopathy may be an important component of its success. Hierro and Callaway (2003) suggest that allelopathy "may be more important in recipient communities than in origin communities because the former are more likely to be naive to the chemicals possessed by newly arrived species." They do not suggest that allelopathy is a unifying theory or a dominant way that plants interact or the only way to explain diffuse knapweed's dominance. They do suggest that such nonresource mechanisms should not be dismissed as irrelevant.

With this kind of evidence one is inclined to agree with Putnam's (1985) suggestion that not believing in allelopathy, now, is like not believing in genetic inheritance before DNA's structure was known. One area to explore might be testing for suppression of weed seed germination and seedling emergence by potential allelopathic species. Work to date has shown this to be an inconsistent effect, and, if developed, it could be used with other methods of weed management. Allelopathy isn't, and will never be, a panacea for all weed problems. It is another weed management tool to be placed in the toolbox and used in combination with other techniques. It is not a technique that will finally solve all weed problems or make the hoe obsolete.

The second strategy where allelopathy may be used is weed suppressing crops. This can be realized by discovering, incorporating, or enhancing allelopathic activity in crop plants. This technique would be most useful in crops maintained in high-density monocultures, such as turf grasses, forage grasses, or legumes. Olofsdotter (2001) notes that while allelopathy has been demonstrated with varying success, it has been much more difficult to use the principle in crop production. She suggests that if genetic mapping of quantitative traits can be linked to understanding of allelopathic mechanisms, it may lead toward optimization of a plant's allelopathy and production of more competitive crops—crops with an allelopathic advantage. It may be possible with modern techniques to transfer (genetically modify) the ability of any plant to produce a weed-controlling allelochemical to a crop plant (for example, the work on rye done by Barnes and Putnam, 1983, 1986). Much more physiological and chemical knowledge is required before this can be done successfully, but it is an enticing possibility—a crop that does more, perhaps all, of its own weed control because it has a chemical advantage.

The third area for allelopathic research and development includes the use of plant residues in cropping systems, allelopathic rotational crops, or companion plants with allelopathic potential. Many crops leave residues that are regarded as a necessary but not a beneficial part of crop production, except as they contribute to soil fertility or tilth. Research (Putnam, 1985, 1994; Rice, 1979) indicates that plant residues have allelopathic activity, but the nature of this activity has not been explored sufficiently to permit effective use. Rotation, a neglected practice in many agricultural systems, is being studied because of its potential for weed management through competition and allelopathy. Companion cropping is a new and interesting technique for agricultural systems in developing countries. Multiple cropping is common in many developing countries where allelopathy may be operational without being obvious and defined. These systems may hold valuable lessons for further agricultural development of allelopathy as a useful weed management tool.

Weed scientists need to look beyond the immediate assumption that interference is always competition and see what they may not be looking for: an allelopathic effect, which can be an unexpected, but good, thing. Perhaps there are expressions of allelopathy before our eyes that we don't see because we're not looking for them. If there are compounds in nature with such great specificity, they should be examined. The patterns of herbicide development point to greater specificity, and nature may have solutions in natural products if we recognize them, learn how they work, and exploit their capabilities.

One of the first and quite potent phytotoxins found in higher plants was 1,8-cineole released by sagebrush species (Muller and Muller, 1964). Cinmethylin was developed as an herbicide for weed control in rice, cotton, soybeans, peanuts, some vegetables, vine crops, and ornamentals. It is not sold in the United States. Chemically, it is a structural analog of 1,4-cineole, which inhibits asparagine synthetase, the enzyme responsible for biosynthesis of the amino acid asparagine (Romagni et al., 2000). Cinmethalin controls many annual grasses and some broadleaf weeds and sedges. It is produced synthetically, but the thought behind it was probably derived from the known phytotoxicity of the allelopathic cineoles.

A second and clearer example of a natural herbicide is AAL-toxin, a natural metabolite produced by *Alternaria alternata* f. sp. *Lycopersici*, the pathogen that causes stem canker of tomato (Abbas et al., 1995). The phytotoxic effects of AAL-toxin were tested on 86 crop and weed species (Abbas et al., 1995). Monocots were generally immune to its effects. Black nightshade, jimsonweed, all species of tomatoes tested, and several other broadleaved plants were susceptible at low doses. Other broadleaved species were susceptible but only at higher doses. Abbas et al. (1995) proposed that the differential susceptibility of species to AAL-toxin could be exploited for selective weed control. There may be other potentially valuable chemicals hidden from us because we are looking for something else. Promising observations await the good observer?

However, Duke et al. (2002) present five problems associated with natural products, including allelochemicals, that describe why there has not been more research and development of these potent chemicals. Perhaps the most important reason is that natural products that have or potentially have phytotoxic activity are usually structurally complex and therefore expensive to manufacture. Second, these chemicals often have high mammalian toxicity (AAL-toxin is toxic to mammalian cells; Abbas, 1996), which makes them undesirable from a public health standpoint. Many potentially beneficial natural products (phototoxins, pharmaceuticals, etc.) are derived from plants found only or mainly in developing countries. These countries have charged, with adequate justification, that developed nations have exploited their resources with inadequate or no compensation. Laws have been passed in many countries to prevent exploitation of indigenous natural resources and to retain some level of ownership. The cost of compound identification (discovery), isolation, structural identification, and manufacture has been very high, with no assurance of a return to justify the initial costs. Finally, many natural products have relatively short environmental half-lives. This is desirable from a nontarget species view but not from a weed management view, where some persistence in time is a good thing.

THINGS TO THINK ABOUT

1. What is the present role of allelopathy in weed management?
2. What is the potential role of allelopathy in weed management?
3. Why has so little research been done on allelopathy?
4. What are the essential ingredients of a research program to discover allelochemicals?

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CHAPTER 9

The Significance of Plant Competition

FUNDAMENTAL CONCEPTS

- There is no complete explanation of, or a scientific basis for, plant competition.
- The concept of competitive ability is useful but cannot be precisely defined.
- A proposed biochemical basis for plant competition is based on six factors.
- Plants fix atmospheric carbon dioxide via a C_3 and a C_4 pathway. The latter is generally regarded as more efficient.
- Plants have definable characteristics that make them competitive.

LEARNING OBJECTIVES

- To understand a theoretical biochemical basis for plant competition.
- To know the difference between C_3 and C_4 carbon fixation.
- To understand the role of carbon fixation in plant competition.
- To know the arguments against the primacy of carbon fixation in plant competition.
- To know the basis for other explanations of plant competition.
- To know the characteristics that lead to competitiveness.

I. GENERAL CONSIDERATIONS

> It is a salutary thought that we do not know—nor have we even given the matter much consideration—what determines the density of population of cereal plants giving maximum yield. Yet until we know this, and especially until we understand the interaction of density with such factors as water and nitrogen, then the development of suitable varieties of plants must depend in the future—as in the past—on

> empirical plant breeding. We can claim great advances in genetics, and great advances in producing plants with drought escape or disease resistance, fatter pods, or finer flowers. And the breeder can point to varieties which quite apart from these specific virtues, are able under the keen intraplant competition of a commercial crop, to yield more grain, more leaf, more dry matter. Why? The breeder has no idea. Indeed, the answer to such question will often be that it yields more because it has more ears, or more florets, or more fertility, or less abortion, which of course is little more than a paraphrase of the statement that it yields more. Actually what happened was that the breeder selected it because it yielded more, not that it yielded more because it was consciously bred to do so. Why does a modern wheat variety, whether in Greece or New Zealand, yield more than a variety of like maturity and disease resistance of 50 years ago? Because it either (A) fixes more carbon or (B) has a greater proportion of the carbon in the grain. Why? No one knows. Perhaps it has a different root system, better leaf arrangement and light utilization, more glume surface, or one of many factors affecting growth and photosynthesis. And, in particular, it has the desired characteristics when growing under the acute stress conditions of a commercial crop.
>
> C. M. Donald (1963)

These words, written in 1963, are still largely true. There is no complete explanation of, and scientific basis for, plant competition, but we are getting closer. We know that yield and growth are a function of carbon assimilation by photosynthesis, and plant growth is affected by many environmental and physiological factors. It is known that carbon dioxide uptake and fixation are primary determinants of growth, and plant environmental responses are mediated through biochemical reactions and genetic control. In agriculture, some plants have high yields, grow fast, are competitive, and may be weeds. Black et al. (1969) tried to provide a scientific basis for plant competition and weediness. They took data from the work of others, applied unique ideas, and proposed a biochemical basis for plant competition, based on the assumption that the primary determinant of success is the capacity to fix carbon. Their work is not conclusive and has not been included as the only definitive explanation of competition and weediness. It is included because it provides clues to how the process of competition has been studied and about how to think about weed-crop competition. Their theory has not been widely accepted or soundly rejected, but it is provocative and worthy of consideration.

Black et al. (1969) classified plants as efficient or nonefficient on the basis of six factors:

1. Light intensity response
2. Temperature response
3. Response to oxygen
4. Presence or absence of photorespiration
5. Pathway of photosynthetic carbon dioxide assimilation
6. Photosynthetic compensation point level

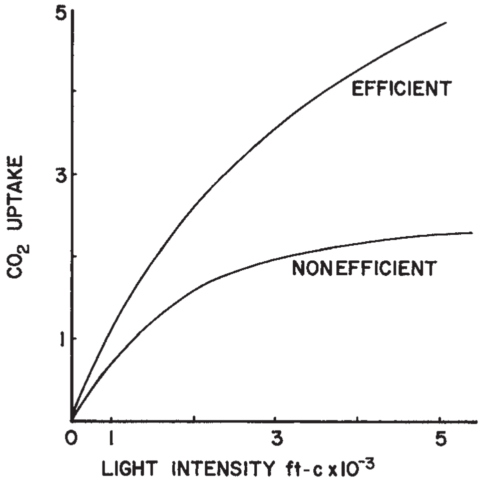

FIGURE 9.1. The response of photosynthesis to increasing light intensity for efficient and nonefficient plants (Black et al., 1969).

They developed the hypothesis that efficient plants are often used in agriculture because of their high production *and* because they are often competitive. Almost all the weeds they examined were efficient given their definition.

In efficient plants, carbon dioxide uptake increases with light intensity (Figure 9.1). The ability of nonefficient plants to fix carbon dioxide levels off rapidly as light intensity increases, whereas efficient plants continue to fix carbon as light intensity increases to near full sunlight. The same is true for the response of plants to temperature. Nonefficient plants peak in their ability to fix carbon around 20°C (Figure 9.2). Efficient plants continue to fix carbon at higher temperatures, although both curves plateau. Efficient plants fix carbon at much higher light intensities and temperatures than nonefficient plants.

At normal atmospheric oxygen concentration (21%), photosynthesis in nonefficient plants is inhibited by oxygen. Photosynthesis in efficient plants is not inhibited by oxygen.

In some plants, respiration decreases with increased light—a phenomenon called photorespiration that has not been demonstrated in efficient plants. It is a wasteful, light-stimulated oxidation of photosynthetic intermediates to carbon dioxide and other products for which plants have no useful purpose.

The C_3 cycle for carbon fixation is the dominant mechanism in plants. Ribulose diphosphate (RuDP), a five-carbon sugar, is the carbon dioxide acceptor. Some plants also fix carbon dioxide in a 4-carbon dicarboxylic acid (malic and aspartic acid) cycle. This is the Hatch-Slack or C_4 cycle in which

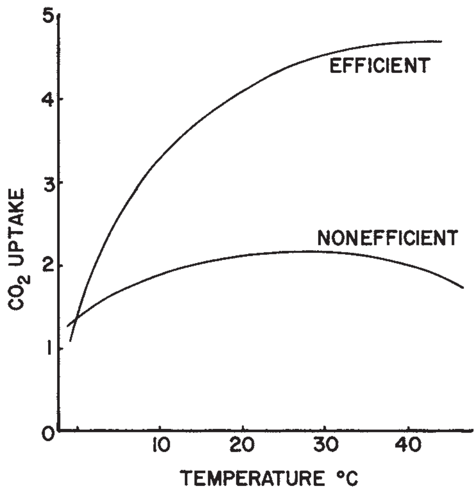

FIGURE 9.2. The response of photosynthesis to increasing temperature for efficient and nonefficient plants (Black et al., 1969).

phosphoenolpyruvate (PEP) is the carbon dioxide acceptor. The efficiency of C_4 fixation results from the fact that phosphoenolpyruvate has a much higher affinity for carbon dioxide than ribulose diphosphate carboxylase, the enzyme responsible for initial fixation in C_3 plants. Black et al.'s survey (1969) of a number of plants showed that the presence of the C_4 cycle was characteristic of efficient plants. Plants do not fix carbon dioxide by the C_3 *or* C_4 cycle. The C_4 cycle, characteristic of efficient plants, supplements but does not replace the C_3 cycle. Table 9.1 shows some characteristics usually associated with the C_4 pathway. Table 9.1 demonstrates the proposed superiority of the C_4 pathway, which is superior mainly under conditions of high irradiance. It is a reasonable generalization that C_4 plants have higher photosynthetic rates. Corn, a C_4 plant, has a maximum photosynthetic rate (measured as CO_2 fixed in μmol m^{-2} s^{-1}) between 20 and 40, whereas soybean, a C_3 plant, fixes 10 to 20. For further discussion of pathways of carbon fixation, readers are referred to any good plant physiology or biology text.

The sixth characteristic of the Black et al. (1969) hypothesis is the level of carbon dioxide compensation point. Under normal physiological conditions, efficient plants have a carbon dioxide compensation point of 5 ppm or less. Nonefficient plants have a compensation point in the range of 30 to 70 ppm CO_2. The compensation point is the concentration of carbon dioxide below which net carbon assimilation does not occur via photosynthesis. In plants, carbon dioxide released by respiration is used in photosynthesis with no net

TABLE 9.1. Some Physiological and Performance Characteristics Associated with the C_4 Pathway.

Characteristic	Approximate quantitative relationship compared with C_3 species
High temperature optimum for photosynthesis	30°–45° vs. 15°–30°C
High light optimum for photosynthesis	Full sunlight vs. 30% full sunlight
High photosynthesis rates per unit leaf area	About twice as much under optimal conditions
High growth rates under optimal conditions for photosynthesis	About twice as much
High dry matter production per unit of water used	Two to three times as much

oxygen evolution at the compensation point. Obviously, plants with a high compensation point fix less carbon because of the inefficiency of their respiration.

A list of efficient and nonefficient plants from Black et al. (1969) is shown in Table 9.2. Applying their hypothesis to explain weed-crop competition, one finds that many weeds are efficient and many crops are not.

When their hypothesis is used to compare Kentucky bluegrass and crabgrass, a common weed in bluegrass turf (Table 9.3), the data illustrate that crabgrass is efficient and will be a good competitor with Kentucky bluegrass, an observation turf managers verify.

The data on water requirements of different plant species (Shantz et al., 1927) have been combined with the hypothesis of Black et al. (1969) (Table 9.4). The data show that some crops and weeds with the C_4 pathway have a low water requirement, and others with the C_3 pathway typically have a higher water requirement, lending additional credence to, but not proving, the hypothesis.

The Weed Science Society of America composite list of weeds (Anonymous, 1989) contains over 2,000 species from 500 genera and 125 families. Of that number, 146 species in 53 genera and 10 families have C_4 carbon fixation. This is 17 times higher than the percentage of C_4 plants in the world's plant population.

Fourteen of the 18 worst weeds in the world (Holm et al., 1977) are C_4 weeds, and 8 of the top 10 are. Forty-two percent of the 76 worst weeds of the world are C_4, but only 20% of the 15 major world crops are. The C_3 pathway of photosynthetic fixation dominates among crops. There are many C_4 weeds, but there is an equal number of important weeds that fix carbon by the C_3 pathway.

TABLE 9.2. A List of Efficient and Nonefficient Plants (Black et al., 1969).

Efficient	Nonefficient	
Crops	**Crops**	
Corn	common bean	ryegrass
Sugarcane	soybean	wheat
Sorghum	sugarbeet	oat
	spinach	barley
	tobacco	Kentucky bluegrass
	cotton	rice
	lettuce	
	orchardgrass	
Weeds	**Weeds**	
Pigweed	lambsquarters	
Saltbush	velvetleaf	
Common purslane		
Russian thistle		
Barnyardgrass		
Crabgrass		
Foxtails		
Johnsongrass		
Witchgrass		
Nutsedge		

TABLE 9.3. A Comparison of Kentucky Bluegrass and Crabgrass Using the Hypothesis of Black et al. (1969).

Factors	Kentucky bluegrass	Crabgrass
CO_2 uptake increases with light intensity	Light saturation @ 1,000 to 3,000 foot-candles	Light saturation @ 5,000 foot-candles
	Assimilates 15 to 35 mg CO_2/sq dm/hr	Assimilates 50 to 80 mg CO_2/sq dm/hr
Optimum temperature	10° to 25°C	30° to 40°C
Ps inhibited by O_2	No information	—
Photorespiration	Yes	No
C fixation cycle	No information	—
Ps comp. point	30 ppm CO_2	5 ppm CO_2

TABLE 9.4. Grams of Water Required to Produce One Gram of Dry Matter for Several Plants (Black et al., 1969; Shantz et al., 1927).

Species	Grams of water required per pound of dry matter
C^4 pathway	
Prostrate pigweed	260
Common purslane	281
Foxtail millet	285
Sorghum	304
Corn	349
Average	296
C^3 pathway	
Wheat	557
Cotton	568
Cowpea	569
Common lambsquarters	658
Prostrate knotweed	678
Rice	682
Beans	700
Prostrate vervain	702
Smooth brome	977
Average	667

In the eastern United States, C_3 and C_4 plants are poor competitors, and many weeds have C_3 carbon fixation. Baskin and Baskin (1978) proposed that C_4 photosynthesis is less important than other features in determining competitive ability, whereas Black et al. (1969) believed that the rate of carbon dioxide fixation was the main determinant of competitive ability. This difference is one reason why the Black et al. (1969) hypothesis is presented as a way to think about weed-crop competition but not as a definitive explanation of competition. With natural temperature and radiation in arid southwest Australia, two C_3 species, rape and sunflower, had higher net assimilation rates and relative growth rates than corn, a C_4 plant (Baskin and Baskin, 1977). Baskin and Baskin (1978) proposed that C_3 and C_4 weeds compete well with crops but not with climax vegetation. Among successful southeastern US pasture grasses, there is about an even distribution between C_4 and C_3 carbon fixation pathways. Bermudagrass, bahiagrass, and pangolagrass are all C_4. Kentucky bluegrass, orchardgrass, and fescue are C_3. Table 9.5 shows the presence of the two pathways in several crops and weeds.

TABLE 9.5. Photosynthetic Pathways of Some Crops and Weeds (Patterson, 1985).

Crops		Weeds	
C_3	C_4	C_3	C_4
Alfalfa	Corn	Ageratum	Barnyardgrass
Banana	Foxtail millet	Canada thistle	Bermudagrass
Barley	Pearl millet	Catchweed bedstraw	Common purslane
Bean	Sorghum	Cocklebur	Cogongrass
Cassava	Sugarcane	Common chickweed	Crabgrass
Coconut		Common milkweed	Dallisgrass
Corn		Docks	Dropseed
Cotton		Field bindweed	Fall panicum
Oats		Hairy beggarticks	Foxtail
Orchardgrass		Jimsonweed	Garden spurge
Peanut		Common lambsquarters	Goosegrass
Potato		Largeleaf lantana	Guineagrass
Rice		Morningglory	Itchgrass
Rye		Mustards	Johnsongrass
Soybean		Nightshades	Kikuyugrass
Sugarbeet		Plantain	Kochia
Sweet potato		Poison ryegrass	Nutsedge, purple and yellow
Tomato		Quackgrass	Pigweeds
Wheat		Ragweeds	Puncturevine
		Sensitive plant	Russian thistle
		Sicklepod	Sandburs
		Sida, prickly	Signalgrass
		Smartweeds	Sprangletop
		Velvetleaf	Texas panicum
		Waterhyacinth	Torpedograss
		Wild oats	
		Witchweed	

At high temperatures (34°C day/38°C night), redroot pigweed, a C_4 plant, outcompetes common lambsquarters, a C_3 plant, but at low temperatures (18°C day/14°C night), the reverse is true (Pearcy et al., 1981). There is no inherent advantage to C_4 photosynthesis (Baskin and Baskin, 1977). Rate of leaf production or time of emergence may be more important determinants of a weed's competitiveness than rate of photosynthesis. This is not to say that carbon fixation is not important. Life is complex, and explanations of behavior and competitiveness will not to be found in single causes.

II. CHARACTERISTICS OF WEEDS

There is a lot to learn about why weeds are such good competitors. What makes some plants so capable of growing where they are not desired? Why are weeds such good competitors? What are their modes of competition and survival?

Weeds share some traits (see Chapter 2). Not all weeds have all traits, but all weeds have some of the following characteristics related to growth and physiology (competitive ability), reproduction, and cultural practices (Baker, 1965; Baker, 1974; Bazzaz, 1979; Elmore and Paul, 1983).

A. Competitive Ability

Weeds that are most competitive have rapid seedling growth and a high growth rate compared to the crop with which they are interfering. They will also have a short vegetative period before flowering and be able to complete seed production quickly. They often produce seeds that mature soon after flowering. Canada thistle matures seed within two weeks of flowering. Russian thistle seeds held at 80°F will germinate within 90 minutes of wetting. This weed would spread more than it does, except it must germinate in loose soil because the coiled root unwinds as it pushes into the ground; in hard soil, the seedling dies before it roots successfully.

Weeds with great competitive ability have fast seedling growth and grow tall quickly or gain competitive ability by twining on larger plants. They may also be tolerant of shade and their highest carbon dioxide assimilation rate may not be in full sunlight.

Consistent with the hypothesis of Black et al. (1969), the most competitive weeds have a high photosynthetic rate and rapid partitioning of photosynthate into new leaf production. They have a high light saturation intensity and a low carbon dioxide compensation point.

Competitive weeds quickly develop a large exploitative root system and have a high tolerance for climatic and soil variations. Their general purpose genotype frees them from many environmental constraints; they grow well in many places. This genotype enables weeds to grow under adverse conditions, have a great ability to recover quickly from resource limitation, to acquire resources fast, and ensures that some survive in many different environments.

Many common agricultural weeds are not good competitors in the ecological sense. They have evolved to be successful competitors in the intensely managed and regularly disturbed habitats characteristic of cultivated fields. Weeds and crops benefit from things that reduce environmental stress such as irrigation, fertilization, and pest control. Most agricultural weeds lack the ability to tolerate extreme shade and do not invade or survive well in established vegetation. There are notable exceptions, e.g., kudzu, that tend to show that sweeping generalizations about weed characteristics are usually wrong. Weeds, important in crop competition, are often present in the earliest ecological successional stages (the ecological red cross) following abandonment of crop land because there is an absence of competition and a large weed seed bank in the soil that still has abundant nutrients. Many agricultural weeds do not compete well in resource starved environments. Some of the best weeds have the ability to compete by special means such as allelopathy (see Chapter 8). Other successful weeds have adaptations that repel grazing such as spines, bad taste, or bad odor.

B. Reproductive Characteristics

The most successful weeds have no special environmental requirements for germination. They may be especially detrimental in crops because their success, after germination, is tied to the same factors that lead to crop success. They succeed in well-fertilized fields, planted at certain times, often with irrigation or regular rainfall.

Successful weeds have a relatively long period of high seed production with favorable growing conditions. Some have almost continuous seed production. Redroot pigweed is able to produce seed as early as when it is 1 to 8 inches tall and for a long time after it first flowers. Good weeds produce some seed under a wide range of environmental conditions.

Weeds have special adaptations for short and long distance dispersal of their seeds in space. They are usually self-compatible but not obligate self-pollinators. Cross-pollination is achieved by nonspecialized flower visitors or wind.

C. Cultural Practices

Weed seeds resist degradation in soil and disperse in time via seed dormancy. Even though they produce a large number of seeds per plant, many of which may germinate immediately, they can acquire secondary dormancy. Weed seed often has the same size and shape as many crop seeds, and weed maturation coincides with crop maturity. Morphological and physiological similarity to crop seed makes weed seed hard to detect and clean from crop seed.

Plowing and preparing soil for planting are vigorous practices that disturb plant growth. Most crop plants, turf, and ornamentals do not survive these practices, but many weeds can. In fact some weeds—for example, nightshades—are dependent on tillage for establishment. Weeds survive and prosper under the disturbed conditions of a cropped field or an environment created to favor human crops or goals. Weeds have the environmental plasticity to do well under these conditions.

If a weed is a perennial, it has vigorous vegetative reproduction with large food reserves in roots. Perennials also may have dual modes of reproduction and do not rely solely on vegetative or sexual reproduction. Perennials normally are brittle (break easily) at lower rhizome or root nodes and cannot be pulled from the soil. Perennials usually have the ability to regenerate from small (often as small as 1 inch, if a bud is present) root segments.

Perhaps of greatest importance to the success of many weeds is their resistance to, or ability to develop tolerance of, different methods of control, including chemical control.

THINGS TO THINK ABOUT

1. What are the six factors included in the Black et al. (1969) scheme to explain plant competition?
2. What is the definition of an efficient and a nonefficient plant and how are the concepts used?
3. Carbon fixation is a logical determinant of plant competitiveness. Why does it fail in some cases?
4. What are the characteristics of plant growth, reproduction, and response to cultural practices that contribute to weediness?
5. What factors contribute to a plant's competitiveness?

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CHAPTER 10

Methods of Weed Management and Control

FUNDAMENTAL CONCEPTS

- Weed prevention, control, eradication, and management are different concepts, and each uses and combines technologies differently.
- Prevention of invasion is the best strategy to combat weeds.
- Many important weeds in any country are escaped imports.
- Mechanical, nonmechanical, and cultural weed control techniques each have distinct advantages and disadvantages.
- No weed control method has ever been abandoned. Each new method introduced in large-scale crop culture has reduced the need for human and animal power.
- Cultural weed control is intuitively sensible.

LEARNING OBJECTIVES

- To know the definition and relative merits of weed prevention, control, eradication, and management.
- To be familiar with weed seed laws and the federal noxious weed law.
- To understand the importance of planting clean crop seed.
- To know the practices that prevent introduction and spread of weeds.
- To know the advantages and disadvantages of each mechanical, nonmechanical, and cultural weed control technique.
- To know the present role and to consider future weed management roles of living mulches and companion cropping.
- To appreciate the role of minimum and no-tillage in weed management.

I. THE DEFINITIONS OF WEED PREVENTION, CONTROL, ERADICATION, AND MANAGEMENT

When students who are taking a weed science class are asked what the class is about, they often respond "weeds" or "weed control." Those who work on weeds often spend a great deal of time on weed control, but weed science is not only about weed control. Weed scientists try to answer fundamental questions about weeds and weed management. For example, they want to know *why* weeds are problems—that is, what is the nature of weed-crop competition? Why are some weeds problems in many places and others in relatively restricted habitats? Why do different weed management strategies work differently in different cropping systems? Why are some plants so successful as weeds? Answers to these and similar questions lead to hypotheses and theories and greater clarity about what ought to be done to manage weeds and why.

A. Weed Prevention

The most difficult part of weed management is *prevention*, defined as stopping weeds from contaminating an area. It is a practical means of dealing with weeds, but it takes time and careful attention to many details. Experience has shown that it is much easier to make the case and gain support for controlling weeds. After all, if control is successful, as it frequently is, results are easily observed, and something good has happened. Prevention addresses a potential problem, one that does not yet exist, and results of preventive efforts are harder to observe and measure. It is hard to demonstrate that because of weed prevention, a weed did not appear. Science cannot prove a negative. But it is as true for the agricultural ailment, weeds, as it is for human ailments: an ounce of prevention is worth a pound of cure. Effective preventive techniques may reduce short-term economic gain.

Here are a few weed prevention measures:

- Isolating imported animals for several days
- Not importing weeds or weed seeds in animal feed (buying only clean hay)
- Using only clean crop seed that is free of weed seed
- Cleaning equipment between fields and especially between farms
- Preventing weed seed production, especially by new weeds
- Preventing vegetative spread of perennials
- Scouting for new weeds

- Small patch treatment to prevent patch expansion and large infestations
- Education about weeds (e.g., weed identification)

B. Weed Control

Weed control includes using several techniques to limit weed infestations and minimize competition. These techniques attempt to achieve a balance between cost of control and crop yield loss, but weed control is used only *after* the problem exists; it is not prevention. Weed control techniques have been adopted widely because control is the easiest thing to do, and it is usually effective. The problem is known or can be seen, and actions can be tailored to the observed problem. Control works well with short-term economic or cultural planning goals.

C. Weed Eradication

Weed eradication is the complete elimination of all live weeds, weed parts, and weed seed. It is 100% or complete control. It sounds easy, but it is very difficult to achieve, and eradication efforts have rarely been completely successful. It is usually easy to eliminate live plants because they can be seen. It is difficult to eliminate seed and vegetative reproductive parts in soil. Eradication is the best program for small populations of perennial weeds, but present technology does not make it easy.

In weed science, as in medical science, prevention is better than control, but control is required because weeds and other pests arrive without notice and are present before they can be prevented. Prevention and eradication require long-term thinking and planning.

D. Weed Management

Weed management is the combination of the techniques of prevention, eradication, and control to manage weeds in a crop, cropping system, or environment. Weed managers recognize that a field's or area's cropping history, the grower's management objectives, the available technology, financial resources, and a host of other factors must be combined to make good management decisions. Complete weed control in a crop may be the best decision in some cases, but it is not automatically assumed to be the goal. Maintenance of a weed population at some level in a cropping system may be the most easily achievable and financially wise goal for a weed management program.

II. WEED PREVENTION

People want to be and stay healthy. When we become ill, we are pleased to have competent physicians, hospitals, and medical services. People would rather remain healthy than have to cure an illness. The same logic applies to weed management. Weed control tries to cure but does not prevent weeds.

A good weed management program includes vigilance or watchfulness. The good weed manager can identify weed seeds, seedlings, and mature plants, and has a management program for each crop and field and appropriate follow-up programs. The good manager is ever watchful for new weeds that may become problems and whenever possible emphasizes prevention rather than control. Several preventive practices can be included in management programs:

1. Isolation of introduced livestock to prevent spread of weed seeds from their digestive tract.
2. Use of clean farm equipment and cleaning of itinerant equipment, including combines, cultivators, and grain trucks.
3. Cleaning irrigation water before it enters a field.
4. Mowing and other appropriate weed control practices to prevent seed production on irrigation ditch banks.
5. Inspection of imported nursery stock for weeds, seeds, and vegetative reproductive organs.
6. Inspection and cleaning of imported gravel, sand, and soil.
7. Special attention to fence lines, field edges, rights-of-way, railroads, and so on as sources of new weeds.
8. Prevention of deterioration of range and pasture to stop easy entry of invaders such as downy brome (Mack, 1981).
9. Seed dealers and grain handlers should clean crop seed and dispose of cleanings properly.
10. Cleanings should be heated or ground to prevent seed dispersal.
11. Fields should be surveyed regularly to identify new weeds.
12. When identified, small patches of new weeds should be treated to prevent growth and further dispersal.

The first rule for weed prevention and the first step of any good weed management program is the purchase and planting of clean seed. The US Federal Seed Act of 1939 regulates transport and sale of seeds in foreign and interstate (but not intrastate) commerce. The law is enforced by the US Department of Agriculture, which has provided supplementary rules aimed primarily at interstate movement of parasitic plants and noxious weed seeds. The Federal Seed Act and state laws mandate labeling of crop seed to show the kind of seed, its variety, and the state and specific locale where it was grown. Complete labels also show percent pure seed, percent weed seed, percent other crop seed, percent inert matter, percent germination of pure seed, percent hard seeds (those seeds that are viable but not capable of immediate germination), and the date on which the tests were performed. Seed labels also include the name and number per pound of each noxious weed seed.

Each US state has a noxious weed seed law that identifies and regulates sale and movement of crop seed containing what the state law has identified as noxious weed seed. These laws may prohibit importation of crop seed with greater than a certain percentage of specific noxious weed seed and require identification of each noxious weed seed. The presence of noxious weed seed in excess of 1 gm in 10 gm of the crop seed results in exclusion from sale in most states. For large-seeded crops, such as beans, the exclusion is often 1 gm in 100 gm of crop seed. These laws may also regulate import and sale of crop seed screenings because they contain viable weed seed. State seed laws are designed to protect seed consumers (farmers and other purchasers). These laws do not mean and should not be viewed as implying equal regulation of weedy plants that may be detrimental to agriculture or the environment.

On October 30, 2004, President Bush signed the Noxious Weed Control Act of 2004 (Public Law 108-412). It was passed after several years of effort as an amendment to the Federal Plant Protection Act of 2000. It is a first step, and only a bit ($15 million) of the funding requested was received. But it demonstrates the benefit of groups working together to pass federal legislation and an increasing recognition of the importance of weed management.

Seed standards are not restricted to the United States. The regulations of the Canada Seeds Act of 1987 allow various levels of weed seed to be present, depending on the crop and the level of classification desired. The standards apply to barley, buckwheat, lentils, rye, and sainfoin and with minor variation for wheat, canola, flax, and oats. The seller must supply a certificate, on request, that states the number and kinds of weed seed present.

A bushel of clover seed weighs 60 pounds and was 88% clover, with 35% germination. Therefore, in 1 bushel, there was 18.5 pounds of live clover seed, 34.3 pounds of dead clover seed, 4.2 pounds of weed seed that represented 11 different species, 2.8 pounds of inert matter, and 0.2 pounds of other crop seed. The purchased seed contained 7,800 Canada thistle seeds per bushel; 5,700 curly dock seeds per bushel; and 114,000 wild mustard seeds per bushel. This bargain seed cost $5.90 per bushel or $19.14 per 60 pounds of 100% viable seed. The same variety of certified clover seed could have been purchased for $8.40 per bushel. That bushel had 99.15% purity and 95% germination, or a cost of $8.84 per

60 pounds of 100% viable seed. The difference in cash cost ($8.40 – $5.90 per bushel) was $2.50. The cash cost is the only thing most buyers care about. The bargain seed cost $19.14 for 100% good seed versus $8.84 for 100% good seed in the second source—a difference of $10.30 per bushel in favor of the second source (Barnes and Barnes, 1960). Purchasing bargain seed or cheap seed is rarely a good idea and can create weed problems.

About one-third of US states have no limitation on total weed seed in crop seed. Limitations range from 1 to 4%. Most state laws exempt seed sold by a grower without advertising. All state laws designate certain weeds as noxious. About 20 states have no limitation on prohibited or restricted noxious weeds. Prohibited noxious weed seeds are usually seed from perennial, biennial, or annual plants that are highly detrimental to crop yield and difficult to control. The presence of these seeds in any amount prohibits sale of crop seed for planting purposes in many states.

Restricted noxious weed seeds are seeds of plants that are very objectionable in fields, lawns, or gardens but can be controlled by good cultural practices. Over 175 different species are named as noxious weed seeds by the 48 continental United States. An additional 50 species are named in Hawaii. It is important to note that these are legal, not botanical, definitions that are informed by agronomic and horticultural practice.

Most states have state seed laboratories that determine seed quality. One aspect of quality is the number of weed seed or other crop seed in a sample (Tables 10.1 and 10.2). In these examples, too many weed seeds were sown when the purchased seeds were sown. Planting clean seed is an easy method of preventing weeds.

In 1975 weed prevention took a major step forward when the federal noxious weed law empowered the secretary of the US Department of Agriculture to control import, distribution, and interstate commerce of weeds declared to be noxious. Previous laws regulated just seed, not plants.

Nearly all US states list some prohibited agricultural weeds in addition to those included in the federal noxious weed law. At present these laws provide some protection but in most states it is inadequate for agriculture and the environment. The federal law includes 93 weedy species, but at least 750 weeds that meet the act's definition remained unlisted in 1993 (US Congress, 1993). Many of these are agricultural problems, but some infest other environmental areas such as wetlands and natural areas. Invasive species are discussed in Chapter 7; four important invasive weedy species are purple loosestrife, Brazilian peppertree, Eurasian watermilfoil, and smooth cordgrass (US Congress, 1993).

TABLE 10.1. Sample Seed Analysis from Colorado State Seed Testing Laboratory.

Bromegrass, smooth—61% germination	
Seeded @ 4–6 lb/A	136,000 seeds/lb
Redroot pigweed	27,968 seeds/lb
Japanese brome	512 seeds/lb
Stinkgrass	256 seeds/lb
Barnyardgrass	64 seeds/lb
Oldfield cinquefoil	64 seeds/lb
	28,864 seeds/lb
Timothy	448 seeds/lb
Barley	64 seeds/lb
Sweetclover	64 seeds/lb
Sand dropseed	64 seeds/lb
Bentgrass	64 seeds/lb
	704 seeds/lb

TABLE 10.2. Sample Seed Analysis from Colorado State Seed Testing Laboratory.

Alfalfa,	Sample 1		
	84% germination, 84% live		
	224,000 seeds/lb	seeded at 8–10 lb/A	
		dodder	432/lb
		mallow	180/lb
		groundcherry	90/lb
At 10 lb/A 4,320 dodder and 2,240,000 alfalfa seeds will be sown per acre.			
Alfalfa,	Sample 2		
	66% germination, 84% live		
		Russian knapweed	9/lb
		Chicory	270/lb
		Netseed lambsquarters	360/lb
		Kochia	180/lb
		Buckhorn plantain	117/lb
		Other weeds	189/lb
		Other crop	
		Red clover	6,930/lb
At 10 lb seed/A, 1,478,400 alfalfa seeds, 11,250 weed seeds, and 69,300 red clover seeds will be sown/A			

TABLE 10.3. A Survey of Weed and Seed Laws in Five Western States (US Congress, 1993).

State	Number of species listed	Adequacy of protection	Number of potential threats omitted
Idaho	47	adequate	6
Oregon	67	more than adequate	few
Utah	23	inadequate	11
Washington	75	more than adequate	few
Wyoming	34	barely adequate	11

A survey of weed and seed laws in five contiguous western states—Idaho, Oregon, Utah, Washington, and Wyoming (US Congress, 1993)—showed the laws provided adequate to inadequate protection based on the likelihood of unlisted weeds causing economic or ecological problems. Many potential threatening weeds were omitted (Table 10.3).

Federal and state laws do not include enough weedy plants, and they regulate only agricultural and vegetable seed. The laws do not cover horticultural seeds, including known sources of weed seed such as wildflower and native grass mixtures (US Congress, 1993).

In spite of existing laws, regulations are not stringent, and it is not surprising that 36 weed species now resident in the United States were imported and escaped to become weeds—in some cases, noxious weeds (Williams, 1980). Of the 36, 2 were imported as herbs, 12 as hay or forage crops, and 16 as ornamentals. Weeds were imported as a windbreak (multiflora rose), for possible medicinal value (black henbane), for use in aquaria (hydrilla), as a fiber crop, just for observation, and as a dye (dyer's woad).

Bermudagrass, a valuable forage species in the southern United States and many other parts of the world, is also an important weed in many areas and was introduced into the United States as a forage crop. In 1849 the US Cotton Office proposed and introduced a new forage grass crabgrass (Brosten and Simmonds, 1989). More recent introductions of grassy weeds include sorghum-almum promoted as a drought-resistant, emergency hay/forage crop with names such as perennial sudangrass, sorghum grass, and Columbia grass. It is a hybrid between johnsongrass and grain sorghum and was first described and cultivated in Argentina (Brosten and Simmonds, 1989). Wild proso millet was first recognized as a weed in the north central United States in the early 1970s and now infests several million acres in Wisconsin and Minnesota, as far west as Colorado, in the midwestern states, and Canada. It is the same species as cultivated millet and difficult to control in corn. A major reason it is such a good weed is that its seed germinates throughout the growing season rather than in a short period, as the crop's seed do, and it thereby escapes control by nonresidual herbicides and single cultivations.

The latter two cases are interesting cases of failure to prevent and because of their implications for biotechnology. Hybridization of weeds and crops is uncontrolled and may be uncontrollable. Cross-pollination is inevitable when two phenologically similar, outcrossing plants share a small area (exist in an overlapping range). Research to determine the potential for gene transmittal, in cropped fields, from weeds to crops or vice versa is ongoing. There is a possibility that a crop that was genetically engineered for high yield or herbicide resistance will contribute to the generation of new, difficult to control weed hybrids (Brosten and Simmonds, 1989).

Two species of toadflax were introduced as ornamentals and became weeds. Jimsonweed and kochia were brought to the United States for use as ornamentals, and kochia was studied as a forage crop. The artichoke thistle escaped to become a weed in artichokes and is a recurring problem in California (Brosten and Simmonds, 1989).

Waterhyacinth was introduced from South America to the United States by Japanese entrepreneurs as part of a horticultural exhibit at the Cotton Centennial Exposition in New Orleans in 1884 (Penfound and Earle, 1948). It originally came from the Orinoco River in Venezuela, and single plants were given away at the Cotton Exposition. It has been introduced around the world primarily because its flowers are pretty. At the New Orleans exposition, people liked it so much that they took it home and put it in ponds and gardens, after which it escaped because people discarded it or water flowed out of these places and carried the weed with it. It reproduced profusely in ponds and escaped to the St. John's River in Florida, where it became a major weed problem by clogging the waterway. Waterhyacinth was brought to the Tonkin region of China (now Vietnam) in 1902 as an ornamental. It reached southern China and Hong Kong in the same year. Soon after it was observed in Sri Lanka and then India, where the sluggish rivers of east Bengal were ideal for its growth. In the 1950s it was discovered in Africa (Vietmeyer, 1975), and in 1958 it had infested over 1,000 miles of the Nile River from Juba in the south to the Jebel Aulia dam in northern Sudan (Heinen and Ahmad, 1964). It is a serious weed problem in all of these places and many others but not in Venezuela, where its spread is controlled by natural enemies.

Cogongrass or Alang-Alang, a perennial, was introduced at Grand Bay, Alabama, and McNeil, Mississippi (Tabor, 1952). Bare-root orange plants were imported to Grand Bay in 1912, and the cogongrass that lined boxes the plants were shipped in was discarded. In McNeil, scientists were searching for better forage plants, and cogongrass escaped from farmer's fields and the experiment station and spread rapidly.

Kudzu, a nonindigenous species, was introduced to the United States at the Philadelphia Centennial Exposition in 1876 (Shurtleff and Aoyagi, 1977). It was promoted by the US Department of Agriculture for erosion control and forage, but it became a major weed and now grows in many areas throughout southeastern United States and has spread to some midwestern states.

Further evidence of distribution of the world's weeds and the necessity for vigilance to prevent introduction of new species is shown in Table 10.4. Most

TABLE 10.4. Origin and Distribution of Some of the World's Most Serious Weeds (Holm et al., 1977).

Weed	Origin	Distribution (number of countries)	Associated crops
Purple nutsedge	India	92	52
Bermudagrass	Africa or Indo-Malaysia	80	40
Barnyardgrass	Europe and India	61	36
Junglerice	India	60	35
Goosegrass	China, India, Japan, Malaysia	60	36
Johnsongrass	Mediterranean	63	30
Cogongrass	Old world	75	35
Spiny amaranth	Tropical America	54	28
Sour paspalum	Tropical America	30	25
Tropic ageratum	Tropical America	46	36
Itchgrass	India	28	18
Carpetgrass	Tropical America	27	13
Hairy beggarticks	Tropical America	40	31
Paragrass	Tropical Africa	34	23
	Mexico, West India, tropical South America	23	13
Smallflower umbrella sedge	Old world tropics	46	1
Rice flatsedge	Old world tropics	22	17
Crowfootgrass	Old world tropics	45	19
Eclipta	Asia	35	17
Globe fringerush	Tropical America	21	(rice)
Witchweed	Europe or South America	35	2
Halogeton	Asia	unk.	rangeland
Russian knapweed	Asia	unk.	>10
Quackgrass	Eurasia	>80	many

of our important weeds have come from somewhere else, and vigilance is necessary to prevent new problems. Among 300 nonindigenous weeds in the western United States, 8 were former crops, and 28 escaped from horticultural areas (US Congress, 1993).

All is not lost because weed entry is not prevented. Most imported plants don't become weeds. In the United Kingdom about 10% of the invaders became established but only 1% of those became weeds (Williamsen and Brown, 1986). In Australia only 5% of introduced plants became naturalized and only 1 to 2% of those became weeds (Groves, 1986). Once a plant is naturalized in an area, whether it remains insignificant or becomes a weed problem depends on the absence of damaging natural enemies and the presence of suitable soil, crops, land use and weed management practices, and how the plant responds to the local climate (Panetta and Mitchell, 1991). The few that become weeds can be costly problems. Although the chance is small, the consequences can be great. We can identify areas at risk of invasion, but weediness cannot be predicted as easily (Panetta and Mitchell, 1991).

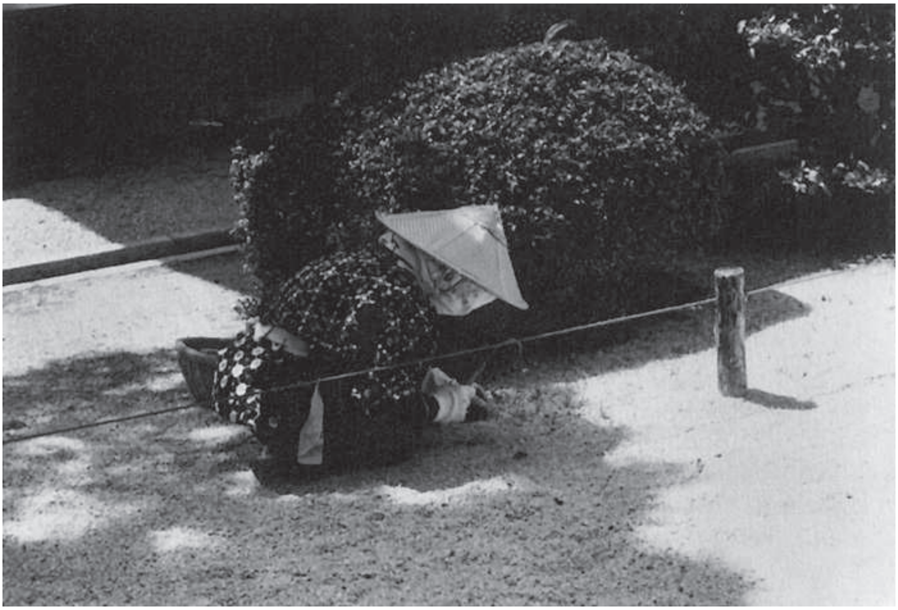
III. MECHANICAL CONTROL

No weed control method has ever been abandoned completely. New techniques have been added in large-scale agriculture, but old ones are still used effectively, especially in small-scale agriculture. Mechanical weed control methods have a long history. They are a primary weed control method in many crops and in many of the world's developing countries. Although they have been used widely, they have not been studied extensively. Improvement of mechanical methods of weed control is required if they are to become acceptable alternatives to chemical control. This is especially true in organic agriculture where chemical control is forbidden and hand-weeding, if hand labor is available, is expensive, arduous, and often not effective because it is delayed. Mechanical control of intrarow weeds is often unsuccessful for the following reasons:

1. Cultivation is delayed and weeds are only susceptible to uprooting and subsequent drying in early growth stage.
2. Achieving crop-weed selectivity is difficult in early crop growth stages.
3. The weed response to mechanical damage is highly dependent on weather conditions after cultivation (Kurstjens et al., 2004).

Mechanical weed control is also expensive due to the time required, the cost of equipment, and the cost of fuel. Successful mechanical weed control nearly always requires more trips over the field than chemical control, precise timing, and favorable subsequent weather. More knowledge of the weed and crop is required by the farmer. In other words, to be successful with mechanical control, farmers must rely more on skill and planning to get the timing right and to select the proper mechanical tool (Kurstjens et al., 2004) than is required with what many refer to as the brute force of chemical control.

A. Hand-Pulling



Hand-pulling weeds on the grounds of the Imperial Palace, Kyoto, Japan.

Hand-pulling is practical and efficient, especially in gardens, but it is hard work. It's very effective for annual weeds but not for perennials capable of vegetative reproduction because shoots separate from roots that then produce a new shoot. A disadvantage is that hand-pulling doesn't get the job done when it's most needed. Most of us are too busy or too lazy to go out and weed before weeds become obvious. By the time they become obvious, easy to grab, and pull, yield reduction due to weed competition has occurred.

B. Hand-Hoeing

For the home or small plot grower, unwanted, plants-out-of-place (sigh, *weeds*) are a continuing challenge, especially when situations (my small garden),

Hand-hoeing weeds in rice in the Philippines.

attitudes, or other reasons dictate that herbicides should not be used. The best weeding, then, is an integration of cultural tactics with arduous (i.e., no fun at all), sweat-inducing, manual control that may be complemented by mechanical control with an array of hoes, weed diggers, weed pullers, weed twisters, weed poppers, weed whips, weed hooks, and others. A novel website, http://www.ergonica.com/ergonica_frame.htm?weeder_features.htm&1, can aid those who must sweat as they decide whether to consider circle hoes, push-pull weeders, serrated-edge hoes, oscillating hoes, or even traditional hoes. A chart compares physical descriptions, dimensions, and user accounts of operating performance for the likes of the Angle Weeder, Weed Hound, Weed Claw, Weed Eezy, Uproot Weeder, Weed Ninja, Weed-Ho, and the Speedy Weedy. I still use my trusty, usually dull but not rusty, old hoe that is stored in the pump shed. It keeps my garden fairly clean and me fairly well exercised.

Hand-hoeing has been used for weed control for many years. It is still the method of choice for most gardens and ornamental plantings and is used regularly in many vegetable crops, although California became the first US state to ban weeding of commercial crops by hand in 2004.[1] Hand-hoeing controls the

[1]Olsen, M. 2004. The end of weeding. E-mail from postmaster@metrofarm.com; accessed September 30, 2004.

TABLE 10.5. Time Required for Hand-Weeding.

Crop	Location	Hours per hectare to hand-weed
Soybeans	Peru	360 if 6 hour day
Transplanted tomatoes	Ohio, US	71 after herbicide, 133 after cultivation
Corn	Zimbabwe	24–48 for 6 hour day
Beans	Wyoming, US	4.4–15.5 after broadcast herbicide, 32 if no herbicide
Sugarbeet	Washington, US	2–111 after broadcast herbicide, 141 without herbicide
Vegetables	California, US	10 after broadcast herbicide
Rice	Several	16–500 depending on location and rice culture
Wheat		101
Sorghum		50
Millet		88–298
Cotton		50–700
Jute		140
Groundnut		102–293
Cassava		115–1069

Source: Newsletter. 1979. *Int. Weed Sci. Soc.* 4(1).

most persistent perennials if it's done often enough, although it may take years to achieve complete control. Although efficient and widely used, it takes a lot of time and human energy. Some data on the time required to hand-weed some crops in several different places are shown in Table 10.5. If human labor is abundant, and labor cost is not high, hand-pulling or hoeing is an acceptable but arduous method of weed control. If human labor is not abundant and it is expensive, hand methods are cost-prohibitive and not efficient.

C. TILLAGE

When most people think of mechanical control, the first thing that comes to mind is tillage with an implement to disturb, cultivate, or mix the soil. On arable land, tillage alone or in combination with cropping or chemical treatment may be the most economical system of weed control. Tillage turns under crop residue, conditions soil, and facilitates drainage. It controls weeds by burying them, separating shoots from roots, stimulating germination of dormant seeds and buds (to be controlled by another tillage), desiccating shoots, and exhausting carbohydrate reserves of perennial weeds.

Other reasons for tillage include breaking up compacted soil, soil aeration, seed bed preparation, trash incorporation, and intrarow cultivation in a crop. All of these are important, but the main accomplishment of most tillage done in the world's developed countries is weed control. The advent of no-till farming and minimum-till farming has shown that tillage is not essential to grow crops and may do no more than control weeds. Too frequent tillage can increase soil compaction—a disadvantage. Other disadvantages include exposure of soil to erosion, moisture loss, and stimulation of weed growth by encouraging germination of dormant seeds and vegetative buds. In some soils, without tillage, soil can crust, and there will be poor water penetration. Decisions about the role of tillage must be made for each soil type and farming system.

Cultivating for weed control in beans.

Tillage is usually divided into primary and secondary. Primary tillage is initial soil breaking or disturbance. The depth varies from at least 6 (except where primitive tools are used with limited animal power) to as much as 24 inches. Primary tillage implements include moldboard and chisel plows. These cut and invert soil and bury plant and other surface residue. Primary tillage is often the first step of seedbed preparation. It was made possible by Jethro Tull's (1774–1834) invention of a cast iron plow in England in 1819. That was followed by a steel-blade plowshare introduced by John Lane in England in 1833. John Deere (1804–1886) introduced the first steel moldboard plow in the United States in 1837. The moldboard plow may have been the most important invention of the era. It lifted and inverted soil and greatly expanded the ability of a farmer to till more land. Its invention came at a time when the English were never far from starvation and, quite literally, saved humanity (Faulkner, 1943). Farmers had trouble then, as they still do, keeping unwanted plants from growing in their crops. Plowing, because it buried plants and debris, gave the farmer time to get the crop up before the weeds appeared. Agricultural scientists welcomed the plow, without question, for its crop production and weed control benefits. They developed what Faulkner (1943, p. 53) called "an unquestioning reverence for the plow." Only later were the disadvantages of the plow and the intensive tillage it enabled recognized. The advantages of plowing were clear but few realized that each plowing buried weed seeds for future recovery and germination (Faulkner, 1943, p. 151).

Secondary tillage implements may be subsequent to primary tillage, or they may be the first tillage operation. Soil is disturbed, often vigorously, but upper layers are usually not inverted. A wide selection of tools is available (see Kurstjens et al., 2004). Secondary tillage is fast, inexpensive, and its tools are appropriate for large areas. Secondary tillage implements have been used for a long time; the first revolving disk harrow was invented in 1847. Tools available to modern farmers include the double disk, several kinds of harrows, torsion and finger weeders, field cultivator, rotary hoes, vertical row brushes, spring tooth harrows, rototillers, rod-weeders, and the cultipacker (combination of harrow and roller). This diverse group of implements tills soil from a few inches to a maximum of 5 or 6 inches. Secondary tillage implements break clods and firm soil as they remove weeds. Many regard secondary tillage implements as both weed control and seedbed preparation tools.

Primary and secondary tillage is followed, in many row-crops, by selective inter-row cultivation. Tractor-mounted cultivators or animal-drawn implements move soil between crop rows to loosen it and control weeds. In general, inter-row tillage is just that: It works between crop rows. Some implements prepare inter-row areas for furrow irrigation (water runs down furrows between crop rows). Implements used for inter-row cultivation include a wide range of tine (long, fingerlike rods) and flared or straight steel shovel-like tools at the end of solid or flexible (flat, steel) shanks that travel through soil at shallow depths (1–2 inches). They break soil crusts and facilitate irrigation, but their main purpose is weed control.

Research (Schweizer et al., 1992; VanGessel et al., 1995) has shown that, in corn, intrarow cultivators require early-season weed control (cultivation or herbicide) for optimum efficacy. Intrarow cultivators are more efficient

Most disking accomplishes weed control *and* seedbed preparation. (Courtesy of Deere and Co., Moline, Illinois.)

Plowing is used to prepare land for planting *and* it controls weeds. (Courtesy of Deere and Co., Moline, Illinois.)

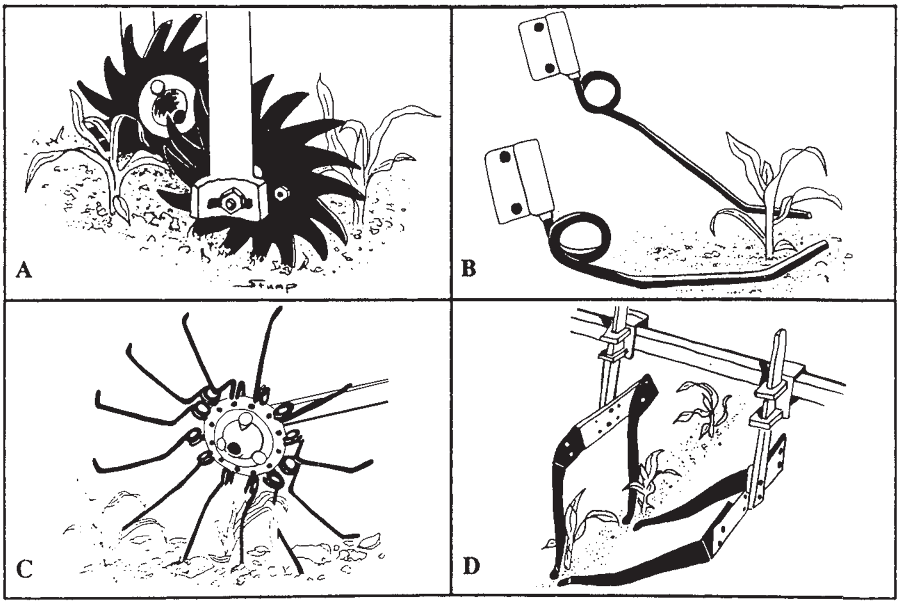


FIGURE 10.1. Types of tlllage implements used for in-row cultivation (Schweizer et al., 1984). Reproduced with permission.

(control more weeds) that inter-row cultivators. Without herbicides, weeds in corn were always controlled better by an in-row cultivator than by the standard inter-row cultivator when each operation was performed at the right time. In-row cultivators have special tools (Figure 10.1 shows some examples) that disturb soil around crop plants and uproot weeds in rows. The tools include spyders (toothed disks that move soil toward or away from crop rows) and torsion and spring hoe weeders that flex vertically and horizontally to uproot weeds in crop rows. Spinners displace weeds in crop rows. Standard inter-row crop cultivators are most effective on weeds 15 cm or shorter. Inter-row cultivators are most effective on weeds less than 6 cm tall (Schweizer et al., 1992). These cultivators do not work well in row crops when weed density is high.

There are situations where plowing and subsequent tillage do not prepare land for planting. These include land that is heavily infested with perennial sod-forming grasses, a situation often encountered in developing country agriculture. Many tillage implements give inadequate results in the crop row after the crop has emerged and begun to grow. Tillage between rows is efficient and can be done to within a few inches of crop plants. Tillage is not as efficient in the crop row except when soil is moved and weeds are buried. To maximize tillage benefits, uniform spacing of crop rows, straight rows achieved by precision planting, gauge wheels, and instrument depth guides are needed. Uneven stands and driver error often lead to damage from mechanical cultivation and destruction of some crop plants.

Successful weed control with tillage is determined by biological factors:

1. How closely weeds resemble the crop. Weeds that share a crop's growth habit and time of emergence may be the most difficult to control with tillage, especially when they grow in crop rows. Weeds that emerge earlier or later than the crop are often easier to control.
2. If a weed's seeds have a short, specific period of germination, it is easier to control them by tillage as opposed to those whose seeds germinate over a long time.
3. Perennial weeds that reproduce vegetatively are particularly difficult to control with tillage alone.

Successful mechanical control of weeds is also determined by human factors. Gunsolus (1990) noted that science could explain why certain weed management practices work the way they do. Science develops basic principles to guide action. Human cultural knowledge is different from scientific knowledge, although each may work toward the end of good weed management. Cultural knowledge tells one when and how to do something on a given soil and farm. Tillage is a cultural practice, and therefore, by definition, it requires cultural knowledge. It requires the mind of a good farmer who knows the land. Successful mechanical control requires managerial skill (cultural knowledge) that cannot be acquired from scientific knowledge. Cultural knowledge is acquired by doing and by observing those who have done things well. Cultural knowledge is the art of farming whereby one knows how to select and apply scientific knowledge to solve problems. Successful mechanical control of weeds, regardless of the implement used, is always related to the timeliness of the operation. Research can determine when to do something, but knowing when to act on a particular farm is part of the cultural knowledge good farmers have.

For example, a three-year study in Pennsylvania showed that corn yields did not differ among no-till, zone-till (surface tillage in narrow rows where corn is to be planted), strip-till (deep tillage in the row where corn is to be grown), and full tillage (chisel plowing followed by disking) (Duiker et al., 2006). The study recommended farmers use no-tillage because it saved fuel, reduced soil erosion, and improved soil and water quality. Cultural knowledge will determine whether farmers will adopt the recommended no-till practices. The scientific knowledge of what is possible will be combined with the cultural knowledge of what should be done on a piece of land.

The operative principle for use of tillage for control of perennial weeds (number 3 in the preceding list) is carbohydrate depletion. The vegetative reproductive system of perennial weeds is a carbohydrate storehouse. When shoots grow and photosynthesize, eventually the storehouse will be replenished. If shoots are cut off, the plant calls on its reserve to create new growth. When tillage is done frequently, the management assumption is that reserves will be depleted and plants will die because of exhaustion of root reserves and increased susceptibility to other stresses (e.g., frost or dryness). Unfortunately, root reserves are vast and outlast human patience and time. Tillage may have to be so frequent that crops cannot be grown. If tillage and destruction of foliage are delayed from a few days to up to a week after emergence, the greatest depletion of root reserves occurs. With most perennial weeds, the great majority of roots and vegetative buds are in the top 6 to 12 inches of soil. Tillage done when a crop is growing cannot go this deep without disturbing crop roots—a disadvantage for control of perennial weeds.

Early research showed that if field bindweed was tilled 12 days after it first emerged, 16 successive tillage operations at approximately 12-day intervals were required to approach eradication. If it was tilled immediately after emergence, about twice as many tillage operations were needed. The efficacy and impracticality of tillage are also illustrated by a 1938 study that showed that purple nutsedge could be controlled in Alabama by disking at weekly or biweekly intervals for 5 months (Smith and Mayton, 1938). Obviously no crop can be grown during the 5 months. Buhler et al. (1994) demonstrated over 14 years that greater and more diverse populations of perennial weeds developed in reduced-tillage systems than on areas that were moldboard plowed. Practices used to control annual weeds and environmental factors interacted with tillage to regulate (but not eliminate) perennial weeds.

It is often thought, incorrectly, that as long as one tills, it doesn't depend on how or when it is done as long as the weed is there to be controlled (Schweizer and Zimdahl, 1984). Studies were established in a field where corn had been grown continuously for 6 years. Half of the plots received regular chemical weed control each year, while the other half had herbicides for the first 3 years, then no herbicide, and only cultivation for the last 3 years. Plots that received herbicide for 3 years also received optimum supplemental weed management including cultivation in each of the 6 years. In the plots with herbicide for the first 3 years but only cultivation thereafter, redroot pigweed dominated. At the end of the 6-year experiment, the field was divided in half; one-half was plowed in January and disked in April prior to normal spring planting, and the other half was disked in January and again in April prior to normal spring planting. More redroot pigweed emerged when the field was disked in the fall than when it was plowed. Where herbicide and optimum weed management had occurred for 6 years, almost no redroot pigweed survived to produce seeds for the last 3 years of the study, and tillage did not make any difference in the redroot pigweed population in the 7th year (see Figure 10.2). Smith (2006) working in Michigan demonstrated the importance

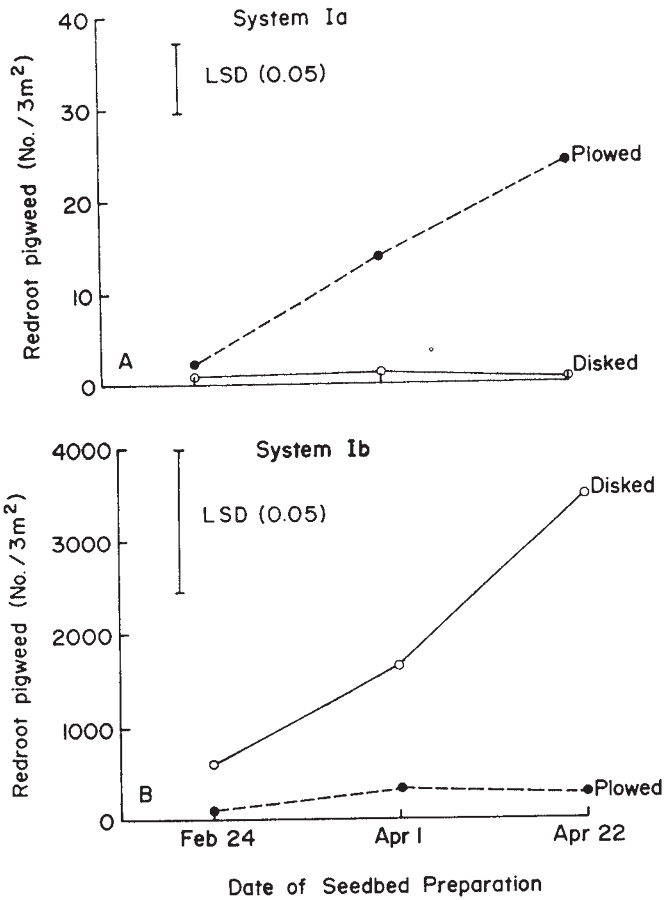


FIGURE 10.2. Population of redroot pigweed seedlings following several conventional tillage practices and atrazine use in continuous corn. In weed management system Ia, 2.2 kg/ha of atrazine was applied preemergence for 6 consecutive years. In weed management system Ib, the same rate of atrazine was applied for the first 3 years and discontinued thereafter. In the fall one-half of each system Ia and Ib plot was plowed (hatched line) and the other half disked (solid line) (Schweizer and Zimdahl, 1984).

of tillage timing. Spring tillage led to weed communities dominated by spring annual forbs and C_4 grasses, whereas fall tillage created communities dominated by later-emerging forbs and C_3 grasses. The traits that determined species' susceptibility to tillage included the seed germination process and the plant's life cycle, which influence how a species responds to changes in soil resources and light availability that are related to the seasonal disturbance regime (the tillage).

Disking soil (secondary tillage) in plots that had only cultivation for 3 years enhanced germination of seeds on the soil surface by bringing them nearer the surface. Plowing (primary tillage) buried seeds. Therefore, in the experiment, if weed control has not been good, disking instead of plowing made the weed problem worse. If weed control had been good, the kind and time of tillage didn't matter (Schweizer and Zimdahl, 1984).

Another example of the importance of tillage timing is from land to be planted to wheat in North Dakota (Donald, 1990). Moldboard plowing 18–20 cm or chisel plowing 9–15 cm deep in the fall (primary tillage) followed by a combined field cultivator-harrow in spring (secondary tillage) controlled established foxtail barley on previously untilled sites. Foxtail barley is a problem only in no-till spring wheat and other spring sown no-till crops in the northern Great Plains. Often it could be managed by changing tillage practices (e.g., rotating from no-till to primary tillage). If land was chisel-plowed in spring and then harrowed, the weed was not controlled (Donald, 1990).

Research to determine the influence of the type of tillage implement and the timing of tillage leads to understanding how land management and weed control may actually create weed problems. Roberts and Stokes (1965) showed that plowing distributes weed seeds throughout the plow layer. Rotary cultivation leaves 50% of weed seeds in the top 3 inches and 80% in the top 6 inches, where they germinate best. Regardless of the type of cultivation, between 3 and 6% of the viable weed seeds in the top 10 cm of soil can be expected to produce seedlings after cultivation (Roberts, 1963; Roberts and Ricketts, 1979). Thus, one concludes that tillage can create more weeds to control.

Spring soil disturbance reduced seedling emergence of large crabgrass, giant foxtail, smooth pigweed, and common ragweed by 1.4 to 2.6 times, but emergence of eastern black nightshade and velvetleaf was unaffected by spring soil cultivation (Myers et al., 2005). The same study showed that the influence of soil disturbance on yellow foxtail and common lambsquarters varied between seasons and location. One must conclude that the type of tillage implement and tillage timing can determine the weed problem. But the effect of tillage is also determined by the weeds present and the time of year tillage is done. One longs for precise generalizations, but weed management is too complex for simple rules.

In a rare study of tillage over time, Wicks (1971) grew winter wheat annually for 12 years and studied the effect of a sweep plow, one-way disk, and moldboard plowing (all primary tillage implements) after harvest on downy brome. The moldboard plow eliminated the downy brome population after 12 years compared to 94 plants per square meter for sweep plowing and 24 for the one-way disk. Sweep plows do not bury seed as deeply as moldboard plows. The moldboard buries seed that germinate but cannot emerge. Spread of downy brome is hastened by changing from spring to winter wheat because land is then plowed and prepared for seeding at exactly the right time for the winter annual life cycle of downy brome (McCarty, 1982).

The same kind of evidence about the effects of timing and type of tillage is found in several farming systems. Evidence from rice culture shows that the method and timing of land preparation influenced the subsequent weed population. In fields where tractor plowing during the dry season was followed by two harrowings in the wet season, junglerice was over 85% of the weed population in rice, and purple nutsedge was negligible. In the same region, where two plowings and two harrowings occurred in the wet season, junglerice was virtually nonexistent, and purple nutsedge was the dominant weed (Pablico and Moody, 1984).

Annual grass weeds are likely to remain a problem with use of minimum cultivation in cereal production, particularly when early planting is practiced (Froud-Williams et al., 1981). Other, previously unimportant, weeds became more prevalent, especially weedy species of brome in winter cereals in the United Kingdom. Buhler and Oplinger (1990) working with spring-sown crops in the United States showed that common lambsquarters' density was not influenced by tillage method, but redroot pigweed density was usually higher in chisel plow systems prior to planting soybeans. Moldboard plowing (primary tillage) followed by cultipacking (secondary tillage) always had greater densities of velvetleaf than no-till, and no-till always had more foxtail than plowing. Giant foxtail and redroot pigweed became more difficult to control when tillage was reduced, whereas velvetleaf was less of a problem.

Growers need to be aware of the effect of tillage type and timing on weed populations and, whenever possible, choose a system that contributes to weed control. That is good management, and the integration of techniques will follow. Reduced cultivation encourages establishment of wind-disseminated species, and annual broadleaved species decline. In corn, green foxtail density was greater in chisel plow and no-till systems than with moldboard plowing, and ridge tillage had lower green foxtail density than all other systems (Buhler, 1992). Common lambsquarters' density was nearly 500 plants per square meter after chisel plowing, whereas it was only 75 in other tillage systems. Redroot pigweed responded differently to tillage with average densities of 307 and 245 plants per square meter after no-tillage and chisel plowing versus only 25 plants per square meter after moldboard plowing or ridge tillage. Weed populations were affected by tillage, but corn yield was not.

Many weed seeds require light to stimulate germination (see Chapter 5). Weed scientists have asked if germination could be reduced if soil tillage or cultivation was done at night. In Oregon's Willamette Valley, cultivating agricultural land during the day increased germination 70 to 400% above levels found after nighttime tillage (Scopel et al., 1994). The effect was attributed to the light seeds are exposed to during tillage. Buhler and Kohler (1994) showed that tilling soil in absolute darkness can reduce germination of some weed species up to 70%. Night tillage is most effective against small broadleaved species such as pigweed, smartweed, ragweed, nightshade, wild mustard, and common lambsquarters. It is not effective to reduce germination of foxtail or barnyardgrass, and it has no effect on large-seeded broadleaved weeds such as velvetleaf, giant ragweed, and cocklebur. Hartmann and Nezadal (1990) were the first to report, after 7 years of study, that tillage between 1 hour after sunset and 1 hour before sunrise reduced weed emergence as much as 80% compared to day tillage. They saw night tillage as a way to manipulate and control weed populations on a purely cultural basis. They also advocated daytime tillage to photostimulate germination of dormant weeds seeds with the goal of diminishing the soil seed bank. They recommended that early primary tillage (plowing) should be carried out in full sunlight to encourage seed germination. Secondary tillage to prepare the seed bed should be done after dark to destroy emerged seedlings and not encourage germination of seeds. However, do not become too enamored of this idea. While it is true that exposure to light favors germination of many weed seeds, some are light insensitive. Light is only one of many environmental factors that affect weed seed germination. Regulating light exposure will favor management of some weeds and enhance chances for success of others. In weed management, absolute rules are hard to find.

When undisturbed in soil, most light-sensitive seeds are not photoinduced to germinate by light penetration below 1 cm. Germination stimulation comes from brief (a few seconds or less) exposure to light during soil disturbance in daylight. This observation is consistent with early work by Wesson and Wareing (1969), who showed weed seed germination was dependent on exposure of seeds to light during soil disturbance. Most weed seeds germinated within 2 weeks after exposure to light. They also demonstrated that stirring soil for 90 seconds in bright light increased weed seed germination up to 60%.

Minimum or no-tillage agriculture is practiced for many reasons, including economic ones, and a desire to reduce soil erosion. As just emphasized, tillage, including minimum or no-tillage, affects the weed population. Any method of weed control that minimizes tillage is potentially of benefit to soil structure. The data in Table 10.6 on ecofarming encourage minimum tillage for production of crops grown under low rainfall conditions. The point is that minimum tillage wheat and minimum tillage grain sorghum yield as well and frequently have lower production costs than more intensive tillage systems. Minimum tillage, nonirrigated corn does not yield what irrigated corn does, but production costs are lower.

In vegetable fields in California, reduced tillage compared to conventional (more vigorous) tillage increased the density of shepherd's-purse in the top

TABLE 10.6. Yield and Production Costs for Different Cropping Systems in Southwest Nebraska (Klein, 1988).

Crop	Tillage	Average yield (bu/A)	Production cost ($/bu)
Wheat	clean fallow	37	3.88
Wheat	stubble mulch	43	3.44
Wheat	ecofallow-reduced tillage	45	3.30
Sorghum	conventional	40	3.09
Sorghum	ecofallow-reduced tillage	65	2.42
Corn	conventional tillage with center-pivot irrigation	140	2.59
Corn	ecofallow-reduced tillage	65	2.52

15 cm of soil (Fennimore and Jackson, 2003). Shepherd's-purse emergence and soil seed bank densities were always lower in plots that had been organically amended (cover crops and compost). The authors suggested that organic matter additions may lead to reduced weed emergence.

The extent of use and weed control implications of no- or minimum-tillage have been reviewed for developing countries (Akobundu, 1982; Buckley, 1980). It has been shown that these systems rely on herbicides and may complicate soil management due to presence of crop residues. With an abundance of weed seed in soil, the best approach may be to use minimum or no-tillage and let natural factors deplete the population of buried seed. If weed control fails one year and the soil weed seed bank has been depleted, the best strategy will be to plow deeply and then use minimal tillage thereafter (Mohler, 1993). In the first year after minimum tillage begins, no tillage will have more seedlings than tillage, but in subsequent years, fewer weed seedlings will emerge unless dormancy is high or there is good survival of seed near the soil surface (Mohler, 1993).

There are important advantages to minimum and no-tillage (Phillips, 1979):

1. Soil erosion is reduced. (A primary disadvantage of tillage is the possibility of increased erosion.)
2. Because of reduced erosion, land subject to erosion can be used more intensively.
3. Reducing tillage saves energy.
4. There is less compaction with decreased travel over soil.
5. Because land is continually covered, soil moisture is not as limiting as it can be on bare soil.

6. Irrigation requirements are lower because post-tillage evaporation of soil moisture is reduced.
7. Less horsepower is required for land preparation and machinery costs can be reduced.

It is generally agreed that reduction or absence of tillage increases problems with perennial weeds. Tillage may increase or decrease weed seedling density (Mohler, 1993). Some studies have found more seedlings in tilled plots, and others have found more without tillage. The effects of tillage vary between species, season, and locations.

Froud-Williams et al. (1981) reviewed changes in weed flora associated with reduced tillage systems. They found several studies where perennial monocot and dicot species increased in the absence of tillage. They suggested that perennial monocot weeds with rhizomes or stolons would be the greatest threat to successful adoption of reduced tillage systems. Murphy et al. (2006) found over 6 years that tillage systems had a major effect on weed diversity and density. No-tillage promoted the highest (20 species), and moldboard plowing the lowest weed diversity. Chisel plowing was intermediate. The soil seed bank declined from 41,000 seeds per cubic meter of soil to 8,000 over 6 years under no-tillage. Crop yield was not affected by the tillage system.

There are equally important disadvantages to reducing or eliminating tillage (Akobundu, 1982):

1. Average soil temperature is lower, and this may delay spring planting and subsequent crop emergence.
2. Insect and disease problems may increase because plant residues on the soil surface provide a good environment for insects and disease pathogens (Musick and Beasley, 1978; Suryatna, 1976).
3. A greater degree of farm managerial skill may be required because:
    a. Fertilizer requirements and application techniques must be changed.
    b. Crop establishment may be more difficult because of surface residue.
    c. Irrigation systems may have to be modified.
    d. Weed control is essential but as species change methods must change.
    e. The variety of available herbicides is not great.

Disadvantages have not deterred growers from learning required skills and shifting to no- or minimum-tillage. In the United States, no-till acreage increased from 10.6 to 32.9 million acres from 1972 to 1980 (Triplett, 1982) and continued to grow. Triplett (1982) suggested that 80% of US crop acreage would be planted using some form of reduced tillage and 50% of the acreage will be no-tillage.

Seed burial studies (see Chapter 5) support the contention that the shift to minimum- or no-tillage systems of crop production will not eliminate the need for weed management. The need will continue, but the weeds to be managed will change as tillage systems change. Data from seed burial studies show that as tillage is reduced, biennial weeds invade cropland, partially because their seeds survive longer when buried (Burnside et al., 1996). Other annuals, adapted to no-till, will appear in cropping systems. Federal farm programs promote conservation tillage and require maintenance of plant and residue cover on the soil surface to reduce wind and water erosion.

D. MOWING

Mowing to remove shoot growth prevents seed production and may deplete root reserves on some upright perennials. If repeated often enough, it can be used to control upright perennials in turf. Prostrate perennials such as field bindweed and dandelion survive mowing.

Mowing followed by application of 3.3 kg/ha of glyphosate to resprouting perennial pepperweed can enhance the weed's control (Renz and DiTomaso, 1998). A similar technique has been successful for control of other perennial weeds. Renz and DiTomasso (2004) proposed that the technique was successful because mowing changed the canopy structure of perennial pepperweed and there was greater deposition of the herbicide on basal leaves with subsequent increased translocation to roots. "The delay between mowing and resprouting synchronized maximal belowground translocation rates with herbicide application timing." Brecke et al. (2005) showed similar results for a similar reason for control of purple nutsedge with herbicides.

To maximize mowing's benefits, it must be done before viable seeds have been produced. Weeds should be cut in the bud stage or earlier. Table 10.7 shows the percentage of germinable seeds produced at various stages of maturity.

Mowing is a useful technique but rarely accomplishes much weed control because it is done late. It removes unsightly growth and, if done at the right time, can prevent seed production, which is important in control of annuals and biennials. Its effectiveness for control of the biennial musk thistle is shown in Table 10.8.

The foregoing deals with mowing performed to control weeds or clean up an area. Mowing is a normal cultural operation for some crops (e.g., turfgrass and hay) and is properly regarded as a potential weed management technique rather than solely a necessary part of producing the crop. Norris and Ayres (1991) showed that cutting interval (but not irrigation timing after cutting) affected yellow foxtail biomass in alfalfa and alfalfa yield. Percent yellow foxtail ground cover was greatest after a 25 day cutting interval and least after a 37 day interval (Figure 10.3). Yellow foxtail biomass was also greatest for the

TABLE 10.7. Germination of Weed Seeds from Plants at Three Stages of Maturity (Gill, 1938).

	Cut		
Weed in bud	Flowering	Medium Ripe	Ripe
Annual sowthistle	0	100	100
Canada thistle	0	0	38
Cat's ear, spotted	0	0	90
Common chickweed	0	56	60
Common groundsel	0	100	100
Curly dock	0	88	84
Dandelion	0	0	91
Meadow barley	0	90	94
Shepherd's-purse	0	82	88
Soft brome	0	18	96
Corn speedwell	0	69	70

TABLE 10.8. Seed Production by Musk Thistle (McCarty, 1982).

Time of harvest	Seeds/plant
Full bloom	26
+2 days	72
+4 days	774
Mature plant	3,580

short cutting interval and least for the longest interval. In the 3 years of the study, the 37-day cutting interval always had a higher yield than the 31- or 25-day interval (Table 10.9), thus demonstrating the utility of mowing for weed management.

E. Flooding, Salt Water, Draining, and Chaining

These techniques cause ecological change. If a normally dry area is flooded or a normally wet area is drained, ecological relationships are changed, and weed species will change. The techniques are effective only when an area is immersed or drained for 3 to 8 weeks. Immersion, an anaerobic treatment, is

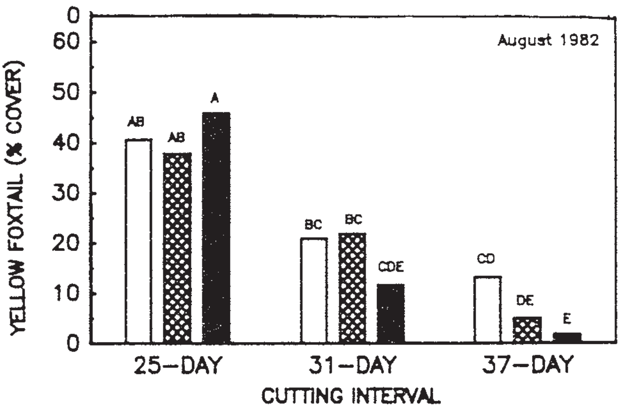


FIGURE 10.3. Percent yellow foxtail cover in relation to cutting frequency and duration of irrigation delay following cutting. Columns with different letters are different at P = 0.05 according to the LSD (Norris and Ayres, 1991).

TABLE 10.9. Alfalfa Dry Matter Yield in Relation to Cutting Interval (Norris and Ayres, 1991).

	Alfalfa yield tons / acre with different cutting intervals (days)		
Year	25	31	37
1	10.0	12.8	14.9
2	15.0	21.7	24.0
3	11.0	16.2	20.0

not equally effective on all weeds; lowland or paddy rice fields have weeds such as barnyardgrass and junglerice that survive flooded conditions of the rice paddy as well as rice does. Flooding does not eliminate all weed problems, just some of them, and it creates an environment where other weeds succeed. Weeds found in lowland rice are generally different from those found in upland rice. Purple nutsedge occurs in both systems. Flooding will control established perennials such as silverleaf nightshade, camelthorn, and the knapweeds in arid areas, but the expense of creating dikes and obtaining water make the practice economically unfeasible (Slife, 1981).

Reestablishment of natural flooding in the southwestern United States may be useful as a way to reestablish native cottonwoods. Flooding can be risky because some invasive species such as tamarisk (tamarix) can also be encouraged. Research by Sher et al. (2000) demonstrated that because native cottonwoods were larger and had superior competitive ability, they dominated when historical flooding regimes were restored, even in the presence of an invader like tamarisk that responds well to disturbance.

Ocean water with its salt content has been shown to be an effective method to control mimosa-vine and large crabgrass in seashore paspalum and bermudagrass turf on the island of Guam (Wiecko, 2003) but was less effective on yellow nutsedge. The turf was not flooded. Ocean water was applied as an herbicide at concentrations up to 55 dS/m (decisiemen per meter, a measure of electrical conductivity).

Draining is an excellent control for cattails, bulrushes, and reed canarygrass that grow best in wet areas. Draining and flooding are not applicable to most agronomic or horticultural environments, but they should not be forgotten when considering weed management for appropriate sites.

Chaining has been employed on rangelands to destroy emerged vegetation. A large chain similar to a ship's anchor chain is dragged between two bulldozers and uproots sagebrush, rabbitbrush, and other range weeds. Chaining removes emerged growth and completely controls annuals but not perennials that reproduce vegetatively. The technique is not suited for most cropland. Chains are also used to stop passage of weeds in irrigation channels in many countries. Removing collected weeds from the impoundment created by the chain is a labor-intensive, smelly, unpleasant operation.

IV. NONMECHANICAL METHODS

A. Heat

Flaming

Many plant processes are susceptible to high-temperature disruption attributed to coagulation and denaturation of protein, increasing membrane permeability, and enzyme inactivation. Photosynthesis is decreased or stopped. Initial thermal disruption of cellular membranes is followed by dehydration. Heat, short of setting fire to an area, usually does not kill by combustion. The thermal death point for most plant tissue is between 45° and 55°C (113° to 131°F) after prolonged exposure. Temperatures of the flame in a flamer used for weed control approaches 2,000°F but flamers may be used selectively when distance from the crop and speed are controlled.

A flamer directs a petroleum-based fuel emitted under pressure and ignited. Plant size at treatment influences efficacy much more than plant density. To achieve 90% control of white mustard with one to two leaves required at least 40 kg/ha (36 lb/A) of propane, whereas plants with 2 to 4 leaves required 70 kg/ha (62 lb/A) (Ascard, 1994). Required dose increased with growth stage, and some species of annual weeds are more tolerant than others. The most tolerant species cannot be controlled with one flaming regardless of dose (Ascard, 1994).

Weeds with unprotected meristematic areas and thin leaves such as common lambsquarters, common chickweed, and nettle were completely killed by 20 to 50 kg/ha of propane when they had less that five true leaves (Ascard, 1995). Shepherd's-purse and pineapple-weed have protected growing points and were killed by flaming only at very early growth states. Annual bluegrass could not be killed with a single flaming regardless of its size or the propane rate. Plants with up to four true leaves were killed by 10 to 40 kg propane ha^{-1}, whereas those with 4 to 12 leaves required 40 to 50 kg/ha (Ascard, 1995).

Corn between 2 and 12 inches tall cannot withstand flaming. Before corn is 2 inches tall its meristematic region is underground and will regenerate the plant. After 12 inches, the flame can be directed at the plant's base and used selectively if the weeds are shorter than the crop. Intensity and duration of exposure are important. If one held a flame on a corn plant for several minutes, the plant would die, so flamers must be kept moving and speed affects selectivity. Flame has been used selectively in cotton and onions. When cotton stems are 3/16 inch in diameter or greater, flaming can be used.

Flaming kills green shoots where tillage is impractical, such as along railroad tracks. Buried weed seeds or perennial plant parts are not affected. Dry seeds withstand high temperatures and rather long exposures because soil protects and insulates. Burning can destroy weed seeds but only if they are on the soil surface. Even a small layer of soil will protect most seeds. Therefore, flaming is effective only for controlling emerged weeds.

Burning mature weeds destroys debris but doesn't prevent crop losses from competition. Flaming has no residue, a problem with chemical methods of control. Other than high rainfall conditions, flaming is not affected by prevailing environmental conditions. It may induce erosion by eliminating vegetation that holds soil. Heat could induce germination of dormant seeds or create conditions favorable for their germination by eliminating emerged, competing plants. This is especially true when brush is burned.

Controlling a flamer's direction eliminates drift, and one can achieve some degree of insect and disease control. An additional advantage is immediate observation of results. Flaming is often used to eliminate vegetation along irrigation ditches. In spite of its advantages and proven success, flaming is not used much in crops due to its cost and the success of other methods. The presently high cost of propane and other combustible fuels indicates flaming is probably not economically sensible.

Burning is nevertheless a valid, useful weed control method. Regular fire has played a significant role in development and stability of many ecosystems

(Hatch et al., 1991). Native plants often depend on regular fires to reduce competition, remove thatch, scarify seeds (break dormancy), and cycle nutrients (Kyser and DiTomaso, 2002). In many grassland and forest communities, fire is not a hazard but a necessary part of community stability. In the absence of periodic natural or planned fires, it may be much more difficult and perhaps impossible to maintain grasslands in a natural state and prevent invasion of weedy species such as yellow starthistle (Kyser and DiTomaso, 2002). Burning has been combined successfully with an herbicide (clopyralid) for management of yellow starthistle in California (DiTomaso et al., 2006). The combination was most effective when burning in the first year was followed by clopyralid in the second year.

Solarization and Heat

It is feasible to use the heat of the sun to control weeds in a process called solarization. Weed seed germination is suppressed by high soil temperatures and seedlings are killed. Transparent and opaque polyethylene sheets raise soil temperature above the thermal death point for most seedlings and many seeds.

Solarization uses plastic sheets placed on soil moistened to field capacity and thus heats soil by trapping solar radiation just as a greenhouse does (Horowitz et al., 1983). Its effectiveness for weed control is dependent on a warm, moist climate and intense radiation with long days to raise soil temperature enough to kill weed seeds and seedlings. Moisture increases soil's ability to conduct heat and sensitizes seeds to high temperatures (Horowitz, 1980). Solarization also can control soil-borne diseases and increase crop growth due to soil warming.

When different types of plastic were used for four weeks in Israel, the temperatures under clear plastic exceeded 45°C. Temperatures under black plastic exceeded 40°C about half the time, but did not reach 45°C. UV-absorbing transparent plastic raised temperatures above 50°C. At 5 cm, temperatures increased 9° for black and 19° for clear plastic.

The effects of solarization on weed emergence were apparent for a short time after plastic was removed. During the first two months after removal, the number of emerging annuals was less than 15% of an untreated check, and clear plastic was more efficient. Only clear plastic reduced weed populations for one year after solarization (Horowitz, 1980). Table 10.10 shows some data on the sensitivity of annual weeds to solarization.

In other work, a month after solarization, field bindweed, annual sowthistle, and prostrate pigweed covered 85% of the soil surface in plots not solarized compared to only 18% in solarized plots (Silveira and Borges, 1984). A one-week period of solarization reduced the percentage of buried seeds of prickly

TABLE 10.10. The Sensitivity of Annual Weeds to Solarization (Horowitz et al., 1983).

Weed	Weeks of solarization to reduce seedling numbers to less than 10% of control
Blue pimpernel	2–4
Bull mallow	>8
Fumitory	6
Heliotrope	4
Horseweed	>8
Pigweeds	2

sida, common cocklebur, velvetleaf, and spurred anoda in soil in Mississippi (Egley, 1983). Solarization reduced emergence of all weeds except purple nutsedge. Total weed emergence was reduced 97% one week after removal of plastic and up to 77% for the season (Egley, 1983). Work in Hawaii (Miles et al., 2002) showed a different effect on purple nutsedge tubers. Five weeks of solarization with clear polyethelene film raised mean soil temperature, 15 cm deep by 5.8°C in spring and 7.2°C in summer, and both increased the final sprouting percentage of purple nutsedge tubers from 74 to 97% in the spring and from 97 to 100% in summer. These increases, especially only 3% in summer, may seem small, but because purple nutsedge is such an aggressive weed, complete or increased tuber germination should lead to more complete control. Solarization has been combined with a green manure crop in a study of annual bluegrass survival (Peachey et al., 2001). Clear polyethylene film (0.6 mil) applied for 53 or 59 days reduced annual bluegrass 89 to 100% in the upper 5 cm of soil but did not affect survival below 5 cm and may have even enhanced it. Green manure, cover crops of barley, rapeseed, and sudangrass generally increased survival of annual bluegrass seed buried 2.5 to 15 cm deep. Combining green manure crops and solarization did not improve annual bluegrass control over solarization alone, although solarization significantly improved the efficacy of metham (a soil fumigant) for control of annual bluegrass seed.

Solarization with transparent polyethylene were combined with a chicken manure mulch to study the effect on scarified and nonscarified field dodder seed (Haidar et al., 1999). Only seeds on the soil surface were affected consistently. For scarified seed, 95% germination reduction occurred after 10 days under the plastic. Chicken manure reduced the required period of solarization for nonscarified seed from 6 to 12 weeks, but the effect of manure on total seed germination disappeared after 6 weeks. Solarization for 2 to 6 weeks with or without chicken manure reduced weed growth in cabbage, but manure increased yield (Haidar and Sidahmed, 2000). Solarization with clear plastic for 60 days during tomato growth killed 95% of branched broomrape seed and induced secondary dormancy in the remaining seed (Mauromicale et al., 2005). In solarized soil, no broomrape shoots emerged and no parasitic attachment to tomato roots was detected. The authors recommended solarization as a good technique for organic farming.

The major effect of high soil temperature (up to 150°F) is killing weed seedlings that germinate under the plastic. Solarization has not been employed on a large scale in field crops but is used effectively in high-value vegetable crops in California's Imperial Valley. Because there is no cold winter season, solarization is used for 6 weeks before crops are planted. The plastic is removed prior to planting and must be disposed of—a problem all by itself—but solarization nearly eliminates use of herbicides. Solarization has potential to improve weed management, but costs, compared to other methods, preclude widespread adoption in other than high value crops.

Research by Campbell's Soup Company in California has used solarization in a different way (Hoekstra, 1992). The previous comments related to use of plastic mulch to heat soil and kill weeds. D. Larsen of Campbell's Soup has experimented with a solar-powered lens that heats soil and kills weeds. The curved lens is an acrylic sheet made of an array of small lenses. It is cheaper and lighter than glass and not as easily damaged. Lens concentration of solar energy has two primary disadvantages:

1. It does not work on cloudy days.
2. The lens must be pulled slowly over the field to focus energy sufficiently to kill seedling weeds. Stronger lenses capable of concentrating more energy may enable faster movement.

Steam (heated water vapor) has been used to sterilize greenhouse and nursery soil for many years. Its use has been limited in the field, especially for weed control. Kolberg and Wiles (2002) studied steam as an alternative weed control method that does not have the disadvantages of herbicides and lacks environmental persistence. Emergence of a few common annual weeds was not affected, and control was similar to glyphosate. The amount of steam applied, the speed of application, the weed species, and their growth stage at application determined steam's effectiveness.

B. Mulching

Mulching excludes light and prevents shoot growth. Wide mulches are required to control perennials that can creep to the edge of a mulch and emerge. Mulches increase soil temperature and may promote better plant growth.

Several different materials have been used for mulch, including straw, hay, manure, paper (first used on sugarcane in Hawaii), and black plastic. It is common to see mulches used in greenhouses where plants grow in soil. Mulches are used most in high-value crops grown on small areas and in crops (e.g., sugarcane) where laying the mulch can be mechanized. Hartwig and Ammon (2002) reviewed the status and promise of cover crops and living mulches for vineyards, orchards, and some agronomic crops in terms of their beneficial effects on soil erosion, nitrogen budgets, weed control, management of other pests, and the environment.

Shredded paper was one of the first mulches used in a crop. It has been replaced by plastic mulch but use of either is rare. Pellett and Haleba (1995) evaluated use of chopped paper in perennial nursery crops over two seasons. Their work showed that paper was an effective mulch that provided weed control over two seasons, especially when the paper was wetted and rolled after application. They applied 2.3 or 3.6 kg/m^2. The higher rate was 15 cm thick. The equivalent rate per hectare was almost 38 tons, and the cost of hand application of baled paper, in Wisconsin, was over $2,500 per hectare. The mulch provided good weed control for two years, and it was possible to rototill paper into soil with power equipment. A tackifier (a substance to make the paper sticky) was important to prevent paper from blowing away or piling due to wind. Cost of the paper and its application prohibit consideration of use of paper mulch in any but high-value crops.

As the amount of wheat straw mulch increased in a wheat-corn-fallow dryland production system, weed growth decreased (Crutchfield and Wicks, 1983). Others have shown that planting no-till corn into a desiccated green wheat cover crop reduced morningglory biomass 79% compared to a non-mulched, tilled treatment (Liebl et al., 1984). Rye mulch was also successful in reducing biomass of three annual broadleaved species in three crops (Liebl et al., 1984). Rye has been used successfully as a crop mulch in the fall and winter before corn (Almeida et al., 1984), a practice known as green manuring. The rye contributed to weed control in corn because of its allelopathic activity. Its foliage was dense enough so a contact herbicide had to be applied before corn planting.

Penny and Neal (2003) showed that mulching helps to control mulberry weed, a new invasive weed of container nurseries and landscapes in the southeastern United States. Light stimulates mulberry weed seed germination, and mulches that prevent light penetration effectively prevented seed germination.

Yellow sweetclover residues left after growth ceased provided excellent weed suppression of annual and two perennial weeds (dandelion and perennial sowthistle) in Canada (Blackshaw et al., 2001). Weed suppression was similar whether yellow sweetclover was harvested as hay after growth as a green manure fallow replacement crop or its residues were incorporated in soil or left on the surface as a mulch. Allelopathy was possible.

A mulch compost made from swine bedding material and swine manure was tested for its effects on corn (Liebman et al., 2004) and soybean (Menalled et al., 2004) yield and growth of weeds associated with each crop. The compost consistently increased corn height but had no effect on yield compared to corn grown without swine manure compost but with nitrogen fertilizer. Similarly, the compost did not increase soybean yield, but it did increase the competitiveness of common waterhemp. The authors concluded that if composted swine manure is to be used in corn or soybeans, effective weed management practices must be considered. In these cases the compost/mulch provided nitrogen fertility, which was equally beneficial to the crop and weeds.

Black polyethylene mulch was about 1.5 times more effective (72% reduction in shoots) than clear polyethylene mulch (46% reduction) for control of yellow nutsedge in Georgia. Neither mulch was effective for control of purple nutsedge (Webster, 2005), indicating a possible shift to purple nutsedge in mulched vegetable production systems.

A synthetic black cloth available for mulching is sold commercially in rolls about 6 feet wide and can be applied by machine when trees are planted. It is easy to spread and prevents emergence of most annual weed seedlings.

C. Sound and Electricity

Use of high-frequency energy and electricity has been considered since the late 19th century. Ultra-high-frequency (UHF) fields are selectively toxic to plants and seeds and the first use of sound for weed control was patented in 1895. UHF fields produce thermal and nonthermal effects, but thermal effects are the chief source of toxicity. There is a linear and positive correlation between seed water content and susceptibility to electromagnetic energy. Lower frequencies have broken seed dormancy. Commercial weed control devices using UHF fields have been developed, patented, and commercialized but without lasting commercial success. These have been used for selective vegetation control in cotton and for aquatic weeds but have not achieved great commercial success. They require a great deal of power but can be used preemergence or postemergence. Postemergence use forces plants to conduct current and in effect "boils" plant solutions and ruptures cell walls. Vigneault et al. (1990) reviewed what they called "electrocution" for weed control. They concluded that use of electricity may have a place in high-value, specialty crops such as fine herbs. It may be especially appropriate when the treated area is small, no herbicides are available, and cultivation is undesirable because of the potential for root damage and the risk of soil erosion. Advantages include lack of any chemical residue and no soil disturbance.

D. Light

Agriculture students are well aware of the role of light in seed germination and photosynthesis. It may not be as common to think of the difference in plant's light reflectivity as an aid in weed management. Research has demonstrated that different plant surfaces reflect light differently and that the difference can be used to differentiate weed from crop plants and to determine if weeds are present on a particular patch of ground. Optical sensing and optical reflectance (e.g., the ratio of red to near-infrared light—650 nanometers vs. 750 nm) can be used in weed management (Shropshire et al., 1990). Machines have been developed that use optical reflectance to determine if a weed is present and then turn on an herbicide spray. This reduces the amount of herbicide applied, saves money, and is environmentally beneficial.

V. CULTURAL WEED CONTROL

Cultural weed management is an important part of nearly all weed management systems, even when it is not recognized. Cultural weed management techniques are especially important in crops where other weed management options are limited or not available. They should be included in weed management programs although they should not be regarded as solutions to all weed problems. Similarly, despite the outstanding success of herbicides, absolute reliance on them to solve all weed problems is economically and environmentally unfeasible (Gill et al., 1997). Gill et al. provide a complete review of nonmechanical and cultural methods of weed management.

A. Crop Competition

The techniques of cultural weed control are well known to farmers and weed scientists. In fact, they are employed regularly but often are not conscious attempts to manage weeds. Planting a crop is a sure way to reduce growth because the crop interferes with the weeds. It is a fundamental method of weed management, but most often cultural weed control just happens rather than occurring as a planned addition to weed management programs. Methods of cultural weed management include conscious use of crop interference, use of cropping pattern, intercropping, soil amendments, and no or minimum tillage.

Weed scientists have investigated the relative competitiveness of crop cultivars. As reported by Mohler (2001) and reviewed in Zimdahl (2004), "The role of crop genotype in weed management has received growing attention over the past 30 years." The reports indicate there has been attention but the role of genotype has not been a major area of weed science research. As cited in Mohler (2001), Callaway (1992) reviewed the literature on crop varietal tolerance to weeds, and Callaway and Forcella (1993) examined the prospects for breeding crops for improved weed tolerance. There are differences in crop varietal tolerance (often defined as competitive ability) to weeds. Mohler's (2001) Table 6.3 identifies 25 crops in which such differences have been found. For many crops only a few reports are included, but for the major crops (barley, beans, corn, rice, soybean, and wheat) there are many reports (e.g., 14 for soybean). However, despite many years of research and several reports, few crops have been bred to be more competitive (Caton et al., 2001). The essence of the problem is that neither weed scientists nor plant breeders know what makes a plant more competitive.

Several crops exhibit genotype differences in competitiveness (Burnside, 1972; Monks and Oliver, 1988). Weed biomass differences up to 45% have been reported among soybean genotypes (Rose et al., 1984). Wild oat competition with wheat was greater than intraspecific competition in wheat. The competitiveness of six wheat cultivars with wild oat was similar for all factors measured (Gonzalez-Ponce, 1988). The most weed-suppressive of 20 winter wheat cultivars reduced weed biomass 82% compared to the least-suppressive cultivar (Wicks et al., 1986). With weed interference, the lowest yielding varieties produced 66 and 54% of the highest yielding varieties of wheat (Ramsel and Wicks, 1988) and rice (Smith, 1974), respectively. Other work showed that short-stemmed cultivars were more affected by taller wild oats because of light competition (Wimschneider and Bacthaler, 1979). The quest to develop integrated weed management systems has encouraged research on the competitiveness of crop cultivars. That cultivars differ in competitive ability was amply demonstrated several years ago in soybeans (McWhorter and Hartwig, 1972; Table 10.11). Research in Denmark showed that spring barley varieties vary in weed-suppression ability (Christensen, 1995). Weed dry matter in the most suppressive variety was 48% lower than the mean dry matter of all varieties, whereas it was 31% higher in the least suppressive variety.

More vigorous, taller, faster growing cultivars are likely to be better competitors, but too little is known about what makes a cultivar competitive and whether it is a trait that plant breeders can select for and develop. Christensen's (1995) work demonstrated no correlation between varietal grain yields in pure stands and competitiveness, suggesting that breeding to optimize yield and competitive ability may be possible. Research is being done to develop crop cultivars that can be bred or managed for high levels of crop interference via high rates of resource uptake or possible allelopathic (see Chapter 8) interference with weeds (Jordan, 1993).

Alfalfa and other hay crops are smother or cleaning crops. Land is not plowed when they are grown, making it hard for annuals to succeed, but

TABLE 10.11. Yield Reduction in Selected Soybean Varieties Due to Johnsongrass or Cocklebur Competition (McWhorter and Hartwig, 1972).

Soybean variety	Yield reduction with weed competition from %	
	Johnsongrass	Cocklebur
Davis	34	56
Lee	41	67
Semmes	23	53
Bragg	24	57
Jackson	30	67
Hardee	23	26

perennial weeds do well in perennial crops such as alfalfa. Sudangrass, planted in dense stands, can compete effectively against many, but not all, weeds.

Crops can be favored by knowing and using the effect of row width and crop seeding rate. Khan et al. (1996) showed that spring wheat yields were as great or greater when early seeding or a double seeding rate was used as a substitute for a postemergence herbicide to control foxtail species. Early and middle seeding dates favored the increase of green foxtail over yellow foxtail, whereas late seeding favored yellow over green. Spring wheat competing with foxtail had a higher yield when the seeding rate was 270 kg/ha (twice the normal rate) than when it was 130 or 70 (1/2 normal rate) kg/ha unless the seeding was late. Yenish and Young (2004) demonstrated that seeding rate of winter wheat in Washington had a consistent effect on wheat yield. Yield was about 10% higher when the seeding rate was 60 as opposed to 40 seeds per meter of row when jointed goatgrass was the competing weed. Tall wheat varieties competed best. Early, high-seeding rates increase crop density and biomass early in the season and this suppresses weed growth. Seeding wheat at higher than normal rates in Alberta, Canada, improved performance of herbicides used to control wild oats (O'Donovan et al., 2006). Increasing wheat seeding rate from 75 to 150 kg/ha reduced wild oat biomass up to 18% and the soil seed bank up to 46% even when herbicides were not used. On average, wheat yield improved 19% and net economic return 16% with the higher seeding rate.

Decreases in weed growth have been observed in narrow (about 8 inch) versus wide (about 30 inch) row spacing in several crops. For example weed growth was reduced 55% in peanuts (Buchanan and Hauser, 1980) and 37% in sorghum (Wiese et al., 1964). Varying row width uses the principles of plant population biology to achieve competitive interactions that favor the crop. Research is proceeding in the midwestern United States to devise narrow row production techniques for soybeans. When these are combined with minimal tillage and the right herbicides, yield is maintained or increased, soil erosion is reduced, and excellent weed management is obtained. Row spacing is not always an effective weed management technique. Esbenshade et al. showed that row spacing had little effect on burcumber emergence or control in corn (2001a) and soybean (2001b). Tharp and Kells (2001) showed that corn yield was not affected by row spacing and corn population, and row spacing did not influence weed emergence following glufosinate application. Common lambsquarters' biomass was reduced as corn row width was reduced from 76 to 38 cm spacing. In Minnesota, narrow rows (51 vs. 76 cm) did not affect late-season weed density, but corn grain yield increased in two of three years (Johnson and Hoverstad, 2002). Other work showed a significant reduction in weed density by careful selection of early-maturing corn hybrids planted in narrow (38) versus wide (76 cm) rows (Begna et al., 2001). Combining narrow rows and high population density increased corn canopy light interception 3 to 5%, decreased light available to weeds, which produced 5 to 8 times less biomass. In contrast, Norsworthy and Oliveira (2004) suggested that increasing corn population in the row might be a more effective strategy to reduce weed competition than decreasing row width. They found light interception and the critical period for weed control were similar in narrow-row (48 cm) and wide-row (97 cm) corn, and the end of season weed biomass was similar.

An interesting study of the effect of soil amended with residue of the weed wild radish showed that the competitiveness of tomato and bell pepper with yellow nutsedge was enhanced by the weed residue compared to soil with no residue (Norsworthy and Meehan, 2005). This work illustrates the previously suspected but undemonstrated potential of weed residue in weed management and crop competitiveness.

Intercropping is a common, small-scale farming system among farmers of the developing world. The main reasons for mixing crops or planting in close sequence are to maximize land use and reduce risk of crop failure. Intercropping maintains soil fertility, reduces erosion, and may reduce insect problems (Altieri et al., 1983). Intercropping also gives greater stability to yield over seasons and provides yield advantages over single crop agriculture (Altieri, 1984). The National Agricultural Library published a useful bibliography of citations on green manure and cover crops (MacLean, 1989). The positive and negative effects of Brassica cover cropping systems have been reviewed by Haramoto and Gallandt (2004).

It is claimed (Altieri et al., 1983; Moody and Shetty, 1981) that one reason for intercropping is weed suppression, but other than work in Nigeria (Chikoye et al., 2001), there has been little experimental evidence to support this conclusion (Shaw, 1982). Similarly, there is little evidence that intercropping requires less weed control. It is assumed that intercropping saves labor because weeding is less critical, and some operations such as planting a second crop and weeding the first can be combined (Norman, 1973). Intercropping's effectiveness for weed control depends on the species combined, their relative proportions, and plant geometry in the field. All reports recommend additional weeding with intercropping, and weeds can often be worse than in sole crops (Moody and Shetty, 1981). Successful use of interseeded cover crops in vegetables has been limited by their tendency to inadequately suppress weeds or to suppress weeds and the crop. For example, winter rye sown in broccoli was successful only when sown at high density, in locations or seasons with low soil temperatures (e.g., spring), and when combined with other weed management methods (Brainard and Bellinder, 2004). When these conditions were not met, rye was often detrimental to weed management and reduced broccoli yield. Rye sown as a cover crop in soybean reduced total weed density and biomass compared to no cover crop. However, costs were higher and the rye cover crop system was less profitable than soybean grown without a cover crop where weeds were controlled with conventional technology (Reddy, 2003).

Several cover crops were compared in the moist savanna regions of Nigeria (Ekeleme et al., 2003). Weed density was negatively correlated with percent ground cover of five legume cover crops. Only one, lablab (hyacinth bean), produced adequate ground cover and good weed suppression in all locations independent of varying duration, distribution, and amount of rainfall. Others were successful in high-rainfall regions. Readers must note the variation between rainfall regions. The same variation will be observed across the regions of the United States or Europe. No system will be developed that will work equally efficiently in all regions. Other work with cover corps in Nigeria has been quite successful. For example, 12 months after planting corn, cassava, or a corn/cassava intercrop plots with cover crops had 52 to 71% less cogongrass (a hardy, difficult to control perennial weed) and 27 to 52% more corn grain yield at three locations in Nigeria (Chikoye et al., 2001). The cover crops were centro, copwea, hyacinth bean, egusi melon, tropical kudzu, or velvetbean all known as tropical food crops (cowpea and egusi melon) or green manure crops. Higher crop yield was a result of one or a combination of three things: reduced weed competition from the cover crop, a mulching effect that conserved soil moisture and prevented weed growth, and a contribution of nitrogen from the leguminous cover crops. It has been demonstrated that cover crops such as hairy vetch can improve corn and soybean productivity, and, when they are combined with reduced rates of environmentally benign herbicides, will minimize the requirements for herbicides (Gallagher et al., 2003).

Annual intercrops can enhance weed suppression and crop production compared to sole crops. Studies in Canada with wheat-canola and wheat-canola-pea intercropping demonstrated that intercropping tended to provide greater weed suppression compared to sole cropping; there was a synergism of weed suppression among the intercrops compared to any sole crop (Szumigalski and Van Acker, 2005). Studies of intercropping do not confirm that any plant grown with a crop will always provide adequate weed control. Intercropping is a common practice in many agricultural systems, and these systems should be studied to develop complementary plants, control soil erosion, and prevent or reduce weed growth. It is undoubtedly true that plants that are not crops are classified by most farmers in the developed world as weeds. Other farmers classify noncrop plants in a way that judges their potential use or their effects on soil and crops. Western farmers see noncrop plants as weeds, but subsistence farmers have a different understanding of the use and value of plants that are neither crop nor weed.

A variation on intercropping is the intentional growth of spring-seeded smother plants for weed management. The intent is to eliminate the plants after the crop has grown and is a better competitor and before the smother plants become competitive, as intercrops often do. Berseem clover, four species of medic, and yellow mustard were planted immediately after corn and soybean planting in a 25 cm band over the crop row. All species achieved 45% or greater ground cover within 10 weeks of seeding. Yellow mustard grew most rapidly, and it and sava medic gave greater weed suppression than other species. When the medic was killed 30 days after planting, it reduced weed suppression but did not increase corn yield compared to season long presence (Buhler et al., 2001).

Research on these alternative, generally nonchemical systems of weed management is continuing as environmental concerns, sustainability questions, and debate over long-term efficacy of present weed management and crop production systems intensifies. They are alternative systems not panaceas. Weeds will adapt and change as weed management systems change, just as they have adapted to herbicides. Weeds will always be a part of agriculture.

B. Planting Date and Population

The trend in crop production is early planting to optimize yield. Yield is increased because crops have a longer growing season and photosynthesize for more days (Barrett and Witt, 1987). Early planting provides a competitive edge to adapted crop cultivars. Early-season establishment of a crop, such as corn, provides it an advantage compared to yellow nutsedge, a warm-season weed (Ghafar and Watson, 1983). The competitive advantage could be due to the weed's light requirement for growth and to shading by the crop that emerged first. Choice of planting date should be considered part of integrated weed management. Planting date of any crop plays a role, as illustrated by a 60% reduction in kochia population when proso millet was planted June 1 rather than May 15, although millet yield was not affected (Anderson, 1988). Planting date can also play a role in crop choice. Longspine sandbur emerges in late May and June in Colorado and flowers in late July. The seed, in its bur, reduces the value of hay. Foxtail millet is planted in early June and, when harvested as hay in late August (Lyon and Anderson, 1993), will be contaminated with the burlike seed if longspine sandbur is present. Oats can also be grown for hay when planted in early April and harvested in late June, before the longspine sandbur seed develops. The oat hay will not be contaminated with the burlike seed.

Sunflower and safflower are grown as oil crops in the US Great Plains states. Safflower is planted in early April and sunflower in early June. Because of its early planting, over 70% of weed seedlings emerge within 10 weeks of planting safflower. These weeds are easily controlled by tillage or herbicides, and sunflower is planted in a more weed-free field after mid-June (Anderson, 1994). Early planting requires weed control for longer periods. Late planting is usually preceded by tillage that destroys emerged weeds and reduces their population in the crop. Advantages gained by later planting are often outweighed by decreased crop yield over a shorter growing season.

In Minnesota, delaying soybean planting until early June instead of early May permitted the use of preplant tillage to control early germinating weeds (Gunsolus, 1990). This reduced maximum soybean yield potential 10%. When corn planting was delayed from the normal time in the beginning of May until after May 25, maximum yield potential was reduced 25% (Gunsolus, 1990). The same study also showed rotary hoeing for weed control when either crop was young reduced corn plant stand up to 10% but did not affect soybean stand. In Minnesota, a 10% loss in corn stand reduced final yield 2% but did not affect soybean yield. This small set of data illustrates the complexity of agriculture; extrapolations cannot be made between crops and certainly not between regions. Sweeping generalizations are rare.

Khan et al. (1996), in a different kind of study about planting date, reported that crop management practices related to planting date could substitute for herbicide use to control foxtail species in wheat. Spring wheat yields in North Dakota were equal to or greater when early seeding or a doubled seeding rate was substituted for postemergence foxtail control with an acceptable herbicide. Yield of spring wheat was greater with a high seeding rate (240 lb/A) than with normal (116 lb/A) or low (62 lb/A) seeding rates for early (late April to mid-May) or midseason (mid- to late May) seeding but not for late (early to mid-June) seeding. It is interesting to note how seeding date in this work affected certain weeds. Early and middle seeding dates favored the relative increase of

TABLE 10.12. Effect of Row Width and Cultivation on Yield of Grain Sorghum (Wiese et al., 1964).

Row width (cm)	Seeding rate (kg/ha)	Grain yield (kg/ha)		Yield loss (%)
		Weedy	Hand-weeded	
25	5.6	3,326	4,861	31
	11.2	4,188	5,466	23
51	5.6	3,125	5,152	39
	11.2	3,987	4,715	16
76	5.6	3,237	5,365	40
	11.2	3,606	5,029	28
102	5.6	3,058	4,491	32
	11.2	3,203	4,637	31

green foxtail, and the late date favored yellow foxtail. In weed management, as in ecology, no one can do just one thing.

Planting date is often dictated by considerations other than weed management. Similarly, plant population is dictated by agronomic studies that have shown the population that gives the best yield. Populations are also determined by row-spacings required by planting, cultivating, and harvesting machines. Increasing crop plant populations can often decrease weed density and growth. Wiese et al. (1964) showed over 40 years ago how row width and seeding rate interacted to reduce competition from weeds in grain sorghum in Texas (Table 10.12). With 25 cm rows, yield loss from weeds was lower with the higher of two seeding rates. This relationship remained true until rows were 102 cm wide.

C. Companion Cropping

Cover crops or living mulches (Akobundu, 1980b) can be used as intercrops or companion plants to suppress weeds (Liebman, 1988, 1989; Shetty and Krantz, 1980). Appropriate weed control practices, for many farming systems, must consider the need to maintain soil fertility and prevent erosion, and open row crops are inimical to these needs. Akobundu (1980a) developed integrated low- or no-tillage weed management systems, compatible with more than one crop plant in a field that reduced herbicide use, fertilizer requirements, and soil erosion. Combinations of a legume or Eugusi melon and sweet potato with corn showed that the companion crops or living mulches maintained corn yield, contributed to nitrogen supply, suppressed

TABLE 10.13. Effect of Weeding Frequency and Ground Cover on Weed Competition and Maize Yield (IITA, 1980).

	Unweeded check[a]	
Ground cover	Weed dry weight (T/ha)	Grain yield (T/ha)
Conventional tillage	1.5 a	1.1 e
No tillage	1.4 a	1.8 bcd
Maize stover	1.3 a	1.6 cde
Maize and groundnut	0.3 c	1.3 de
Maize and wild winged bean	0.1 c	2.1 abc

[a]Values in one column followed by the same letter are not statistically different at the 95% level of probability.

weed growth, and reduced soil erosion. Groundnut, centro, and wild winged bean have been used as living mulches with corn. Living mulches incorporate organic mulch, no-tillage, and weed control. Centro and wild winged bean grew so vigorously that a growth retardant had to be applied to bands over corn rows to gain a growth advantage for corn (Akobundu, 1980b). In unweeded no-till plots, corn grain yield was 1.6 T/ha, whereas with conventional tillage it was 2.3 T/ha. Corn yield in unweeded, live mulch plots averaged 2.7 T/ha. Yields were not different, and live mulch plants did not reduce yield; they were complementary, not competitive. Further studies (IITA, 1980) verified these results (Table 10.13).

Clover has been grown successfully with corn and has reduced weed growth (Vrabel et al., 1980). Crimson clover and subterranean clover were the most promising cover crops in cucumbers and peppers in Georgia and contributed to effective management of diseases, nematodes, and insects (Phatak et al., 1991). Sweet corn in a living mulch of white clover had high yields in early years but lower yields later because a contact herbicide used over the corn row allowed invasion of perennial weeds that were not suppressed by white clover (Mohler, 1991). A dead rye mulch decreased weed biomass and did not decrease corn yield (Mohler, 1991). A living mulch of spring planted rye reduced early season biomass of common lambsquarters 98%, large crabgrass 42%, and common ragweed 90%, compared to unmulched controls. Barnes and Putnam (1983) also reported that the age of rye when it was killed with herbicides was important to the subsequent emergence of yellow foxtail and lettuce.

Companion cropping can be a good weed control technique, but research is needed to determine how appropriate it may be in specific situations. Limited evidence supports the contention that it can provide weed competition, build soil organic matter, reduce soil erosion, and improve water penetration (Andres and Clement, 1984). In some climates when spring soil moisture is limiting, cover or companion crops can deplete moisture and be detrimental to crops in spite of weed control advantages. Companion crops may also have to be killed before a crop is planted or they become competitors.

In Pennsylvania, crownvetch, a legume, was tried as a living mulch in a no-tillage corn (Cardina and Hartwig, 1980; Hartwig, 1987). Crownvetch is difficult to establish, but once established, it provides soil erosion control, improved fertility through reducing nutrient loss via erosion, and by contributing nitrogen and weed control. Weed control must be supplemented with herbicides that will not kill the crownvetch. The system is amenable to rotation of corn with other crops. Work in Ohio demonstrated use of hairy vetch for weed management (Table 10.14). Unsuppressed hairy vetch reduced weed biomass in corn 96% in one year and 58% in another. When corn was planted in late April into hairy vetch in the early bud stage of growth, corn yield was reduced up to 76%. Hairy vetch competition was reduced or eliminated when corn was planted into hairy vetch in mid- or late-bloom in May or early June. Because of the shortened growing season and competition from hairy vetch, corn planted in May into untreated hairy vetch yielded similarly to corn planted in the no-cover crop, weed-free check. Use of the contact, nonresidual herbicide glyphosate to kill vetch and eliminate competition with corn was helpful with early and midbloom planting but not with late planting because of the lack of continuing weed control.

In Wisconsin, spring planted winter rye has been a successful living mulch for weed control in soybean (Ateh and Doll, 1996). A system employing just rye for weed control reduced weed shoot biomass from 60 to 90% over three

TABLE 10.14. Corn Grain Yield After Planting in Hairy Vetch at Three Growth Stages (Hoffman et al., 1993).

	Corn grain yield when planted into hairy vetch growth stage kg/ha		
Weed control treatment	Early bud	Midbloom	Late bloom
Untreated	130*a	7,350 b	6,520 b
Rolled with water filled roller	40*a	7,630 b	7,510 b
Mowed with flail chopper	3,000*a	6,830*b	5,900 b
Glyphosate 2.8 kg/ha	8,020*a	7,700 a	5,630 b
Weed-free control	9,770 a	8,560 a	5,310 b

*Values are statistically different from the weed-free control in a column, lower case letters indicate statistical differences across a row.

years. Rye worked best for weed control and did not reduce soybean yield when weed density was low and ground cover from the mulch and soil moisture were adequate for growth. Rye interference with soybean was minimal if rye was killed within 45 days after soybean planting.

Other successful companion crops have been low-growing plants such as cowpea and mungbean in India (Shetty and Rao, 1981). Seed costs of companion plants and expected competition to the primary crop were offset by the value of companion plant yield, a more permanent soil cover (less erosion), reduced nitrogen fertilizer requirement, and reduced cost of hand weeding. Attempts have also been made to try different cover crops to manage noxious weeds such as cogongrass in India, Malaysia, Nigeria, and Kenya (Vayssierre, 1957). The smothering effect of velvetbean on cogongrass in corn was equivalent to 1.8 kg/ha of glyphosate but less than that of imazapyr at 0.5 kg/ha in Nigeria (Udensi et al., 1999). The work suggests that planting velvetbean to manage cogongrass may be a “better alternative for farmers without the resources to purchase herbicides.”

Another example of a weed used to gain interspecific competition is the use of azolla as a weed control technique in lowland rice. *Azolla pinnata*, a free-floating fern, has been used in Asian rice culture because of its symbiotic relationship with *Azolla anabena*, a nitrogen-fixing blue-green algae. This symbiotic relationship can contribute up to 100 kg of nitrogen/ha. A second use of azolla is for weed control due to the competitive effect of an azolla blanket over the surface of paddy water.

When azolla is used, some farmers can grow rice without the addition of nitrogen fertilizer. Success of the azolla technique depends on the ability of the farmer to control water supply and on the weed species present. Perennial weeds such as rushes and annuals with strong culms (e.g., barnyardgrass) are not suppressed and must be controlled in other ways. Many other weeds are controlled well.

Azolla has been successful but cannot be universally recommended because there is an increase in labor (skill) to manage it. Some land must be devoted to supplying a continuing source of inoculum of azolla for paddies, and azolla may complicate other pest problems. In fact, azolla may become a weed.

An interesting twist in companion cropping is the use of genetic engineering to make a companion crop self-destruct. A potential problem with companion cropping is that the companion may become a competitor if it is allowed to grow too long or if it becomes too large. Herbicides or tillage may then be required to eliminate (control) the companion crop. Stanislaus and Cheng (2002) tried to design a cover crop that would self-destruct in response to an environmental cue. If self-destruction could be achieved, no supplemental herbicide or tillage would be required after the cover crop had completed the task of early weed control. They incorporated a heat-shock-responsive promoter to direct expression of the ribonuclease *Barnase*, which is extremely toxic to cells. The heat-shock-responsive promoter very effectively caused heat-regulated plant death and was sufficient to kill the transgenic plants. They concluded that although work with temperature sensitivity showed its potential, that temperature may not be the best factor to study. Temperature is not a completely reliable environment factor (it is not always hot). Therefore, self-destruction based on photoperiodic sensitivity is a more promising research area.

D. Crop Rotations

Crop rotation is done for economic, market, and agronomic reasons. Some weeds associate with certain crops more than with others. Barnyardgrass and junglerice are common in rice. Wild oat is common in irrigated wheat and barley but almost never occurs in rice. Nightshades are common in potatoes, tomatoes, and beans, and kochia and lambsquarters are frequent in sugarbeets. Dandelions are common in turf but not in row crops, although without management, dandelions can increase in row crops and in pastures and long-term hay crops such as alfalfa.

These associations occur because of similarity in crop and weed phenology (naturally occurring phenomena that recur periodically, e.g., flowering), adaptation to cultural practices (e.g., tillage, mowing, irrigation), similar growth habits (e.g., time to mature or to reach full height), and perhaps of most importance, resistance or adaptation to imposed weed control methods. When one crop is grown in the same field for many years (monoculture), some weeds, if they are present in the soil seed bank, will be favored, and their populations will increase. Weed-crop associations are not accidental and can be explained. Associations can be changed by rotating crops, altering time of planting, or changing weed control methods. Annual grass weeds can be reduced in small grain crops by growing corn in the rotation and using herbicides selective in corn plus cultivation to control the grasses when corn is grown. The same herbicides and cultivation cannot be used in small grain crops.

A good rotation includes crops that reduce weeds that are especially troublesome in succeeding crops. Removal is accomplished by competition or through use of different weed control techniques in different crops. In Canada, yellow foxtail populations in flax were highest when flax followed oats, lowest after flax, and intermediate after wheat, corn, and sorghum (Kommedahl and Link, 1958). Sugarbeets grown after beans in Colorado were always more weed-free than sugarbeets grown after sugarbeets, barley, or corn (Dotzenko et al., 1969). Beans are cultivated well, and intensive chemical weed control is practiced. The number of weeds was highest where corn preceded sugarbeets and lowest with beans. Barley was intermediate (Table 10.15).

In many places, barley is planted in spring before soil temperatures are ideal for germination of most annual weeds. Beans, on the other hand, are planted in late spring, and tillage can be used to destroy most summer annual weeds.

Ball and Miller (1990) showed that weed species composition varied with cropping sequence among rotations of corn for three years, pinto beans for three years, or two years of sugarbeets followed by one year of corn (Figure 10.4). Hairy nightshade seed bank population increased after three years of

TABLE 10.15. Effect of the Preceding Crop on Weed Numbers. Weed Numbers Are Those That Germinated in a 400 g Sample of Soil Following Three Years of Each Sequence (Dotzenko et al., 1969).

	Number of				
Preceding rotation	Kochia	Pigweed	Annual grass	Lamb's quarters	Total
Barley-beets	32	15	18	18	109
Corn-beets	67	44	48	7	166
Beans-beets	16	7	11	9	44

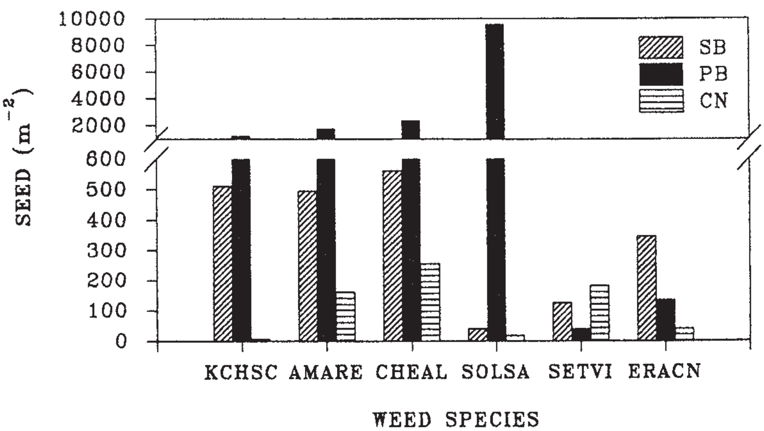


FIGURE 10.4. Influence of cropping sequence on dominant weed species in the soil seedbank 15 cm deep. SB = 2 years sugarbeets + 1 year corn, PB = 3 years pinto beans, and CN = 3 years corn. KCHSC = kochia, AMARE = redroot pigweed, CHEAL = common lambsquarters, SOLSA = hairy nightshade, SETVI = green foxtail, and ERACN = stinkgrass (Ball and Miller 1990). Reproduced with permission of Weed Sci. Soc. of America.

pinto beans, green foxtail increased after three years of corn, and the sugar beet-corn sequence caused an increase in kochia. Ball and Miller attributed the differences to the herbicides used in each cropping sequence. Crop cultivation, land preparation time and method, and time of planting and harvest may also favor some weeds and discourage others.

Crop rotation regularly changes the crop in each field, soil preparation practices, subsequent soil tillage, and weed control techniques. All of these affect weed populations, and while crops are not commonly rotated to control weeds, the effect of rotation as a determinant of weed problems must be recognized.

The relative dry weight of weeds in four cropping systems in the Philippines is shown in Table 10.16. Two weeds dominated, but their relative magnitude in the cropping systems, on the same soil, was different. In a rice-sorghum rotation, itchgrass dominated, but with continuous sorghum, itchgrass nearly disappeared and spiny amaranth dominated. Different cropping systems affect weed populations and favor or deter some species. This is observed in vegetable crops where intensive cultivation and weed control are regularly practiced, and weed populations can be reduced (Roberts and Stokes, 1965).

Long-term studies to determine the effect of different cropping sequences on the population dynamics of winter wild oat (Fernandez-Quintanilla et al., 1984) showed that continuous winter cereal cropping (with or without herbicides) increased the winter wild oat soil seed bank from 26 to 80% per year. With spring barley the soil seed bank declined 10% per year. When sunflower was a summer crop or a 12-month fallow was included in the rotation to prevent new seed production, the soil seed reserve declined 57 to 80% annually. There was a great reduction in the size of the soil seed bank of winter wild oats if the cropping program was other than continuous winter cereals (Fernandez-Quintanilla et al., 1984).

Crop rotation has significant effects on the soil seed bank. A 35-year study at two locations in Ohio showed that crop rotation was a more important

TABLE 10.16. Relative Dry Weight of Weeds in Unweeded Plots in Four Cropping Systems 5 Weeks After Crop Emergence (Pablico and Moody, 1984).

Cropping system	Spiny amaranth (% dry weight)	Itchgrass
Corn-corn-corn	65	21
Rice-corn	42	48
Rice-sorghum	12	83
Sorghum-sorghum-sorghum	95	3

determinant of soil seed density than moldboard plowing, chisel plowing, or no-tillage, although the two were related (Cardina et al., 2002). Initial seed density was highest with no tillage and declined as tillage intensity increased. The research showed how weed species' composition of the soil seed bank changed in response to crop rotation and soil management and provides leads on how complex plant communities are assembled and endure.

E. Fertility Manipulation

Manipulation of soil fertility solely to manage weed populations is virtually unknown. However, as is true of most soil manipulations, fertility affects weeds. Walters (1991) suggests that most weeds can be controlled by simple manipulation of soil nutrient levels. His claims are supported by abundant anecdotal evidence but not by any planned, peer-reviewed scientific research. Nevertheless, they should not be dismissed as idle speculation. Farmers fertilize to maximize yield and attain greater assurance of crop success and profit. They do not fertilize or withhold fertilizer to manipulate weed populations.

Fertilizer is added to improve crop yield, but weeds are often more competitive with crops at higher nutrient levels (DiTomaso, 1995). When weed density is low, added fertilizer, particularly nitrogen, increases crop yield and makes a crop a more vigorous competitor with weeds. But when weed density is high, added nutrients favor weed over crop growth. DiTomaso (1995) summarized much of the literature on this subject. (The subject was discussed in section V-C of Chapter 6.) Crop yield reduction when additional nitrogen fertilizer is added in the presence of weeds is illustrated by the data in Tables 6.8, 6.9, and 6.10.

An excellent illustration of the potential of fertility manipulation as a method to change plant populations is the Park Grass Experiment at the Rothamstead Agricultural Experiment Station in England. The official title of the experiment is "The Park Grass Experiment on the effect of fertilizers and liming on the botanical composition of permanent grassland and on the yield of hay." The work was started in 1856 by Sir John B. Lawes, the son of the manor and founder of Rothamstead as an agricultural research center, and J. H. Gilbert. In many ways, the experiment continues in its original form and is the longest ecological study in the world. The ecological insights were reviewed by Tilman et al. (1994).

In unlimed plots amended with a complete fertilizer with nitrogen primarily as ammonium sulfate, a pure stand of common velvetgrass has developed. It was selected out of the original mixture solely by fertility manipulation and lack of lime. It has one of the heaviest hay yields of any plot, but the hay is unpalatable. With complete fertilizer and lime, plots have one of the heaviest hay yields and a very diverse flora, including orchardgrass and meadow foxtail. In unlimed plots amended with ammonium sulfate and no phosphorus, the vegetation is completely different from either of the preceding. If potassium is absent, dandelions are absent because they flourish only with potassium and a pH above 5.6.

In winter wheat, downy brome was least responsive to nitrogen applied during fallow (Anderson, 1991). Nitrogen applied during winter wheat's growing season increased downy brome growth and decreased wheat yield. When crop season rainfall was only 70% of normal (21 vs. 62 mm), nitrogen fertilization reduced wheat yield 12 to 20%.

Competition for nutrients is not independent of competition for light and water. The complexity and opportunity of fertility manipulation are well illustrated in work by Liebman (1989) and Liebman and Robichaux (1990). They demonstrated improved weed control because of differing nitrogen use efficiency of crops and weeds (Table 10.17). With no added nitrogen, total crop seed yield was identical for the long-vined Century or short-vined Alaska pea cultivars. Century's yield was 45% greater than Alaska's under these conditions. Adding nitrogen dramatically increased barley yield and reduced yield of Alaska peas. Barley can compete for the added nitrogen and Alaska cannot, but the latter cultivar does well with no added N. The seed yield of white mustard increased with nitrogen fertilization, and it was much more competitive with short-vined Alaska than with long-vined Century peas. Results of this study were supported by greenhouse research in Canada that showed that green foxtail grown under low nitrogen required approximately six times as much nicosulfuron for control as plants grown under high nitrogen (10 times

TABLE 10.17. Effect of Pea Cultivar and Nitrogen on Seed Yield and Final Above-Ground Biomass of White Mustard in a Barley/Pea Intercrop. Numbers in Parentheses = % of Total Yield (Liebman, 1989).

	Seed yield g/sq m			Dry weight g/sq m
N treatment/pea cultivar	Barley	Pea	Total	White mustard
No nitrogen				
Alaska	133(37)	230(63)	363	189
Century	16(5)	334(95)	350	105
90 + 90 kg/ha				
Alaska	262(79)	69(21)	331	1,766
Century	204(33)	406(67)	610	948

higher). Higher doses of four herbicides were required to achieve 50% reduction in biomass of redroot pigweed, but there was no similar affect on velvetleaf (Cathcart et al., 2004).

Further evidence of the potential role of soil fertility in weed management is in studies done in Alabama (Hoveland et al., 1976). Soils with low potassium were dominated by buckhorn plantain and curly dock. Soils with low soil phosphorus were dominated by showy crotalaria, morningglory, coffee senna, and sicklepod. The shoot and root growth of several weeds increased with added phosphorus, but the magnitude of the response varied among species. With increasing phosphorus, 17 weed species increased shoot biomass more than wheat and 19 increased shoot biomass more than canola (Blackshaw et al., 2004). The studies that have been done clearly show that manipulating soil nutrient status can change weed populations, and fertility manipulation should be regarded as a potential weed management technique.

VI. HERBICIDE-RESISTANT CROPS

The first herbicide-resistant weed was common groundsel (see Chapter 12; Ryan, 1970). The efficacy of herbicides to control weeds was well known, and it was logical to search for ways to make crops resistant to efficacious herbicides. If concern about crop selectivity could be removed, then an herbicide that killed most weeds could be used without fear of crop injury. The first herbicide-resistant crop appeared in 1996 when canola resistant to atrazine was made available. It was developed as an afterthought (a good idea) following the detection of chlorotriazine-resistant broadleaved weeds in corn in Ontario, Canada (Hall et al., 1996). A breeding program was established at the University of Guelph to transfer the source of triazine resistance from birdsrape mustard to canola (rapeseed). The first atrazine-resistant canola cultivar (OAC Triton) was released in 1984 (Beversdorf and Hume, 1984), others followed in 1986 and 1987.

Herbicide-resistant crops have been adopted readily by farmers across the world. In developing countries, weeds are the most commonly cited constraint to increasing crop production or expanding the amount of land farmed. Development of herbicide-resistant crops through biotechnology has the potential to reduce the weed control problem for farmers in the developing world. To date, the technology has been widely promoted and adopted in developed countries, but efforts and adoption in developing countries have been much less. This may be because after more than a decade of development, there is still little evidence of production cost reductions or increased yield for any crop (Martinez-Ghersa et al., 2003). The agricultural, environmental, economic, and regulatory aspects of herbicide-resistant crops were reviewed by

Duke (1996). The greatest weed control success and best economic return in no-till, herbicide-resistant corn were obtained with an early residual herbicide (i.e., atrazine + acetachlor) followed by application of the postemergence herbicide to which the corn was resistant (Hellwig et al., 2003). Research has shown that the combination of herbicides is always best.

All major herbicide development companies have research programs that deal with herbicide-tolerant/resistant crops (i.e., genetically modified or transgenic crops). Success has been achieved with five individual herbicides and other herbicides from three chemical families (imidazolinones, sulfonylureas, and triazines). These are the five herbicides and some of the resistant crops:

Herbicide	*Resistant Crops*
Bromoxynil	Cotton, potato, tobacco
Glyphosate	Canola, corn, cotton, potato, soybean, tobacco, tomato
Glufosinate	Alfalfa, barley, canola, corn, creeping bentgrass, peanut, rice, sugarbeet, sugarcane, soybean, tomato
Sethoxydim	Corn
2,4-D	Cotton, potato

Most research has focused on major crops: corn, soybean, wheat, rice, cotton, and tobacco (Duke et al., 1991). From the mid-1980s to 1994, more than 1,500 approvals for field testing of a wide range of transgenic organisms were granted, and 40% of them were for herbicide tolerance (Hopkins, 1994). The technology has spread rapidly around the world. James (2005) reported that 54 million hectares or 60% of the world soybean crop (all herbicide tolerant) were planted in the world in 2005, 21.2 million hectares of corn (24%, all Bt = insect resistant), 9.8 million hectares of cotton (11%), and 4.6 million hectares of canola (5%) were biotech crops. Herbicide resistance was the dominant trait followed by insect resistance or stacked genes that incorporated both features (primarily in cotton). Biotech crops were grown in 21 countries, of which 11 were developing countries. The United States grows almost 50% of the world area of biotech crops.

There are three physiological mechanisms for natural or induced tolerance or resistance to an herbicide:

1. Reduced sensitivity at a molecular site-of-action
2. Increased metabolic degradation
3. Avoidance of uptake or sequestration (hiding) after uptake (Duke et al., 1991)

Each of these has potential use in development of resistance in crops.

Criticism of herbicide-resistant crops is common and is usually related to all or some of four perceived risks. The first is *public health* concerns about water or food contamination from increased herbicide use. Additional concern centers on the use of herbicides in crops that do not metabolize the herbicide. Therefore, the unaltered herbicide could be consumed by people.

There are also *environmental* concerns about the increased use of herbicides. Some *social* concerns are about technology favoring large farms and contributing to the destruction of small farms and small-scale farmers. There are also fears that the cost of food production and products will rise.

Weed control concerns center on the issue of herbicide resistance, which may become more widespread from continuous use of herbicides. The fact that not all herbicides have the same probability of selecting for resistance is illustrated well by Beckie et al. (2001). They propose that the higher the risk of an herbicide mode of action group selecting for resistance, the less frequently herbicides from the group should be applied by a grower. Herbicides have been classified into 28 mode of action groups (Mallory-Smith and Retzinger, 2003; Vencill, 2002, pp. 473–479; see Chapter 13). Herbicides in group 1 (inhibitors of acetyl CoA carboxylase, including aryloxyphenoxy propionates and cyclohexanediones) and group 2 [inhibitors of acetolactate synthase (ALS) = inhibitors of acetohydroxyacid synthase (AHAS), including imidazolinones, pyrimidinylthiobenzoates, sulfonylaminocarbonyltriazolinones, sulfonylureas, and triazolopyrimidines] pose a high risk of rapid development of resistant weed biotypes and should not be used frequently. Herbicides in group 9 (inhibitor of EPSP synthase—glyphosate) and group 22 (photosystem I electron divertors—diquat and paraquat) can be used preseeding to reduce the number of weeds available for selection by higher-risk in-crop herbicides (Beckie et al., 2001). Figure 10.5 (Beckie et al., 2001) illustrates herbicide classification using the risk of resistance development. Readers are encouraged to consult local recommendations when planning a weed management system.

The best weed management practice is to know what herbicide families develop resistance rapidly. A monocultural cropping system that relied on glufosinate-resistant rice for weed control would develop resistant weeds within three to eight years (Madsen et al., 2002). Using tillage for supplemental weed control and increasing weedy rice seed predation delayed, but did not prevent, resistance development. Resistance to glyphosate has occurred in several populations of rigid ryegrass in Australia (Wakelin and Preston, 2006). The resistance is encoded in the nuclear genome in the eight populations studied and is inherited as a single dominant allele in four of the five resistant populations.

There are also concerns about *resistant gene flow to sexually compatible plants*. This is acknowledged as one of the greatest potential risks of introducing any genetically engineered (transgenic) crop variety. The risk is transfer of desired herbicide resistance from the crop to a weed where undesirable

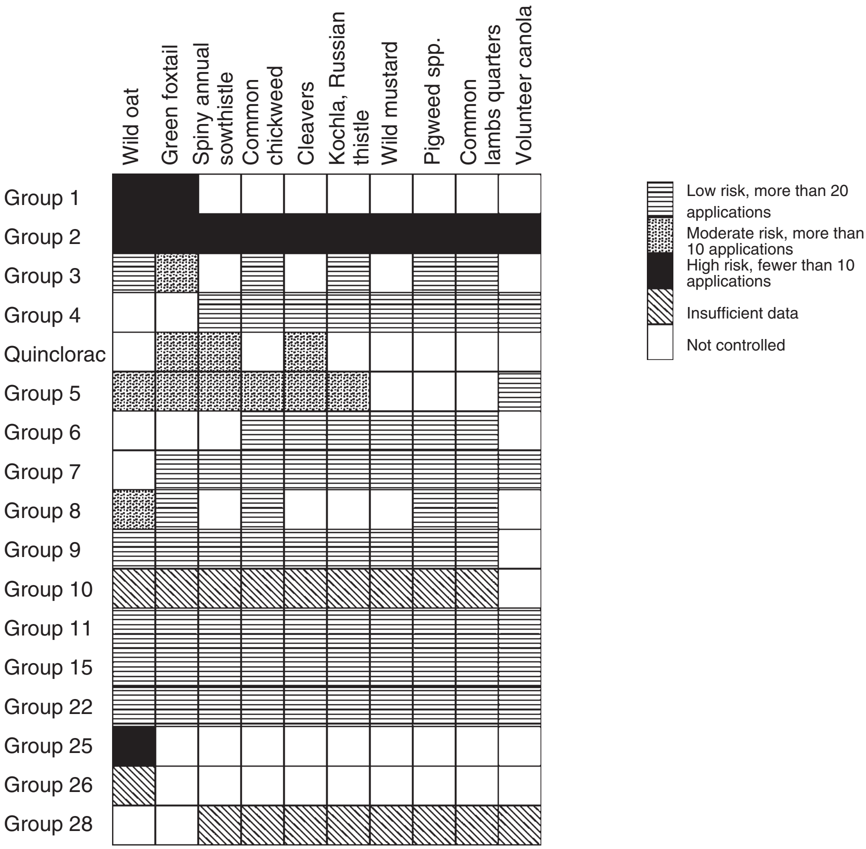


FIGURE 10.5. Classification of herbicide mode of action by risk (high, moderate, and low) for selection of resistance in specific weed species in Canada. Reprinted with permission from Beckie et al. (2001).

resistance persists by natural selection. It is worth noting that this has happened when genes from herbicide-resistant canola moved to a nonweedy relative in the mustard family and then to wild mustard in a short time.[2] The risk may be especially high where the crop and weed are closely related and can interbreed. For example, red rice and rice (Gealy et al., 2003), wheat and jointed goatgrass (Hanson et al., 2005), or wild and cultivated sunflower (Burke et al., 2002), canola and wild mustards (Snow et al., 1999), and between wild and cultivated cucurbits (e.g., squash; Spencer and Snow, 2001). Feral, herbicide-resistant oilseed rapeseed has become established on roadsides

[2] *Denver Post*, April 14, 1996, and *New York Times*, March 7, 1996.

in Europe but has not yet become a problem (Scott and Wilkinson, 1999). Gene flow to near relatives has not occurred in Latin America. However, gene flow is recognized as a potential future problem especially from rice to weedy red rice (Riches and Valverde, 2002).

Resistant crop plants becoming hard-to-control *volunteer weeds* is another issue. This has not been shown, but Keeler (1989) urged caution and pointed out the example of wild proso millet that emerged as a weed in the 1970s after over 200 years of successful cultivation of proso millet in North America without its becoming a weed. Keeler (1989) used wild proso millet to emphasize how much we do not understand about weed evolution. Movement of glyphosate- or glufosinate-resistant creeping bentgrass off site was deemed likely but not problematic because new weed problems were not anticipated to occur (Banks et al., 2004).

The legitimate concerns of epistasis and pleiotrophy must also be recognized. Epistasis is the suppression of gene expression by one or more other genes, and pleiotrophy is defined as a single gene exerting simultaneous effects on more than one character. In short, one of the rules of ecology may apply: you can't do just one thing. When science manipulates a genome, any genome, specific outcomes are intended, and even when these are achieved, other, unplanned (and perhaps, at least, initially, unnoticed) things may also occur. Genetic engineering, with the best intention to do a good thing, may do unexpected things that could be good or bad.

Another common critique of herbicide-resistant crops is that the technology will promote the use of herbicides, not decrease it, while continuing to develop what many view as an unsustainable, intensive monocultural agriculture. A related concern is noted by some in Latin America, where herbicide-resistant technology has progressed rapidly. The technology may encourage expansion of agriculture into uncleared (Amazon rain forest) areas, which become economically attractive because of the efficiency of herbicide-resistant crops. Agricultural expansion would inevitably lead to adverse effects on nontarget organisms and ecosystems (Riches and Valverde, 2002). It is also suggested that herbicide-resistant crops will reinforce farmer's dependence on outside, petroleum-based, potentially polluting technology. An associated concern is that there is no technical reason to prevent a company from choosing to develop a crop resistant to a profitable herbicide that has undesirable environmental qualities such as persistence, leachability, harm to nontarget species, and so on. It is undoubtedly true that nature's abhorrence of empty niches will mean that other weeds will move into the niches created by removal of weeds by the herbicide in the newly resistant crop. In other words, herbicide resistance will solve some but not all weed problems. Weeds not susceptible to the herbicide to which the crop is resistant will appear. Weeds are not conscious, but they seem to be clever.

Marketing and continued development of herbicide-resistant crops are proceeding rapidly, and there are important advantages that provide good reasons for continued development. Many argue that the technology will provide lower-cost herbicides and better weed control. These are powerful arguments in favor of the technology because both can, but to date have not, led to lower food costs for the consumer. It is also true that herbicide-resistant crops are providing solutions to intractable weed problems in some crops. Glyphosate and glufosinate resistance have been created in several crops. Both are environmentally favorable herbicides, and therefore, many argue, it is better to use them in lieu of other herbicides that are not environmentally favorable. An important argument in favor of the technology is that it has the potential to shift herbicide development away from initial screening for activity and selectivity and later determination of environmental acceptability to the latter occurring first. Resistance to herbicides that are environmentally favorable but lack adequate selectivity in any crops or in a major crop so their development will be profitable could be engineered and the herbicide's usefulness could be expanded greatly. This has important implications for minor crops (e.g., vegetables, fruits) where few herbicides are available because the market is too small to warrant the cost of development. If resistance to an herbicide is already successful in a major crop (e.g., cotton), it could be engineered into a minor crop, and manufacturers and users would both benefit. The herbicide chemical industry recognizes the problems of resistance and strongly advocates integrated weed management practices that incorporate herbicide-resistant crops with appropriate cultural, mechanical, and biological management methods (Shaner, 1995).

Biotechnology was discussed by Christianson (1991), a self-acknowledged outsider, and his view is quoted here as an alternative view of this research area:

> I think it would be a pity if the power of the use of mutants and mutation to uncover and describe physiology and development were limited, in the hands of weed scientists, to the isolation and description in yet another species of yet more genes that confer resistance to yet another herbicide. To this outsider, it seems that the central issue for weed science is understanding the nature of weeds: What makes a weed a weed? How can weeds consistently come out ahead when matched up against the finest commercial varieties my plant-breeding colleagues develop? Weeds persist, they spread, and they out compete the crop plants, reducing yields when left uncontrolled. The nature of this 'competitive ability' that weeds possess seems an interesting target for research and an appropriate target for analysis through generation of mutants.

Transgenic crops have developed rapidly (see Hileman, 1995, for a summary of the controversy that has ensued). It is not the purpose of this text to analyze the controversy in depth. A book (Duke, 1996) is available as are articles too numerous to mention (also see Zimdahl, 2006). Much more work will be done and discussed, but it is important to realize that the technique is already widely promoted, accepted, and used.

THINGS TO THINK ABOUT

1. Why is preventing weeds so difficult?
2. Why is eradicating weeds so difficult?
3. What are the advantages and disadvantages of each weed control method?
4. Why are perennial weeds so hard to control by mechanical methods?
5. What is the principle of carbohydrate starvation?
6. How does timing and type of tillage affect weed presence and weed control?
7. Can mowing really be used as a method of weed control? How?
8. Where could soil solarization be used?
9. How can living mulches and companion cropping be incorporated in modern cropping systems?
10. What role does crop rotation play in weed management?
11. What role can fertility manipulation play in weed management systems?
12. What is the present and future role of herbicide resistant crops?

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CHAPTER 11

Biological Weed Control

FUNDAMENTAL CONCEPTS

- Biological control is the action of parasites, predators, or pathogens to maintain another organism's population at a lower average density than would occur in their absence.
- Most biological control organisms have not escaped to become pests.
- Biological weed control cannot solve all weed problems and is best regarded as a technique to be used in integrated weed management systems.

LEARNING OBJECTIVES

- To know the advantages and disadvantages of biological weed control.
- To understand the importance of specificity in development of biological control strategies.
- To know the different kinds of organisms that have been used for biological control of weeds.
- To know the ways that biological weed control can be used.
- To appreciate the opportunities for integration of biological and other weed control methods.

I. GENERAL

Plant distribution is determined by edaphic, climatic, and biotic factors. On a given site, soil type and climate can be discussed and studied but not controlled by humans. The biotic environment can be manipulated. If manipulation is through stable interactions, biological control may be possible.

A. Definition

Biological weed control is the action of parasites, predators, or pathogens to maintain another organism's population at a lower average density than would occur in their absence. The term was first used by H. S. Smith (DeBach, 1964). Biological control is usually thought of as intentional introduction of parasites, predators, or pathogens to achieve control, but it is also a natural phenomenon. Scientists can discover the control potential of natural parasites, predators, or pathogens and exploit it to achieve human ends. The aim is to maintain the offending organism's population at a lower average density, not to eradicate it, but to reduce populations to a noneconomic level. Biological control will never be the solution to every weed problem. It will be employed as one weed management practice among many. Primarily because of well-known problems with chemical weed control, biological control may become more important relative to other control techniques but it will never be the solution to all weed problems in intensive monocultural agriculture.

B. Advantages

In its classical or idealized form, biological weed control can be permanent weed management because once an organism is released, it may be self-perpetuating, and control will continue without further human intervention (see Table 11.1). This is true when some fungal species are released in an innundative approach to control a weed. Subsequently, if theory becomes reality, the weed doesn't have to be actively managed by people, the biological control provides control without further human intervention. This ideal biocontrol is certainly not always and, in fact, rarely, achieved.

Self-perpetuation is an advantage other weed control techniques do not have. There are no chemical environmental residues from biological control other than the organism, which some consider to be a potential problem because it is foreign or unnatural in the environment in which it is released. In the classical or idealized version of biological control this doesn't happen because extensive research before release establishes, one hopes, that the organism is environmentally benign. In theory, there is no environmental pollution (i.e., there is no chemical pollution; there may be biological pollution) from biocontrol organisms and no environmental or mammalian toxicity as there may be after chemical use. Because they most often invade environmentally sensitive areas where all kinds of pollution are to be avoided (aquatic and stream-side areas), biocontrol may be the best option for management of invasive species (see Chapter 7; Myers and Bazely, 2003, p. 12). In ideal cases, initial costs are nonrecurring and usually, once the organism is established,

TABLE 11.1. A Summary of the Advantages and Disadvantages of Biological Weed Control (Wapshere et al., 1989).

Advantages	Disadvantages
1. Reasonably permanent.	1. Control is slow.
2. Self-perpetuating.	2. No guarantee of results.
3. No additional inputs required once agent is established successfully.	3. Establishment may fail for many reasons.
4. No harmful side effects.	4. There may be unknown ecological effects, but mutation to an undesirable form is possible.
5. Attack is limited to target weed and a few close relatives.	5. If target is related to a crop, the number of potential biocontrol agents is low.
6. Risks are known and evaluated before release.	6. Some risks may not be known and cannot be evaluated.
7. Control often dependent on host density.	7. Does not work well in short-term cropping cycles. Works best in stable environments.
8. Self-dispersing spread to suitable host habitats.	8. Restriction of spread to area of initial dispersal is impossible.
9. Costs are nonrenewing.	9. Initial investment of time, money, and personnel can be very high.
10. High benefit:cost ratio for successful programs.	10. Eradication is not possible. Must maintain host population at low level to maintain control agent.

no further inputs are needed. Development costs may be lower than those for herbicides (Auld, 1991). While all of these advantages do not accrue to all organisms developed for biological weed control, they are cited commonly to justify research and greater employment of biological control.

C. Disadvantages

There are some situations where biological control is not appropriate. If a plant is a weed in one place and valued in another place, in the same general geographic region, biological control is inappropriate (see Table 11.1). Spread of a biological control organism, once introduced, cannot be controlled. The control organism is unable to distinguish plants that humans may regard as valuable from weedy relatives. For example, artichoke thistle (also called cardoon) is a weed on some California rangeland. It is closely related to cultivated artichoke. Introduction of a biocontrol agent to control the weedy artichoke thistle is discouraged by artichoke growers because the biocontrol agent would lack specificity. A Eurasian weevil was introduced to North

America to control the invasive, and generally weedy, musk thistle, but it is now attacking native, nonpest thistles (Mack et al., 2000). There are ornamentals species of delphinium related to weedy larkspurs, which make the weed a questionable target for biological control. Other weedy species may be related to valuable native plants. Controversy over problems related to how closely related potential target species are to native or desired species focuses on two issues (Mack et al., 2000). The first asks whether there is sufficient administrative infrastructure to monitor and detect nontarget effects. The second, a scientific question, addresses the likelihood that an introduced biocontrol agent will evolve to attack other possible hosts. Biocontrol scientists usually have "very limited knowledge of the factors that limit effectiveness of control organisms, and much of that knowledge is subjective" (McEvoy, 2002). Safety concerns are best addressed by research on host specificity because it is the criterion that provides the best assurance that a biocontrol organism will suppress the host without harming other species (McEvoy, 2002). An absolute demand for specificity of biocontrol agents means development must be research intensive, may often require a large budget, and several years of research. Research must address the uncertainty about organism movement, evolution, indirect effects, and the severity, probability, and consequences of nontarget effects (McEvoy, 2002). These are not easy or inexpensive tasks, and therefore, it is highly unlikely that biological weed management will ever become an important weed management technique except for a very few species (Hobbs and Humphries, 1994).

Biological control is inherently slow, and results are not guaranteed. In many crops, but not in noncrop or natural areas, weeds must be controlled during a brief, critical period, often of days or weeks, to prevent yield reduction. In addition, because eradication is not an appropriate goal for biological control, weeds that should be eradicated on some sites (e.g., larkspur on rangeland) may be better controlled with other techniques. Some species are geographically local, minor weeds, and development of a biological control for them would be very expensive and not financially wise because of the small infested area. Cropland weeds exist in an ecologically unstable habitat that is often a poor environment for successful introduction, survival, and population growth of biocontrol organisms. Cropland weeds also exist in a weed complex, rarely as a single species. Because biocontrol is necessarily directed at a single species, it is often an inappropriate choice for the weed complex found in most crops. Projects are often constrained by the expense of finding a natural enemy in the native habitat. Locating the natural or native habitat is a difficult research task and, even if found, aggressive natural enemies may not be abundant, if they exist at all.

Because science can never know all possible ramifications of any technological intervention, other cautions should be considered. Release of a biological control organism can induce competitive suppression or extinction of native biological control organisms and other desirable organisms. A corollary is that other harmful or beneficial species may increase in abundance. Such events could lead to loss of biological diversity, loss of existing biocontrol, release of species from competitive regulation, disruption of plant community structure, suppression of essential organisms, and disruption of food chains and nutrient cycling (Lockwood, 1993).

In summary, biological control is slow, often less effective, and commonly less certain than herbicides or mechanical control. Biocontrol, particularly in disturbed cropping situations, will not control as many different weeds as other techniques. It won't eradicate weed problems, but most other techniques won't either. It is an intervention technique that may, as herbicides do, have unanticipated effects.

One example of an unanticipated effect is shown by the work of Callaway et al. (1999). Their two-year study demonstrated that the widely used knapweed root moth (*Agapeta zoegana*) had no significant effect on the biomass of spotted knapweed. The counterintuitive result of their work was that herbivory by the moth may lead to increased negative effects of spotted knapweed on neighboring native plant species. In this case, use of the biocontrol to weaken the invader (spotted knapweed) so natives could gain a competitive advantage led to the opposite result.

D. Use Considerations

Conscious use of biological control of weeds depends on two things. The first is that it is usually, but not always, easier to control an introduced species that, in the process of introduction, was freed of natural predators. The second requirement is that it is best to introduce predators that have been freed of their natural predators during introduction to the weed's area. These requirements presuppose, and successful biological control depends on, several assumptions.

The weed to be controlled has a native habitat. Redroot pigweed, groundsel, common lamb's quarters, and common chickweed are distributed worldwide, and their origin is unknown. If the native habitat is unknown, one cannot go to it to find a predator. Some suggest that many weeds are homeless, having evolved from diverse parentage under various kinds of human created agricultural pressure (Ghersa et al., 1994). Their hometowns cannot be identified.

An insect or disease will give control. The question is, can an effective natural enemy be found? The assumption is questionable because many plants may not have effective natural enemies. If an effective natural enemy is found, whether it's an insect or a disease, it is assumed that it will thrive in the weed's habitat.

Natural reproduction. The organism has fecundity or the ability to reproduce in the new habitat, and it will occupy all niches the weed (the host) infests.

Genetic composition. The weed's genetic composition in its new home will be identical to its, now distant, relatives in its old home. In other words, moving will not change the weed in any significant way. This validity of this assumption has not been determined.

The control organism can be reared in captivity. If this is not true, then it will be necessary to import large quantities of the organism, which, of course, may not be possible.

Searching capacity. After the organism is released it will search out the weed to be controlled and be self-dispersing in the right places.

Each of these assumptions is important, and organisms proposed for biocontrol of weeds often fail because one or more of the assumptions is false. Mistakes have been made when all of the complexity was not understood or ignored. In fact, the history of biological control has demonstrated that it is easy to make mistakes when a biocontrol agent is introduced. Each introduction creates a new combination of organism and environment. Both must be understood, and often they are not (US Congress, 1993). Scientists have used the vacant niche hypothesis to rationalize introductions. The concept is that some ecological roles (i.e., population-regulating organism) are not filled in a place where biological control is desired; thus, the niche is empty and can be filled. Few species fit the narrow ecological vacancy identified by those who wish to control weeds, and it is virtually impossible to predetermine the role a species will play after release (US Congress, 1993).

There are several examples of poor understanding. The mongoose (*Marathi mangus*) was imported to Hawaii to control rats that reduced yield and made sugarcane harvest unpleasant. A mongoose will kill any rat it meets, but rats are nocturnal, and the mongoose hunts during the day, so they don't meet very often! The mongoose eats bird eggs, had no natural enemies in Hawaii, and became and remains a huge pest.

Problems can arise when an introduced species moves beyond the area intended. The cactus moth (*Cactoblastis cactorum*) was introduced to the West Indies to control prickly pear cactus, a native of tropical America, a task it did well. It moved north to Florida, where, it is feared, it threatens indigenous, nonweedy prickly pear cacti in Florida and neighboring states (Kass, 1990), 16 species of which are rare (US Congress, 1993).

The seven-spotted ladybeetle (*Coccinella septempunctata*), an aphid predator, has dispersed throughout much of the United States. It appears to be outcompeting the native nine-spotted ladybeetle (*C. novemnotata*) and has displaced that species in alfalfa. Finally, the US/EPA and the Oregon Dept. of Environmental Quality funded a large project to eradicate weeds in Devils Lake on the northern Oregon coast. About 30,000 weed-eating carp (*Ctenopharyngodon idella*), a successful aquatic weed control agent, were introduced into the lake to control Eurasian watermilfoil. The liquefied fecal waste from the fish created new, unprecedented algal blooms and new weed crops. Six years after the project was initiated, there was no significant reduction in the total amount of aquatic vegetation, but only 4,000 carp still survived. Intensive real estate development in the lake's pristine watershed, clear-cut logging, and recreation proceeded without inhibition and were all major contributors to the lake's pollution and eutrophication (Larson, 1996).

We are residents of the world, not its custodians or rulers. We must learn to understand nature's purposes and our role in aiding or defeating them. Biological weed control, similar to other technologies, can lead us toward harmony with nature or away from it.

Scientists must determine, and users must understand the place of biological weed control in nature's scheme. These are some of the important control questions:

1. Will the insect or disease organism remain free of its old predators and not be subject to new ones in its new habitat? Will the imported, potential biological control agent find the neighborhood in which it must live to be a congenial one? This may be a reason some potentially good biological control agents are abandoned; they meet too many new enemies in their new home.
2. What is the most important criterion and the absolute rule for successful biological control? It is that if an insect or disease is able to clear all the aforementioned hurdles, it must be specific. Specificity means that it will attack and control one plant (the weed) and no others. This is the acid test for biocontrol agents.

It would be a tragedy if a biocontrol agent were released to control a particular weed, and it was discovered after the weed's population was reduced that the biocontrol organism had a natural appetite for rosebushes. Only a very few of the more than 100 organisms released for biocontrol of weeds worldwide have become pests subsequent to their release, but as the preceding examples show, it *can* happen. Biological control research is difficult and crucial to success. Plants in the weed's host range that are tested to ensure specificity include (Strobel, 1991) the following:

1. Those related to the target weed.
2. Those not adequately exposed to the agent for ecological geographic reasons.

3. Those for which little is known about their natural enemies.
4. Those with secondary chemicals or morphological structures similar to those of the target weed.
5. Those attacked by close relatives of the agent.

About 40% of the successful instances of pest biocontrol have involved an unrelated natural enemy. These were new associations between a host and biocontrol agent, and the host lacked all natural resistance to the new enemy (Pimentel, 1963, 1991). The real risk in biological control is not in finding an introduced species or in ensuring that the proposed biocontrol agent clears all the hurdles. The risk is misunderstanding the nature of host specificity. Not enough is known about how natural enemies find and control weed hosts. Why do they do it?

In addition to the fundamental biological questions, there are questions those who develop to sell must ask (Auld, 1991). These include concern about the size and stability of the market and what competing products there may be. Manufacturers must also be concerned about the ability to patent a product to protect their investment and create a reasonable guarantee of profit. Finally, they must ask what is known about the organism and how much it will cost to develop a biological control agent (Auld, 1991).

Given the advantages and disadvantages of biological weed control, there are, and will continue to be, conflicting interests when biological organisms are used for weed control. A plant that is a pest in one place may be beneficial in another place or at least it may be liked. The spread of an organism once it has been released cannot be controlled. Future and present values must be considered, as well as minority and majority interests, neighboring nations, and direct and indirect effects on other species and the environment (Huffaker, 1964).

A few examples illustrate the complexity (Huffaker, 1964). Prickly pear is one of the best examples of the success of biological control of a weed by an insect. The first prickly pear was introduced to Australia from Brazil by Captain Arthur Phillip in 1788. Myers and Bazely (2003) suggest this was done to develop a source of red dye for the red coats of the British army from the cochineal bugs that feed on the cactus. Prickly pear was spread widely in Australia as an ornamental and a hedgerow plant. It was also valued as a source of fruit and forage for cattle during droughts. Some species are still used as hedgerow fences and for fruit in North Africa. By 1916 the prickly pear species had invaded more than 60 million acres in Australia and was estimated to be spreading at 1 million acres a year. It was an environmental disaster. In 1924, exploration in Argentina found a moth borer that attacked a variety of cactus (*Opuntia*) species in Argentina. Moth eggs were collected, sent to Australia by ship, reared, and released from 1925 to 1929 (Myers and Bazely, 2003). Within three years of the introduction of the moth borer, *Cactoblastis cactorum*, the prickly pear area was transformed as if by magic from a wilderness of 60 million acres of prickly pear to prosperous agricultural land. No one in Australia objected. In Hawaii, there were vigorous objections to introduction of the same moth borer. Cattlemen objected because the tree cactus was useful as feed and as a source of otherwise unavailable water on some ranges. The program was also opposed on the US mainland because of similar sentiments in Mexico and in parts of the United States. However, the moth has invaded and is spreading rapidly in southern US states. No one knows if it will spread to Mexico, a center of cactus diversity, where cactuses are used and valued (they appear on the national flag; Myers and Bazely, 2003). The prickly pear cactus biocontrol story is one of great success, but it also illustrates how little is known about the possible consequences.

In California, control of yellow starthistle involves cattlemen, beekeepers, fruit growers, and seed crop growers. The weed damages grazing land, grain, and seed crops. Cattlemen, those primarily affected, want to get rid of it. However, the thistle is a key plant in maintenance of the bee industry for pollination of fruit and seed crops in California. The fruit and seed crop industry dominated the early debate. Now five insects have been introduced and are established in California, Idaho, Oregon, and Washington. A rust fungus (*Puccinia jaceae* var. *solstitialis*) originally from Turkey was released in California in 2003 for biological control of yellow starthistle (Coombs et al., 2004; Rees et al., 1996).

Wood-boring insects are important for control of mesquite because trees infested with wood borers are easier to burn, a primary control technique (Ueckert and Wright, 1973). Defoliating mesquite with the herbicide 2,4,5-T caused the wood-boring insects to die and resulted in trees that were more difficult to burn. Control techniques can conflict even when each is designed to accomplish the same end.

Table 11.2 lists some of the weeds for which biological control efforts have been established and a few others that show promise for the future (Coombs et al., 2004). The list is included to show the scope of current efforts, although it could be much longer.

II. METHODS OF APPLICATION

There are four methods of applying biological control agents: one theoretical and three that are used (Wapshere et al., 1989; Turner, 1992).

TABLE 11.2. A Partial List of Present and Potential Biological Control Programs.[a]

Weed	Biocontrol agent	Type of agent
Established biocontrol agents		
Musk thistle	*Rhinocyllus concicus*	Beetle
Hydrilla	*Ctenopharyngodon idella*	Fish = grass carp
Leafy spurge	*Aphthona cyparissae* + total of 6 *Aphthona* spp.	Beetle
	Spurgia esulae	Gall tip midge
	There are 12 insects that are used	
Prickly pear	*Dactylopius opuntiae*	Cochineal scale
	Cactoblastis cactorum	Moth
Russian knapweed	*Subanguina picridis*	Gall-inducing nematode
St. Johnswort	*Chrysolina quadrigemina*	Beetle
Tansy ragwort	*Longitarsus jacobaeae*	Flea beetle
	Botanophila seneciella	Seed head fly
Potential weeds for biocontrol		
Brazilian peppertree	*Schinus terebinthisfolius*	Insect: sawfly and thrips
Common teasel	*Dipsacus fullonum*	Flea beetle
Garlic mustard	*Alliaria petiolata*	Weevils
Giant reed	*Arundo donax*	Chloropid fly
Japanese knotweed	*Fallopia japonica*	Rust fungus
Sulfur cinquefoil	*Potentilla recta*	Beetles and moths
Hoary cress/whitetop	*Cardaria draba*	Weevils

Sources of additional specific information: Turner (1992); Julien (1992); Coombs et al. (2004); Rees et al. (1996). Julien and Griffiths (1998) is a world list of 949 releases of exotic agents for control of weeds from the late 19th century to 1992. It records the place(s) of release and known results. Coombs et al. (2004) includes 39 weeds for which biological control agents have been released and 15 other weeds for which studies are in progress but where no releases have been made.

A. Classical, Inoculative, or Importation

This method has been limited to weeds that are not closely related to crop plants and that belong to sharply defined genera or families that, theoretically, are taxonomically well separated from other families (Wapshere et al., 1989). Classical biological control is the introduction of host-specific, exotic, natural enemies adapted to introduced (exotic) or native weeds. The great majority of weeds and nearly all the worst weeds has been introduced to agricultural habitats. The basic theory is that when a weed is introduced to a new region or country, it was freed of natural enemies that regulated its population effectively. Often natural regulation was by an innocuous species in the native place.

This is an ecological approach. The introduced target weeds often occur on undisturbed rangelands or in infrequently disturbed habitats (e.g., a pasture or perennial crop). Classical control works best in habitats with minimal disturbance from man. It is the most used and most successful long-term method.

All of the preceding steps are followed. These include weed identification; identification of native habitat; searching for and importation of a natural enemy; research on rearing, specificity, and so forth; and ultimate release. The method is only appropriate with highly specific natural enemies. Arthropods and fungal pests are first choice because they may be specific. Vertebrate animals are usually nonspecific feeders and not suitable for importation (Turner, 1992). The weeds targeted for classical control have almost always been economically important. No other control method has been successful, and their range has expanded to areas where it is not economical to control them with available methods (e.g., puncturevine, Russian thistle, diffuse and spotted knapweeds).

B. Augmentative or Inundative

When large numbers of control agents are raised and released, their abundance is augmented and an area is inundated with them. Releases can be single or repeated throughout a season. The control and target organisms are usually natives, but they may not be. Inundative control employs ecological knowledge but is essentially technological and short term. The method eliminates costly international searches for a weed's native habitat and an organism suitable for import. It augments the inherent phytotoxicity of organisms by abruptly increasing their population. Biological control is made effective in a short time, perhaps even in an annual crop's season. Specificity, however, must be guaranteed. The best agents must be amenable to large-scale captive rearing and have a reproductive method that allows rapid population increase. This requirement alone has inhibited this technique. A stable but easily changed resting or spore stage is helpful. Organisms used for inundation have been pathogens or nematodes rather than arthropods, which do not satisfy the aforementioned criteria. A *Cochineal* scale is redistributed each year in some areas to control prickly pear, a natural process that has been going on a long time. The conscious use of inundative techniques by man is relatively recent. The natural process is a result of evolution and is reflected in the balance of nature.

C. Conservation

If the number of native parasites, predators, and diseases of native plants could be conserved or protected and thereby increased, they should be more effective and might give control. This theoretical concept rests on the assumption that if the population of organisms that prey on an organism with biological control potential could be reduced, the potential agent could fulfill its long-term control potential. It is the same principle involved in importation, but the approach is different. For example, the insect *Aroga websteri* eats foliage of big sagebrush. It has not been exploited for biological control but presumably could be increased in its natural habitat.

D. Broad-Spectrum Control

Broad-spectrum control involves artificial manipulation of a natural enemy's population so a weed is controlled. Whole habitats rather than just a target weed have been modified with this technique. Ecological appropriateness and effectiveness and the organism's virulence are not as important because they can be changed by the population or the stocking rate of the control agent. Safety and specificity are less important for the same reason. The best example is use of selectively polyphagous grazing animals. Fences or shepherds are required to manage grazing animals and expenses are high, but control is possible. Use of goats in the western United States to manage leafy spurge and other noxious weed infestations is an example of broad-spectrum biological control.

III. BIOLOGICAL CONTROL AGENTS

Biological control of weeds began after the technique was used to control insects. It began in the United States in Hawaii in 1902, when eight fruit- and flower-feeding insects were introduced from Mexico to control largeleaf lantana, a perennial shrub native to Central America. Lantana is used throughout the world as an ornamental and has escaped to become a weed (Goeden, 1988; Huffaker, 1964). Many early biocontrol efforts emphasized insects that bored in roots, stems, or seed. Boring provides avenues for secondary infection by bacteria, and fungi and boring insects are usually host-specific. Early efforts also emphasized agents that destroyed flowers in contrast to those that fed only on foliage. Experience has shown that leaf-eaters may be just as safe and equally effective. Now many organisms other than insects are used for biological control of weeds (Andres, 1966; Goeden et al., 1974; Holloway, 1964). A summary of 73 biological control agents approved for 26 species and several other potential agents is available for weeds in the western United States (Rees et al., 1996). Coombs et al. (2004) provided a broader summary of biological control agents for invasive species in the United States.

A. Classical or Inoculative Biological Control

Insects

Classical biological control has been used for many years. The earliest record of biological weed control was the release of the cochineal insect *Dactylopius ceylonicus* from Brazil to northern India in 1795 to control prickly pear cactus (Goeden, 1988). Actually the insect was not identified correctly and was believed to be a species that produced carmine dye (Goeden, 1988). It readily transferred to its natural host plant and was subsequently introduced in southern India from 1836 to 1838, where it successfully controlled prickly pear cactus. Shortly before 1865, the insect was transferred to Sri Lanka and accomplished the same thing. This was the first successful transfer of a natural enemy between countries for biological weed control (Goeden, 1988).

An example of classical biological control of prickly pear cactus was the introduction of *D. opuntiae* in 1951 to Santa Cruz Islands off the coast of southern California. It is perhaps the best example of successful biological control of a native US weed with introduced insects (Goeden and Ricker, 1980). Over many years the insect has given partial to complete control of prickly pear (Goeden and Ricker, 1980; Goeden et al., 1967).

A second example of weed control by an insect is the use of the French chrysomelid leaf beetle *Chrysolina quadrigemina* for control of St. Johnswort (Klamath weed). After its introduction to California in 1946, St. Johnswort was removed from the state's noxious weed list (Coombs et al., 2004). The beetle's success is due to its great specificity and the synchronization of its requirements with St. Johnswort's growth. It has been successful in the western United States and has been introduced to British Columbia, where it has adapted to the colder winters (Peschken, 1972). Adult beetles strip the plant at flowering in spring and early summer, and larvae feed in fall and winter (Huffaker and Kennett, 1959). The beetle's effectiveness and that of a related species (*C. hyperici*) is limited by fall rainfall patterns. Biological control of St. Johnswort has been aided because the two *Chrysolina* beetles have been joined by a root-boring insect, a gall midge, and a moth (Coombs et al., 2004). The weed is widely distributed in Australia, Canada, New Zealand, and South Africa. In the United States it is especially prominent in California, Montana, Oregon, and Washington. Its presence has been associated with sheep movement. St. Johnswort is susceptible to herbicides, but their cost and the inaccessibility of infested rangeland were problems.

Biological control has been successful in Northern California, Washington, and Oregon against the poisonous, biennial weed of rangeland, tansy ragwort. Two insect species were imported from Europe (Pemberton and Turner, 1990). A cinnabar moth (*Tyria jacobaeae*) attacks leafy and flowering shoots, and larvae of the ragwort flea beetle (*Longitarsus jacobeaea*) attack the roots. These have reduced the weed to less than 1% of its density before their introduction (Turner, 1992). They have been joined by a seed head fly, which is not particularly effective but is the only biocontrol agent that is well established east of the Cascade Mountains in the US pacific northwest.

Control of puncturevine in California and Colorado is one of the few victories over an annual weed (Turner 1992). Two weevils, the seed feeder *Microlarinus lareynii* and the stem and crown feeder *Microlarinus lypriformis*, were introduced from Italy beginning in 1961 (Maddox 1976). The weevils work best where the climate is warm. They do not overwinter well in cold climates (Turner, 1992). An Oregon company (IRV Goatheads; see www.goatheads.com) sells 250 adult weevils for $75, the recommended release for moderate infestations. The promotion is that using the weevils will help prevent injuries to bare feet and flat tires on bicycles caused by the tough seed pods. The weevils seem to be most effective when their use is combined with chemical control (Marston, 2005).

Research has been conducted on several insects for control of leafy spurge. At least 11 different insects have been released in the United States with success varying from minor to spectacular. The leafy spurge hawkmoth (*Hyles euphorbiae*) imported from Austria, Hungary, and India eats leaves and flowers during the caterpillar stage (Harris et al., 1985) but has had only minor success. A stem- and root-boring beetle (*Obera erythrocephala*) imported from Hungary and Italy was established in Montana and North Dakota (Leininger, 1988). The beetles puncture stems and lay eggs. Larvae bore into roots, where they mature and exist on carbohydrate root reserves. There is some evidence that the beetle prefers some biotypes over others (Coombs et al., 2004). Six species of chrysomelid flea beetles—*Apthona abdominalis, cyparissae, czwalinae*, *flava, lacertosa*, and *nigriscutis*—were imported to the United States from Europe. Adult *Apthona* beetles live up to three months and feed on leaves. Adult females lay an average of 250 eggs on stems. Larvae bore into stems and cause extensive damage by feeding on primary and secondary roots and root hairs. Control by *A. nigriscutis*, first released in Canada in 1983, has been spectacular (Coombs et al., 2004). Two clearwing moths, two gall midges, and a hawk moth have been moderately successful for some leafy spurge biotypes.

Another chrysomelid beetle was imported from Argentina to Florida in 1965 and successfully controlled the aquatic alligatorweed (Coulson, 1977). Alligatorweed was introduced in the United States about 1894 from South America in ship ballast and had infested nearly 70,000 acres in the southern United States by the 1960s. Impressive control has been achieved, but the insect's success is influenced by temperature, rate of water flow, other plants, water nutrition, and plant vigor. The weed's population has been reduced wherever the beetle has been introduced. A stem borer and alligator weed thrips have also been successful (Coombs et al., 2004).

A weevil from southern Germany (*Rhinocyllus conicus* Froelich) was introduced to Canada in 1968 and to West Virginia in 1969 for musk thistle control. The adult weevils are dark brown with small yellow spots on their back and are only 3/16 to 1/4 inch long. After feeding and mating on thistles, females lay eggs on the bracts of developing flowers in late spring. The larvae hatch, bore into the base of the flower receptacle, and prevent development of some or all seed. It takes a large number of larvae to completely destroy seed production. Because musk thistle is a biennial, a key to its control is prevention of seed production. Plants produce seed for seven to nine weeks, and the average plant produces 4,000 seeds. Egg laying is favored by hot, humid weather, and late flowers may not be affected. *Rhinocyllus* has been successful with up to 90% control on some pasture sites where plant competition provided additional stress, but it is not a complete control for musk thistle. The weevil, unfortunately, may be a bad case of biological control and an exception to the statement that no biological control has ever escaped to become a pest. It attacks native thistles and can move to other species, including the endangered Sacramento thistle in New Mexico. Rhinocyllus may have a fatal flaw for a good biological control, it is not host specific.

Purple loosestrife has been managed biologically with insects. There are at least 120 species of phytophagous insects associated with purple loosestrife in Europe (Malecki et al., 1993). Three species have shown definite promise: *Hylobius transversovittatus* Goeze, a root-mining weevil, which attacks the main storage tissue, and *Galerucella calamariensis* L. and *G. Pusilla* L., both leaf-eating beetles that are capable of defoliating entire plants. Malecki et al. (1993) predict that once these species establish in the field, the combination of defoliation by the chrysomelid beetles and root destruction by the weevils will lead to long-term negative effects on stands of purple loosestrife.

A major effort is underway to find biological control insects for melaleuca and Brazilian pepper, major invasive species in Florida. Over 200 insects that feed on melaleuca have been found in Australia, its natural habitat, and are being tested. Each of these is an aggressive, nonindigenous plant, and they have replaced large natural plant communities (US Congress, 1993; Langeland, 1990). A beetle and a psyllid are promising and under evaluation for melaleuca control in Florida (Coombs et al., 2004). No effective biocontrols for Brazilian peppertree have been released in Florida, but at least four are under intensive investigation. Three insects (two moths and a beetle) were released in Hawaii but were not effective (Coombs et al., 2004).

A major current concern in the western United States is saltcedar or tamarisk (tamarix), an import from Eurasia. Four species dominate: *T. parviflora, T. ramosissima, T. chinensis*, and *T. gallica*. Each is a deciduous shrub that grows 3 to 30 feet tall, with an average height between 9 and 21 feet. They are highly tolerant of saline soil (up to 30,000 ppm salt). They also tolerate fire, drought, flooding, and cold temperatures (Coombs et al., 2004). In short, they are survivors able to adapt to many environments. The main concern is their ability to adapt to riparian areas in the western United States in which they rapidly exclude native vegetation and use prodigious quantities of groundwater (a stand of saltcedar will use an average of 4 to 5.5 acre feet per year—acre foot = 325,000 gallons of water). The larvae and adults of the saltcedar leaf beetle feed on foliage and have been released in several western US states. They do not destroy the stems, which have to be removed manually. Initial action is slow, but by the third year of beetle infestation, large areas can be defoliated.

B. Inundative or Augmentative

Fungi

An endemic anthracnose disease controls Northern jointvetch, a grassy weed in rice and soybeans in southeastern United States. Application of a dry, powdered formulation of the fungus *Colletotrichum gloeosporioides* (Penz) Sacc. f. sp. *aeschymonene* as a mycoherbicide (trade name COLLEGO™, Ecogen, Inc.) has been effective. Daniel et al. (1973) introduced the concept of mycoherbicide (TeBeest, 1991; Wilson, 1969). It is possible to spray the formulated fungal spores on rice infested with Northern jointvetch (Daniel et al., 1973). After a four- to seven-day incubation period, Northern jointvetch dies in five weeks. The fungus is specific, can be produced in large quantities in artificial cultures, and the cultures are infective in the field. Two isolates of the fungus have been combined for effective control of Northern jointvetch and winged waterprimrose in rice (Boyette et al., 1979). A phenoxyacid herbicide can do the same job in two weeks, so the fungus is slower. The fungus must be sprayed annually and is used only when there is a problem. Introduction does not permanently increase its population level.

Bioherbicides, also known as mycoherbicides, are preparations of living inoculum of a plant pathogen, which has been formulated and are applied similarly to chemical herbicides. They have been available since the early 1960s in the United States and China (Auld and McRae, 1997). Although few commercially successful products have been developed, there is international interest in bioherbicides (e.g., the work of Li et al., 2003, in China). Bioherbicides were reviewed by Boyetchko (2001).

The active ingredient in a mycoherbicide is a living microorganism, applied in innundative doses. The organism is commonly a fungus, and its propagules are spores or fragments of mycelium. They frequently fail because of the pathogen's requirement for extended periods of dew or rain (Auld and McRae, 1997). A mycoherbicide has been successful for control of stranglervine in citrus orchards in Florida after application of live chlamydospores of *Phytophthora palmivora* (Butl.) It was first registered in 1981 and marketed as Devine™ by Abbott Laboratories (it is now marketed by Valent Corp.). Live chlamydospores germinated 6 to 10 hours after application to a wet soil surface. The fungus initiated a root infection that killed stranglervine in 2 to 10 weeks, depending on the vine's size and vigor when Devine was applied. Complete control was not obtained in one year, but the fungus persisted and was effective for up to five years, which is a sales disadvantage. Drift to susceptible plants including cucumber, squash, watermelon, rhododendron, begonia, and snapdragon is a problem. In addition to its persistence and effect on other species, the formulation rapidly lost viability after preparation. It had to be treated like fresh milk and even with refrigerated storage, it could not be stored for use another year.

Another mycoherbicide, BioMal™ manufactured by Philom Bios of Saskatchewan, is registered in Canada for control of common mallow in several crops but its market success has been limited. There are good reasons more such products are not presently commercially available (Auld, 1995; Watson, 1989). The most important reason may be that herbicides have been so successful for control of each targeted weed and for the commonly encountered weed complexes. Specificity is the essence of success for biological control agents, but it may lead to commercial failure because weeds usually exist in complex communities. Removal of one weed with a specific biocontrol agent creates a situation where others, released from competition, flourish. Equally important is the fact that each product targeted a specific weed and that inevitably made its market small. Other reasons include the difficulty of mass-producing the infective agent and formulating it so it could be applied. Low pathogen virulence is a common problem. Whereas chemical herbicides can be applied under a range of environmental conditions with reasonable expectation of success, if bioherbicides are applied with unfavorable moisture or temperature, failure is common. Successful application of mycoherbicides normally requires a long dew period that is difficult to obtain in dry climates. Achieving success with a bioherbicide requires a comprehensive understanding of the pathogen, the biology and population dynamics of the target weed, the optimum requirements for disease initiation, and the interactions within the host-pathogen system (Watson, 1989). Chemical herbicides are similar to the brute force required to win in Japanese sumo wrestling, whereas bioherbicides more closely resemble the finesse of successful judo wrestling.

Fusarium oxysporum f. sp. *cannabis* could provide safe, efficient control of marijuana (McCain, 1978). In inoculation studies and in nature, only marijuana was infected. All marijuana types tested were susceptible and cultivars, grown only for hemp, were resistant. Inoculum for field use can be grown efficiently on mixtures of barley straw combined with alfalfa or soybean oil meal. Inoculum spread at 10 kg/ha resulted in 50% mortality of seeded marijuana. Three-quarters of subsequent marijuana plantings died. The fungus causes disease over a wide temperature range, and once a field is infested, marijuana cannot be grown for many years. There is no known danger from the fungus to humans, animals, or other plants.

A potentially more important application of *Fusarium oxysporum* is control of witchweed, one of the world's worst parasitic weeds. It is considered by many to be the greatest constraint to food production in Africa, particularly in the sub-Saharan region. (For additional information on witchweed, see Chapter 3.) *Fusarium* species from West Africa, grown on sorghum straw, have successfully prevented all emergence of witchweed and increased sorghum dry weight as much as 400%. In growth chambers, the fungus inhibited germination and attachment of witchweed to sorghum roots (Ciotola et al., 1995).

The most extensively studied group of plant pathogens is the fungal genus *Colletotrichum*. *C. coccodes,* isolated from eastern black nightshade (Anderson and Walker, 1985) did not kill velvetleaf, but another isolate did (Wymore et al., 1987). Other strains of the fungus kill tomatoes and potatoes, but the identified strain is harmless to all crops tested. It causes disease on velvetleaf over a wide range of dew periods and temperatures, but it is most effective after a 24-hour dew period at 75°F (Wymore et al., 1987).

Peng et al. (2004) showed that mycelial suspensions of *Pyricularia setariae* had strong specificity for control of green foxtail with no significant pathogenicity on more than 25 other species, including wheat, barley, and oats. When the fungus was applied with 10^5 spores per ml, green foxtail fresh weight was reduced 34%. If 10^7 spores were used, fresh weight was reduced 87%. The efficacy was comparable to the commonly used herbicide sethoxydim, and 80% of green foxtail plants resistant to the herbicide were also controlled.

Several strains of the rust fungus *Puccinia chondrillina* have been tested for control of rush skeletonweed (Lee, 1986) to find one for importation and, subsequently successful, use in Australia and dry Mediterranean areas. It was the first exotic plant pathogen successfully used for weed control in North

America (Coombs et al., 2004). A strain of *P. chondrilla* was released successfully in California in 1976 and spread to Oregon in two years (Lee, 1986). The rust has controlled skeletonweed successfully and is specific. Rush skeletonweed is also affected by a root moth, a gall midge, and a gall mite (Coombs et al., 2004).

Puccinia punctiformis, a rust fungus, is an obligate parasite specific to Canada thistle (Cummins, 1978), and infection can lead to death. Infection reduces flowering and vegetative reproduction (Thomas et al., 1995). However, Canada thistle has been very difficult to control everywhere it exists, and the rust fungus, while present, has not been effective.

Conidia of the fungal pathogen *Myrothecium verrucaria* when sprayed in an aqueous phase crop oil emulsion controlled red, ivyleaf, smallflower, and tall morningglory in the three- to five-leaf growth stage (Millhollen et al., 2003). Conidia continued to be effective after autoclaving indicating the action was not due to fungal infection. Chemical analysis showed the presence of several macrocyclic trichothecenes (potent protein synthesis inhibitors), some of which are known phytotoxins (Lee et al., 1999).

Chandromohan et al. (2002) found that a mixture of fungal pathogens isolated from fungi native to Florida controlled six annual and one perennial grass, as well as any one of the pathogens alone. It was possible to manage all seven weeds in the field with an emulsion mixture of the pathogens. The weeds have been difficult to control because they are tolerant of available herbicides, and their growth habits enable them to resist other control practices.

Wilson (1969) described principles for control of weeds with phytopathogens that are still applicable. The first is that host resistance is the primary deterrent to success and may often restrict disease to insignificant levels. Weeds usually have several, rarely fatal, disease lesions on their foliage. Natural weed populations resist insects and diseases because of climate and soil variability and the regular presence of natural, but not fatal, enemies. Disease susceptibility is the exception rather than the rule. Disease epidemics result from importation of new diseases or more virulent strains rather than mere presence. These principles, while generally true, may fail in specific cases. Weed scientists have isolated, cultured, and redistributed local pathogens such as the aforementioned anthracnose disease to achieve weed control. Further work in this area for terrestrial and aquatic weeds (Zettler and Freeman, 1972) offers promise, but while it has been an active research area, commercial success has been elusive. A 1982 review of biological control with plant pathogens reported 4 projects with bacteria, 42 with fungi, 3 with nematodes, and 6 with viruses (Charudattan and Walker, 1972). The book by TeBeest (1991) has many more, but continued progress has been limited. Research is proceeding; the sixth international workshop, Bioherbicides: The Next Generation, of the International Bioherbicide Group was held in 2003 in Canberra, Australia.

Zorner et al. (1993) concluded that the commercial success of bioherbicides "depends on devoting major efforts toward developing appropriate fermentation, stabilization, and delivery technology." As noted, research is proceeding, but the major efforts required have not followed.

Phytopathogenic bacteria have not been considered to have good potential as biological agents because in spite of their known activity, they do not penetrate plants well. This deficiency has been overcome by combining bacteria with surfactants or a cultural operation that injures plants such as mowing. Spray application of *Pseudomonas syringae* in an aqueous buffer with a surfactant produced severe disease in several members of the Asteraceae including Canada thistle (Johnson et al., 1996). Spray application without surfactant failed to produce disease in any plants. *Xanthomonas campestris* pv. *poannua* controlled several annual bluegrass biotypes in bermudagrass golf greens when it was sprayed during mowing but not when it was applied without mowing. Prior mowing injured the grass and allowed the bacteria to enter and cause lethal systemic wilt (Johnson et al., 1996). This technique may lead to further development of bacterial herbicides. They are not obligate biological agents, but they do not persist so may escape the disadvantage of lack of specificity. They must be applied annually. They also have an advantage over fungi because a dew period (wet period) is not required to activate them.

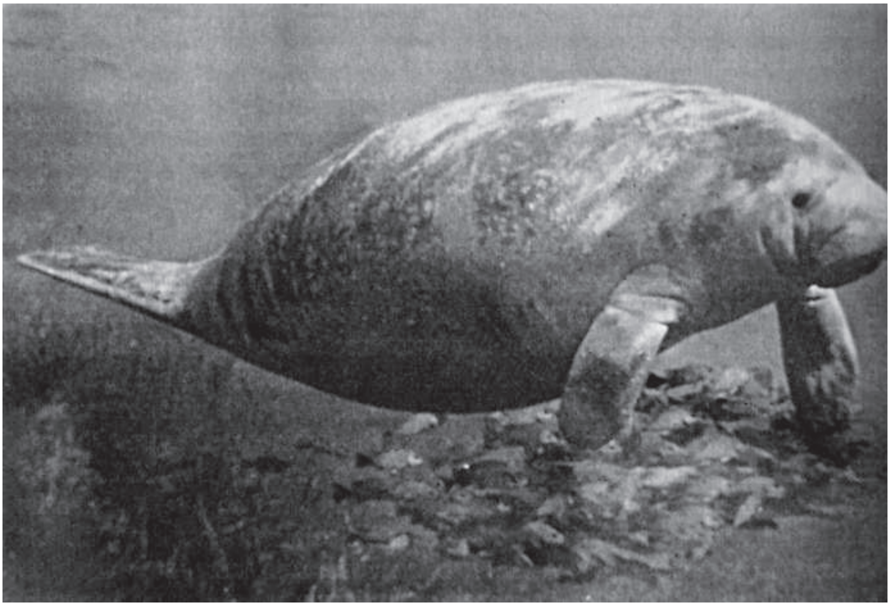
C. Broad-Spectrum Control

Fish

The white amur or grass carp (*Ctenopharyngodon idella* Valenciennes) is an herbivorous fish native to the Amur River, which forms most of the boundary between northeast China and southeast Russia. It can consume 3 to 5 pounds per day of aquatic plants (especially hydrilla); adults may weigh 70 to 100 pounds. It does not spawn in warm water, so it is possible to control its population (Van Zon, 1984). The grass carp breeds but only in large rivers or canals with high water volume and velocity. It feeds on grass and other terrestrial vegetation. Scientists have discovered a way to ensure production of sterile fish. Researchers have tried to cross the white amur and the big-head carp to produce a voracious weed-eating hybrid. There are 240,000 miles of irrigation canals, ditches, and drains in the 17 western United States, and many have aquatic weeds. A theoretical advantage of plant-eating fish is that they may be harvested for food, and, if sterile, their population should be controllable, plus they shouldn't threaten other species.

Resistance to introduction of the grass carp or its hybrids centers around their potential to cause problems similar to those that occurred after introduction of the common carp. These include degradation of water quality

The white amur or grass carp (an herbivorous fish) eats aquatic vegetation.



The sea manatee eats cattails, waterhyacinth, and other aquatic vegetation.

due to the carp's bottom feeding that disturbs sediments and muddies the water and crowding out desirable fish because of the carp's rapid population growth in the absence of natural enemies. A single female grass carp may produce up to a million eggs, and therefore, research has emphasized sterility in released populations.

A concern when a fish is introduced is whether it will prefer and eat selectively the weeds those who introduce it wish to control. Will the fish consider the same species desirable that a Department of Natural Resources or biological control scientists consider undesirable?

Aquatic Mammals

The sea manatee (*Trichechus manatus*) eats cattails and waterhyacinth and can weigh over one ton. It is not discriminatory in its diet and eats many kinds of aquatic vegetation.

Manatees have cleared up to half a mile of canal and banks of a major aquatic waterway in Florida in three weeks. In Florida they had no natural enemies other than man until early 1996 when a over a hundred of about 2,600 remaining manatees died from a poisonous phytoplankton known as red tide. Manatees breath oxygen and often swim just below the surface of the water, where they are hit by boat propellers. They reproduce in both fresh and salt water. However, they are not good biological controls (Etheridge et al., 1985). Estimates of consumption of hydrilla in Kings Bay, Florida, showed that it would take ten times as many manatees just to consume the standing biomass of hydrilla. The natural manatee population (116) was not small for the area, but it was inadequate to control the hydrilla population without even considering increased growth of hydrilla during the winter season.

> It is said that sailors may have seen sea manatees with their fish tail and thought they were mermaids. If you see one, you may think the sailors had a little too much grog. The animal really looks a little like former President Grover Cleveland—chubby with whiskers and thick, wrinkled skin.

Vertebrates

Sheep and goats graze plants that cattle won't eat, such as leafy spurge. Goats relish shrubby species and eat more than sheep, but they are difficult to contain. It takes special attention to fencing to keep them in a place, or it takes a careful herder (usually human and canine); goats love to roam. Sheep- and goat-proof fencing is expensive, as is herding. Goats can be used as a follow-up to mechanical treatments and have killed root sprouts of gambel oak. Goats prefer oak over other plants and don't compete with cattle for forage. They eat brush, leaves, twigs, and almost anything that is organic. Goats have been used successfully to control saltcedar, but 17 months later, the control was not as good as the herbicide imazapyr (Richards and Whitesides, 2006). A combination of grazing one year followed by imazapyr the following year was the most successful. Goats turn to grass when other vegetation has been eaten. They must be removed when they have eaten 90 to 95% of the weedy foliage or they begin to compete with cattle. Goats, because they are aggressive grazers that can denude an area, can destroy wildlife habitat, so regular management is required. But not all is bad. Goats control brush and weeds without disturbing existing grass or the soil. Goats would rather eat brush and weeds than the grasses that cattle prefer. They are browsers, not grazers, as cattle are. Cattle eat as they move, whereas goats move to eat; they browse. Goats also fertilize as they go, and the action of their small hooves literally helps to plant the seeds of the next grazing crop. Goats have been called the next hip things in eco-friendly weed management (Rosner, 2003). They may be more useful for weed management in urban areas than in agricultural fields. Other than the energy to get to a site, no petroleum energy is required for goats to do their work, no chemicals are required, and soil is not disturbed. People seem to like them.

Geese, ducks, and chickens have been used to weed strawberries, raspberries, and some vegetables. They will selectively remove grasses and small broadleaved weeds without crop damage. Chickens and geese selectively control nutsedge in several crops. They are not selective in grass crops. Experiments have shown advantages for geese for weed control during establishment of tree seedlings (Wurtz, 1995). Geese feed almost exclusively on grasses and broadleaved weeds, whereas chickens are omnivorous and eat weed seedlings, seeds, insects, and soil invertebrates (Clark and Gage, 1996). Chickens didn't affect weed abundance or crop productivity (Clark and Gage, 1996). Geese were more effective because they reduced weed abundance and improved potato yield. The problem with geese is they are picky and don't eat all weeds. So species that are unpalatable to geese, such as curly dock and daisy fleabane, increased in abundance (Clark and Gage, 1996). An unsuspected benefit of weeding by geese was a reduction in damage to apples by the plum curculio. Clark and Gage (1996) attributed this to reduced humidity at the soil surface due to weed removal, which reduced plum curculio activity.

IV. INTEGRATION OF TECHNIQUES

Successful, sustainable weed management systems employ combinations of techniques rather than relying on one. Biological control is easy to combine with other methods because, ideally, once established, it can be self-perpetuating. To be successful, an integrated system requires a thorough knowledge of the ecological relationships within the weed-crop system. Knowledge of a farmer's production goals and farming system is necessary but not sufficient. When the goal is sustainable weed management rather than annual control, thorough ecological understanding is required (Wapshere et al., 1989). Successful weed management means that the weed population will be reduced and maintained at a noneconomic level. When annual control is the only aim, rougher techniques can be employed that require less biological knowledge and management skill.

There are several examples of cropping systems in which weed presence actually facilitates biological control of some pest organisms (Table 11.2 includes a few examples). Therefore, it is reasonable to conclude that in some cases complete weed control can be an undesirable goal.

Biological and chemical control have been combined to manage common groundsel (Frantzen et al., 2002). Biological control was based on stimulating epidemic infections of the rust fungus *Puccinia lagenophorae* to reduce the weed's competitiveness at the population level. Common groundsel was controlled well by monolinuron, and the fungus was not needed. The fungus was not compatible with metoxuron, and biological control was contraindicated. However, when pendimethalin was the herbicide of choice, the use of the fungus against common groundsel was complementary to pendimethalin's action on other weeds.

The fungus *Cochliobolus lunatus* is endemic on barnyardgrass (Scheepens, 1987). It has potential as a biological control agent but does not have sufficient activity alone to kill barnyardgrass. It has been successful when combined with sublethal doses (a dose that will not control the weed) of the herbicide atrazine. Under appropriate conditions the fungus produces leaf necrosis and kills seedlings with fewer than two leaves. Plants with more than two leaves recover, although their growth is slowed. It can be used successfully in beans, barley, corn, oats, rye, tomatoes, and wheat. Combination of the fungus with sublethal doses of atrazine enhances control over that achieved with the fungus or atrazine alone (Table 11.3). This is especially true as the weed gets older.

The success of the Chrysolina beetle for control of St. Johnswort has already been mentioned. A successful, integrated system for pastures was developed in Australia (Campbell, 1979) and combined the beetle (biological control agent), an herbicide, and use of plant competition through reseeding in areas where the weed's population had been reduced. On arable land a

TABLE 11.3. Effect of *Cochliobolus Lunatus* and Atrazine on Barnyardgrass in a Growth Chamber (Scheepens, 1987).

	% Necrosis after 9 days		
Treatment	22-day-old plants	30-day-old plants	47-day-old plants
Untreated	0	0	0
C. lunatus	60 +−21	60 +−18	15 +−9
Atrazine @ 40 g/A	60 +−19	60 +−19	3 +−3
C. lunatus + Atrazine @ 40 g/A	100	100	75 +−13

combination of mechanical and cultural control was integrated with biological control. Land is plowed in summer to expose and dry roots, then cultivated in late summer to continue drying and to prepare for seeding an improved pasture mixture. Adequate fertilization is required to guarantee the seeding's success. On nonarable land five techniques are combined. In addition to the beetle, heavy grazing by sheep or cattle is used to remove plants that shade the weed. This is followed by spraying with 2,4-D, planting the proper pasture mixture with adequate fertilizer to take full advantage of plant competition, and well-managed, light grazing and additional fertility to maximize the crop's advantage and competitive pressure on the weed. These methods seem so obvious that one is inclined to say, "Of course, that is what should be done." If these or similar methods are tried in other environments and cropping systems, they might fail unless the ecological relationships have been analyzed and understood. Ecological understanding leads to selection of the best combination of techniques to manage the weed population rather than the best method to obtain a quick kill but no long-term reduction of the weed's population. Chapter 20 has additional examples of integrated weed management systems.

THINGS TO THINK ABOUT

1. What applications are there for biological control?
2. Why hasn't biological control been used more widely?
3. What are some good examples of successful biological control of a weed?
4. What is a bioherbicide or mycoherbicide, and how are they used?
5. Where are vertebrate animals best used for biological weed control?
6. How can biological control be integrated with other methods?

7. What are the economic advantages of biological control?
8. Compare and contrast the advantages and disadvantages of biological weed control.

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CHAPTER 12

Introduction to Chemical Weed Control

FUNDAMENTAL CONCEPTS

- Herbicides created a major change in the way agriculture is practiced by substituting chemical energy for human and animal energy.
- Herbicides have several advantages and disadvantages all of which should be considered prior to use.
- Herbicides can be classified in several useful ways, but no one way integrates all of them.
- Classifications based on chemical structure and site/mechanism of action are common.

LEARNING OBJECTIVES

- To understand the history of chemical weed control.
- To know and understand the advantages and disadvantages of herbicides.
- To understand the different ways of classifying herbicides and the use of each classification system.

A wider range of methods has been offered to vegetation management through the use of herbicides. Herbicide comes from the Latin herba, meaning "plant," and caedere, meaning "to kill." Therefore, herbicides are chemicals that kill plants. The definition accepted by the Weed Science Society of America (Vencill, 2002, p. 459) is that an herbicide is "a chemical substance or cultured organism used to kill or suppress the growth of plants." In effect, a herbicide disrupts the physiology of a plant over a long enough period to kill it or severely limit its growth.

Pesticides are chemicals used to control pests. Herbicides, a subcategory, are pesticides used to control plants. They are different from other pesticides because their sphere of influence extends beyond their ability to kill or control plants. Herbicides change the chemical environment of plants, which can be more easily manipulated than the climatic, edaphic, or biotic environment.

Herbicides reduce or eliminate labor and machine requirements and modify crop production techniques. When used appropriately, they are production tools that increase farm efficiency, reduce horsepower, and perhaps reduce energy requirements. Herbicides do not, of course, eliminate energy requirements because they are petroleum based.

Understanding the nature, properties, effects, and uses of herbicides is essential if one is to be conversant with modern weed management. Weed management is not accomplished exclusively by herbicides, but they dominate in the developed world. Whether one likes them or deplores them, they cannot be ignored. To ignore them is to be unaware of the opportunities and problems of modern weed management. Ignoring or dismissing herbicides may lead to an inability to solve weed problems in many agricultural systems and may delay development of better weed management systems.

I. HISTORY OF CHEMICAL WEED CONTROL

A. The Blood, Sweat, and Tears Era

Agriculture can be thought of as having had three eras. The first is best characterized as the blood, sweat, and tears era. Famine and fatigue were common, and inadequate food supplies occurred frequently. Most people were farmers, and many farms were small and operated at a subsistence level. Life was, for most people, in the words of the British philosopher Thomas Hobbes (1588–1679):

> Wherein men live without other security, than their own strength, and their own invention shall furnish them. . . . In such conditions there is . . . no knowledge of the face of the earth; no account of time; no arts; no letters; no society; and which is worst of all, continual fear and danger of violent death; and the life of man, solitary, poor, nasty, brutish, and short.

Hobbes's dismal view still characterizes the lives of at least 3 billion of our fellow human beings who live on less than the equivalent of US $2 per day (Nielsen, 2005, p. 170).

B. The Mechanical Era

The mechanical era of agriculture began with the invention of labor-saving machines. In 1793, Eli Whitney invented the first workable cotton gin. Cyrus

McCormick invented the reaper in 1834 and began manufacture in 1840. John Deere perfected the steel moldboard plow in 1837. In 1830, four farmers in the United States supported five nonfarmers. In 1910 a farmer fed himself (most were men) and six others. By 1930, one farmer was able to support 10 nonfarmers. One farmer supported 40 nonfarmers in 1965. US Census data show a nearly constant decline in the number of farms, number of farmers, and persons per farm since 1900. Today, fewer farmers support more nonfarmers in the United States and several non-US people through food exports. Much of the increase in farm productivity has been due to agricultural mechanization and improved technology.

C. The Chemical Era

The third era of agriculture, the chemical era, boosted production again. The chemical era really began when nitrogen fertilizer became readily available and increased production of the newly available hybrid corn. In the early 1930s when these things began, one-quarter of the American population lived on farms. When nitrogen fertilizer was combined with hybrid corn varieties, first experimented with by Henry Wallace in 1913, yields went up rapidly. Wallace's early work led to his founding Pioneer HI-Bred Int. in 1926. Subsequently, hybrid corn was popularized by Roswell Garst in Iowa. In 1933, corn sold for 10 cents a bushel, and a fraction of 1% of Iowa land was planted with hybrid seed. In 1943, 99.5% of Iowa corn was hybrid. In 1933 corn yield was 24.1 bushels per acre, about what it was during the Civil War. In 1943 it was 31, but by 1981 it had grown to 109 bushels per acre (Hyde, 2002).

After 1945, when pesticides were developed and became widely available, yields continued to increase. In 1992, about 1% of US citizens were farmers (about 2.8 million), and each farmer fed 128 others (94.3 Americans and 33.7 people in other countries; Krebs, 1992). Now, in agriculture's chemical era, less than 1% of US citizens farm, and they grow more than their grandfathers and great-grandfathers ever dreamed possible. In nearly all US states, the number of farmers has declined, and production and average farm size have increased (farm size averaged 441 acres in 2002; US Census, 2002). Ninety percent of US farms are family or individual farms. Three percent are corporate farms that capture 28% of sales and government payments (USDA, 2002). In fact, USDA data show that just 3.6% (about 68,000) of the 2.13 million US farms produce just over 56% of all agricultural sales.

These changes are not unique to American agriculture. In 1938, Britain employed a million people to produce a third of the food needed for a nation of 48 million. In 1988 only 450,000 British farmers and farm workers produced three-quarters of the food for 58 million people (Malcolm, 1993). Production from each British agricultural worker increased at about twice the rate of increase for the rest of the economy (Malcolm, 1993). Less than 3% of the population of Germany works on farms. Farmers account for less than 2% of Europe's working population. Increases in crop production and labor productivity in each agricultural era were caused by extensive farm mechanization, the use of agricultural chemicals, increased education of farmers, improved crop varieties, and improved farming practices.

Developed-country agriculture is now in the era of extensive and intensive use of chemical fertilizers and pesticides and seems to be moving rapidly toward the next era of agriculture: the era of biotechnology.

The chemical era of agriculture developed rapidly after 1945, but it did not begin then. In 1000 BC, the Greek poet Homer wrote of pest-averting sulfur. Theophrastus, regarded as the father of modern botany (372?–287? BC), reported that trees, especially young trees, could be killed by pouring oil, presumably olive oil, over their roots. The Greek philosopher Democritus (460?–370? BC) suggested that forests could be cleared by sprinkling tree roots with the juice of hemlock in which lupine flowers had been soaked. In the first century BC, the Roman philosopher Cato advocated the use of amurca, the watery residue left after the oil is drained from crushed olives, for weed control (Smith and Secoy, 1975).

Historians tells us of the sack of Carthage by the Romans in 146 BC, who used salt on the fields to prevent crop growth. Later, salt was used as an herbicide in England. Chemicals have been used as herbicides in agriculture for a long time, but their use was sporadic, frequently ineffective, and lacked any scientific base (Smith and Secoy, 1975, 1976).

In 1755, mercurous chloride ($HgCl_2$) was used as a fungicide and seed treatment. In 1763, nicotine was used for aphid control. As early as 1803, copper sulfate was used as a foliar spray for diseases. Copper sulfate (blue vitriol) was first used for weed control in 1821. In 1855, sulfuric acid was used in Germany for selective weed control in cereals and onions. In 1868, Paris green (copper acetoarsenite) was used for control of the Colorado potato beetle (*Leptinotarsa decemlineata*). The US Army Corps of Engineers used sodium arsenite in 1902 to control waterhyacinth in Louisiana.

Bordeaux mixture, a combination of copper sulfate, lime, and water was applied to grapevines for the control of downy mildew in the late 19th century. Someone in Europe noted that it turned yellow charlock leaves black. That led Bonnet, in France in 1896, to show that a solution of copper sulphate would selectively kill yellow charlock plants growing with cereals. In 1911, Rabaté demonstrated that dilute sulphuric acid could be used for the same purpose. The discovery that salts of heavy metals might be used for selective weed control led, in the early part of the 20th century, to research by the

Frenchmen Bonnett, Martin, and Duclos, and the German, Schultz (cited in Crafts and Robbins, 1962, p. 173). Nearly concurrently, in the United States, Bolley (1908) studied iron sulfate, copper sulfate, copper nitrate, and sodium arsenite for selective control of broadleaved weeds in cereal grains. Bolley, a plant pathologist who worked in North Dakota, is widely acknowledged as the first in the United States to report on selective use of salts of heavy metals as herbicides in cereals. The action was caustic or burning with little, if any, translocation. Succeeding work in Europe observed the selective herbicidal effects of metallic salt solutions or acids in cereal crops (Zimdahl, 1995). The important early workers were Rabaté in France (1911, 1934), Morettini in Italy (1915), and Korsmo in Norway (1932).

Use of inorganic herbicides developed rapidly in Europe and England, but not in the United States. In fact, weed control in cereal grains is still more widespread in Europe and England than in the United States. Some of the reasons for slow development in the United States included lack of adequate equipment and frequent failure to obtain weed control because the heavy-metal salts were dependent on foliar uptake that did not readily occur in the low humidity of the primary grain-growing areas. The heavy-metal salts worked well only with adequate rainfall and high relative humidity. There were other agronomic practices such as increased use of fertilizer, improved tillage, and new varieties that increased crop yield in the United States without weed control. US farmers also could always move on to the endless frontier and were not as interested, as they would be later, in yield enhancing technology.

Carbon bisulfide was first used in agriculture in 1854 as an insecticide in France. It was applied as a soil fumigant in Colorado to control *Phylloxera*, a root-borne disease of grapes. In 1906, it was introduced as a soil fumigant for control of Canada thistle and field bindweed. It smells like rotten eggs and may have reached its peak usage in Idaho in 1936 when over 300,000 gallons were used.

Petroleum oils were introduced for weed control along irrigation ditches and in carrots in 1914. They are still used in some areas for weed control. Field bindweed was controlled successfully in France in 1923 with sodium chlorate and it is now used as a soil sterilant in combination with organic herbicides. Arsenic trichloride was introduced as a product called KMG (kill morning glory) in the 1920s. Sulfuric acid was used for weed control in Britain in the 1930s. It was and still is a very good herbicide, but it is very corrosive to equipment and harmful to people.

The first synthetic organic chemical for selective weed control in cereals was 2-(1-methylpropyl)-4,6-dinitrophenol (Dinoseb), introduced in France in 1932 (King, 1966, p. 285). It was used for many years for selective control of some broadleaved weeds and grasses in large-seeded crops such as beans. It is included in the 6th edition of the *Herbicide Handbook* (Anonymous, 1989) but not in the 7th (Ahrens, 1994) or 8th (Vencill, 2002), although dinoterb, a close chemical relative that is not sold in the United States is. Dinoseb is included in the WSSA list of approved herbicides (Anonymous, 2004). Dithiocarbamates were patented as fungicides in 1934. In 1940, ammonium sulphamate was introduced for control of woody plants.

Historians of weed science will note 1941 as an important year. Pokorny (1941) first synthesized 2,4 dichlorophenoxy acetic acid (2,4-D). It was reported to have no activity as a fungicide or insecticide. Accounts vary about when the first work on growth-regulator herbicides was done (Akamine, 1948). Zimmerman and Hitchcock (1942) of the Boyce-Thompson Institute (formerly in Yonkers, NY, now at Cornell University, Ithaca, NY) first described the substituted phenoxy acids (2,4-D is one) as growth regulators (auxins) but did not report herbicidal activity. They also worked with other compounds that eventually became herbicides. They were the first to demonstrate that these molecules had physiological activity in cell elongation, morphogenesis, root development, and parthenocarpy (King, 1966). A Chicago carnation grower's question, "What is the effect of illuminating gas[1] on carnations?" led to the eventual discovery of plant growth–regulating substances by Boyce-Thompson scientists (King, 1966).

E. J. Kraus was the head of the University of Chicago Botany Department and had studied plant growth regulation for several years. He supervised the doctoral programs of J. W. Mitchell and C. L. Hamner, who in the early 1940s were working as plant physiologists with the US Department of Agriculture Plant Industry Station at Beltsville, Maryland. Kraus thought these new, potential plant growth regulators that often distorted plant growth when used at higher than growth regulating doses, and even killed plants, might be used beneficially to selectively kill plants. He saw potential use as chemical plant killers or herbicides and advocated purposeful application in toxic doses for plant control. Because of World War II and the potential for biological warfare against an enemy's crops (e.g., German potatoes), much of this work was done under contract from the US Army (Peterson, 1967; Troyer, 2001). Similar work for similar reasons was done in Great Britain (Kirby, 1980). The chemicals were not used for biological warfare during World War II. A much more complete chronology and history of development of the hormone herbicides is available in Kirby (1980) and Troyer (2001).

Hamner and Tukey (1944a and b) reported the first field trials with 2,4-D for successful selective control of broadleaved weeds. They also worked with 2,4,5-T as a brush killer. At nearly the same time, Slade et al. (1945), working

[1]Acetylene gas.

in England, discovered that naphthaleneacetic acid at 25 lbs/acre would selectively remove charlock from oats with little injury to oats. They (Slade et al., 1945) also discovered the broadleaved herbicidal properties of the sodium salt of MCPA (later called Methoxone; King, 1966), a compound closely related to 2,4-D. Slade et al. (1945) confirmed the selective activity of 2,4-D. Marth and Mitchell (1944), former students of E. J. Kraus, first reported the differential use of 2,4-D for killing dandelions and other broadleaved weeds selectively in Kentucky bluegrass turf. Marth and Mitchell (1944) attribute the quest for selective activity of these compounds to Kraus. These discoveries were the beginning of modern chemical weed control. All previous herbicides were just a prologue to the rapid development that occurred following discovery of the selective activity of the phenoxyacetic acid herbicides. The first US patent (No. 2,390,941) for 2,4-D as an herbicide was obtained by F. D. Jones of the American Chemical Paint Co. in 1945 (King, 1966). There had been an earlier patent (No. 2,322,761) in 1943 of 2,4-D as a growth regulating substance (King, 1966). It is interesting to note that Jones patented only its activity (the fact that it killed plants) but made no claim about selective action (the fact that it killed some, but not all, species; King, 1966).

The effectiveness of monuron, a substitute urea, for control of annual and perennial grasses, was reported by Bucha and Todd (1951). This was the first of many new selective chemical groups with herbicidal activity. The first triazine herbicide appeared in 1956 and the first acylanilide in 1953 (Zimdahl, 1995), followed by CDAA, the first alphachloroacetamide in 1956 (Hamm, 1974).

The great era of herbicide development came at a time when world agriculture was involved in a revolution of labor reduction, increased mechanization, and new methods to improve crop quality and produce higher yields at reduced cost. Herbicide development built on and contributed to changing agriculture. Farmers were ready for improved methods of selective weed control. Farmers' acceptance of technological developments that changed the practice of agriculture has been characterized in terms of economic, social, political, and philosophical attitudes by Perkins and Holochuck (1993). Farmers wanted to improve their operation in competition with other farmers and were willing to adopt new technology that enabled them to improve their economic competitiveness. New technology was socially acceptable because, as independent entrepreneurs, many technological innovations could be used to gain advantage independent of neighbors. Politically, farmers welcomed technical assistance that came from public laboratories (land-grant universities) and government price support systems that allowed farm operations to remain private. Fiercely independent farmers welcomed opportunities to do what they wanted on their own farms. They welcomed technology developed at no apparent cost to them that could be adopted without interference from anyone.

Finally, philosophically, farmers perceived that a major part of their task was controlling nature, bending nature to human will. Although this was a never-ending challenge, success was apparent when technology that increased production was readily available. Herbicides fit well in each category.

It is true that no weed control method has ever been abandoned, but new ones have been added, and the relative importance of methods has changed. The need for cultivation, hoeing, and so on has not disappeared. These methods persist in small-scale agriculture (e.g., I hoe my garden!). Older methods have become less important in developed-world agriculture because of the rising costs of labor and narrower profit margins (Table 12.1).

Rapid development of herbicides occurred after World War II. In 2002, 204 selective herbicides were listed in the *Herbicide Handbook* (Vencill, 2002), and 357 have been approved by the Weed Sci. Soc. (Anonymous, 2004). There are several experimental herbicides in some stage of progress toward marketability. If proprietary labels are considered, there may be more than 1,000 chemical and biological compounds used for pest control in the world (Hopkins, 1994). Table 12.2 illustrates that whether dollars or pounds of product are used, pesticide use has been increasing and herbicide use predominates. In 1997, 1 billion pounds of pesticides were used in the United States, and over 47% (461.4 million pounds) of herbicides (Gianessi and Silvers, 2000; Table 12.2). Just ten herbicides accounted for 75% of sales (Gianessi and Marcelli, 2000). US farmers routinely apply herbicides to more than 85% of crop acres (Gianessi and Sankula, 2003). A study of 40 crops showed treatment of 220 million acres at a cost of $6.6 billion (Gianessi and Sankula, 2003). In 2001, the global market for nonagricultural pesticides was more than US $7 billion per year and was growing about 4% a year. The global market just for turf pesticides is approximately US $850 million per year, with about half of it

TABLE 12.1. The Evolution of Weed Control Methods in the United States (Alder et al., 1977).

	% Control by year in US			
Year	Human energy	Animal energy	Mechanical energy (Tractor)	Chemical energy
1920	40	60		
1947	20	10	70	
1975	5	TR[a]	40	55
1990	<1	TR	24	75

[a]tr = trace.

TABLE 12.2. World Sales of Crop Protection Products 1960 to 1990 with 2000 Estimated in Billions of Dollars (Gianessi and Silvers, 2000; Hopkins, 1994).

	World pesticide sales (million US dollars)					
Pesticide	1960	1970	1980	1990	1997	2000
Herbicides	160	918	4,756	12,600	14,700	16,560
Insecticides	288	945	3,944	7,840	9,100	9,360
Fungicides	320	702	2,204	5,600	5,400	7,560
Other	32	135	696	1,960	1,700	2,520
TOTAL	800	2,700	11,600	28,000	30,900	36,000

used on golf courses. Each year US lawn care firms apply about $440 million of pesticides.

The National Agricultural Statistics service of the US Department of Agriculture regularly surveys selected states and selected crops to determine the extent of fertilizer and pesticide use. The 1997 report (1996 data, http://usda.mannlib.cornell.edu/reports/n...emical_usage_field_crops_summary_09/03.97; accessed August 2000) shows that herbicides were used on a major portion of the acreage of each crop surveyed. Here are the specific figures for the five crops surveyed in 1997:

Crop	Percent of acres treated with herbicides
Corn	97
Cotton	92
Potato	87
Soybean	97
Tobacco	75

Crops surveyed in 2004 (http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0505.txt; accessed October 2005) show similar data, and each set illustrates the dominance of herbicides for weed control. The soybean data show the dominance of glyphosate-resistant soybean, and the wheat data probably illustrate the low profitability of the crop and the lack of weed problems for which herbicide solutions exist.

Crop	Percent of acres treated with herbicides
Peanut	98
Soybean	97
% of acres treated with glyphosate	87
Wheat, durum	99
Wheat, winter	45

The global herbicide market was estimated to be $13.5 billion from 1990 to 1993 and a third ($4.5 billion) was the US market. Japan was the next largest with $1.5 billion in sales. When the entire European market is considered, it is second largest, with France ($1.250 billion) the largest single country (Hopkins, 1994). In 2001, world expenditures on all herbicides were US $14,118 million, and 44% of this for the world and the US was herbicides. The United States spent $6,410 million for 553 million pounds of active ingredient, which was equal to 4,987 million pounds of product. These amounts are lower than purchases in 2000 and have returned to the levels last seen in the early 1970s; US/EPA, 2004). Of these amounts, 78% is used in agriculture, with the rest nearly evenly divided between industrial/commercial/government (12%) and home and garden use (10%).

In 1990 for the world, about 45% of total pesticide sales volume was herbicides (similar to the US data), insecticides were 28%, and fungicides approximately 20% of total sales volume (Hopkins, 1994). Over 85% of herbicides are used in agriculture. The worldwide market is becoming increasingly concentrated in the hands of a few multinational corporations. Nearly half the companies in pesticide discovery (but not in development and marketing) in 1994 were Japanese (Hopkins, 1994). The number of companies marketing herbicides in the United States has steadily shrunk from 46 in 1970 to 7 in 2005 (Appleby, 2005). Three are based in the United States, and the others are based in Europe but operate in the United States (Appleby, A.P., 2005, personal communication).

While the number of companies engaged in herbicide discovery, development, and sales has steadily declined (Appleby, 2005; see Chapter 20), the number of available herbicides has steadily increased. Table 12.3 shows the number of herbicides listed in the first (1967) through the eighth (2002) edition of the Weed Science Society of America's (WSSA) *Herbicide Handbook* has increased, as has the number of different chemical families in which herbicidal activity has been discovered. Similarly, the number of WSSA-approved herbicides has increased from 304 in 1995 (Anonymous, 1995) to 357 in 2004

TABLE 12.3. The Number of Herbicides and Chemical Families in the Eight Editions of the *Herbicide Handbook* of the Weed Science Society of America.

	Year of *Herbicide Handbook* publication							
	1967	1970	1974	1979	1983	1989	1994 + 1998 supp.	2002
Total herbicides	97	115	125	137	130	145	163	211
Number of chemical families	27	27	32	37	35	43	63	75

(Anonymous, 2004). It is clear, and not debatable, that because of their significant production advantages herbicides have dominated modern weed control. Timmons (1970) reported 75 herbicides marketed between 1950 and 1969. Appleby's 2005 paper included 184 herbicides marketed between 1970 and 2005, an increase of 2.4 times. Although the herbicide chemical industry has undergone extensive consolidation, as have many other manufacturing industries, it has not diminished discovery and development of new herbicides in older chemical families or discovery of activity in new chemical groups.

Worldwide sales have continued to increase. World exports of pesticides of all kinds totaled US $15.9 billion in 2004, a new high in sales for the global chemical industry (Jordan, 2006). Use of all kinds of pesticides has risen from nearly 0.5 kg/ha in 1960 to 2 kg/ha in 2004. The recent increase is attributed mainly to the increased use of herbicides on genetically modified crops in China (Jordan, 2006).

II. ADVANTAGES OF HERBICIDES

Agriculture collects and stores the electromagnetic energy of the sun as food energy (chemical energy) in plant and animal products. Food is available because plants do this so well and few other life forms can do it in a way that makes food for people. Farming invests about three calories of fuel energy (which some call cultural energy) in soil tillage, fertilizer, pesticides, irrigation, and harvest to help plants convert sunlight into one calorie of stored chemical energy in food (Lovins et al., 1984). When the energy costs for processing, distribution, and preparation are included, approximately 9.8 calories of energy are expended for every calorie of food energy produced in the United States (Lovins et al., 1984). However, many argue that it is not the task of agriculture to produce energy; the task is to produce food, and that is done very well. Herbicides contribute to abundant production. All pesticides account

TABLE 12.4. Energy Relationships in Weed Control in Six Experiments on Corn in Minnesota (Nalewaja, 1984).[a]

Method of weed control	Energy for weed control (MJ/ha)	Corn yield kg/ha	Corn yield MJ/ha	Net profit from weed control $/ha		Energy output/input MJ/ha	Man-hour/ha
None	0	3,387	56,528	—	—	0	
Cultivation	579	5,080	84,387	151	27,550	48/1	1.41
Herbicide	391	5,645	93,763	194	37,113	95/1	0.12
Hand Labor	337	5,770	—	163	39,251	116/1	148.15

[a]The land was plowed, disked, and prepared for planting corn in the conventional manner. Calculations are based on an average of 2.5 cultivations using 2.8 L of gasoline/ha and spraying using 0.8 L gasoline/ha. Atrazine was applied at 3.4 kg ha^{-1}.

for only 3% of the energy used in agricultural production. On farm energy, consumption represents only a little over 3% of total US energy consumption, and only 18% of the energy used in the entire US food system from farm to table (Lovins et al., 1984).

Any successful technology should create gains in value that are reproducible. Although the data on energy use for weed management are old, no recent and more relevant studies have been done. Table 12.4 shows energy relationships for weed control in corn in Minnesota (Nalewaja, 1974), and Table 12.5 shows similar data for cotton in Georgia (Dowler and Hauser, 1975). The weed density in corn was low, but it was high in cotton. In both cases, the cost-benefit analysis favored herbicides over other methods. Hand labor gave the greatest energy output/input ratio. The data do not consider the energy to house and feed workers or the fact that such work is seasonal (Barrett and Witt, 1987). Soil was plowed, disked, and prepared for planting corn or cotton in conventional ways, and all other cultural practices were uniform. With no weed control, there was, of course, no profit due to weed control and a low yield and crop value. Cultivation and herbicides were not very different, but hand labor produced a net loss because of its high cost and poor weed control.

Herbicide energy efficiency is reinforced by data from the same study showing the energy relationships for methods of weed control. Herbicides consume more energy than hand labor but less than cultivation. Herbicides compare favorably to other methods in net energy profit due to weed control because yield was nearly as high as that achieved with hand labor (Table 12.6).

TABLE 12.5. Energy and Cost for Weed Control in Cotton (Barrett and Witt, 1987).

		Cotton yield				Values $/ha		
Weed control income method	Energy for weed control (MJ/ha)	Lint kg/ha	Seed kg/ha	Energy MJ/ha	Ratio of energy in crop to weed control input	Cost of weed control	Income from lint and seed	Income above cost of weeding
Four herbicides, no cultivation	2,093	619	856	28,310	13/1	64.47	901.11	836.64
Three herbicides, 2 cultivations	1,898	545	754	24,935	13/1	56.96	860.91	803.95
No herbicides, 5 cultivations	1,220	177	244	8,082	7/1	24.69	257.43	232.74
No herbicides, 5 cultivations, 185 man-hour/ha hand-hoeing	1,641	592	819	27,085	17/1	645.06	862.02	216.97

Adapted by Barrett and Witt (1987) from Nalewaja (1984), and Dowler and Hauser (1975). Hoeing cost was estimated to be $91 for a 40-hour week.

TABLE 12.6. Weed Control Energy Relationships for Six Corn Experiments in Minnesota (Nalewaja, 1974).[a]

Method of weed control	Energy input for weed control, kcal/A	Yield of corn/A		Net profit due to weed control control, kcal/A
		Bushels	Kilocalories	
None	0	54	5,443,200	—
Cultivation	56,005	81	8,164,800	2,665,595
Herbicide	37,920	90	9,072,000	3,590,880
Hand labor	32,655	92	9,273,600	3,797,745

[a]The land was plowed, disked, and prepared for planting of corn in the conventional manner.

TABLE 12.7. Average Energy Input to US Corn Production System in 1975 (Pimentel and Pimentel, 1979).

Input	% of total (k/cal/ha)
Labor	0.09
Machinery	8.5
Diesel fuel	19.6
Nitrogen	28.8
Phosphorus	3.3
Potassium	2.0
Lime	0.5
Seed	8.0
Irrigation	11.9
Insecticide	1.3
Herbicide	3.1
Drying	6.5
Electricity	5.8
Transportation	0.5
Kcal output/kcal input	2.93

The total energy required for herbicides for corn, a crop that requires a great deal of energy, is relatively small (Table 12.7; Pimentel and Pimentel, 1979). About 3% of the total energy input for the US corn production system is directly related to herbicides that are used on nearly 100% of US corn acreage (Gianessi and Sankula, 2003). The major energy consumers in US corn production are nitrogen fertilizer, diesel fuel, and irrigation. It is true that the US

TABLE 12.8. Energy and Yield Comparisons of Corn Production Systems (Pimentel and Pimentel, 1979).

Corn production system	Total		
	kcal Output/input	Yield kg/ha	T/ha
United States	2.93	5,394	2.4
Philippines w/animal power	5.06	941	0.42
Mexico w/oxen	4.34	941	0.42
w/manpower	10.74	1,944	0.87
Nigeria w/human labor	6.41	1,004	0.45

corn production system has one of the lowest energy efficiencies among the world's crop production systems (Table 12.8). Available data verify that US agricultural energy efficiency is low, but yields are high.

Broadcast herbicide use in corn is the least time-consuming weeding strategy, whereas preemergence rotary hoeing followed by two cultivations required the most time (Lague and Khelifi, 2001). Others (Swanton et al., 1996) have shown that for the Canadian province of Ontario, energy use per hectare decreased by 19.7% for corn and by 46.3% for soybean production systems from 1975 to 1991. The reasons were the increased use of no-till production systems and herbicides.

An important criterion for a grower is profit or return on investment in technology. Becker (1983, cited in Barrett and Witt, 1987) attributed corn and soybean yield increases after herbicide use to improved weed control and earlier planting when herbicides were available. Combining these two factors reduced cost of production and thus increased profit about 10% (Becker, 1983; Table 12.9). Abernathy (1981) calculated the additional land required to maintain production of seven major US crops without herbicides. He used estimates from several sources to determine likely losses and their value. All aspects of loss were considered, including additional cultivations required to control weeds when herbicides are not used. Abernathy proposed a net loss greater than $23 billion and the need for an additional 28.2 million acres to maintain production. Gianessi and Sankula (2003) calculated a net loss of $21 billion for 40 crops if herbicides were not used on the 220 million acres on which the crops were grown. Three crops (corn, cotton, and soybean) accounted for $7.9 billion of the loss (37%).

Pimentel et al. (1978) estimated costs and losses with herbicide use and with alternative methods of weed control but reached a different conclusion. The primary reason for the difference is that Pimentel et al. (1978) assumed

TABLE 12.9. Cost-Benefit Assessment of Herbicide Use in Corn and Soybean (Barrett and Witt, 1987).

	Corn (cost in $/ha)		Soybean (cost in $/ha)	
	Cultural weed control	Herbicide	Cultural weed control	Herbicide
Yield (kg/ha)	7,212	8,179	2,554	2,084
Herbicide + application cost	0	43.51	0	50.32
Savings in tillage cost	0	9.70	0	7.68
Total herbicide cost and tillage savings	0	33.80	0	44.64
Total crop production costs	799.75	833.59	587.65	632.30
Cost per kg produced	0.11	0.10	0.23	0.21

Data also available in Becker, 1983.

that with careful management, little additional crop loss (only $341 million) would occur by switching from herbicides to alternative weed management techniques. More intensive weed management is proposed frequently as a necessary part of alternative (i.e., nonherbicide) weed management.

No one knows who is correct in this ongoing debate. Clements et al. (1995) provide a clue. They confirm the proposition put forth earlier (see Table 12.7) that energy for weed management represents a small proportion of on-farm energy use for food production. Clements et al. (1995) propose that a "large portion of energy allocated to weed control could be conserved in alternative weed management systems by elimination or reduction strategies for tillage and/or herbicide use." They showed that potential energy savings from reduction or elimination of tillage were greater than for elimination of herbicides. They also suggested that there would be a potentially high energy requirement for tillage when herbicides are eliminated, particularly when numerous inter-row cultivations are required for weed control. Most alternative methods of weed management are more energy efficient than methods based on herbicides (Clements et al., 1995). Energy savings are being achieved by alternative herbicide use techniques such as reducing the total area of application, using band application instead of broadcast spraying, and choosing herbicides that require less energy to produce (e.g., trifluralin or atrazine, as opposed to paraquat or bentazon; Clements et al., 1995).

As just stated, many in agriculture argue that the purpose of agriculture is to produce food, not energy. Others argue that the US system is so dependent on petroleum energy sources that it is not sustainable. Many believe that modern weed control with herbicides is essential to maintain the present, highly productive US agricultural system and is justified because herbicides represent only a small part of the total energy input.

Herbicides are advantageous when labor is expensive. Gianessi and Sankula (2003) claim that growers used to paying 10 cents an hour for labor suddenly found it necessary to pay 50 cents in the early 1950s and $1 in the 1960s. Herbicides reduced or eliminated labor costs. Gianessi and Sankula (2003) say that a 1957 onion experiment showed $8 per acre for herbicide application that substituted for 55 hours of labor at a cost of $41 per acre. Gianessi and Sankula (2003) claim that costs of weed control for organic vegetable growers in California can be as high as $1,000 per acre compared to $50 for herbicides for the same acres and the same result.

Herbicides can control weeds in crop rows where most mechanical methods are ineffective.

Herbicides are not only beneficial and profitable where labor is scarce or expensive, but they may also be advantageous where labor is plentiful and cheap. Herbicides control weeds in crop rows where cultivation is not possible. They can be used in places where other methods don't work. Preemergence herbicides provide early season weed control when competition results in the greatest yield reduction and when other methods are less efficient or impossible to use (e.g., it is impossible to mechanically cultivate when soil is wet).

Cultivation can injure crop roots and foliage. Selective herbicides reduce the need for tillage and control of weeds in crop rows where tillage is not effective. Herbicides reduce destruction of soil structure by decreasing the need for tillage and the number of trips over the field with heavy equipment.

Herbicides permit selective weed control in orchards. Proper herbicide selection maintains plant cover and reduces or eliminates the need for tillage that encourages soil erosion. Erosion in orchards and in other perennial crops can be prevented by maintenance of a sod cover with selective herbicides. Tillage to eliminate weeds is not required at all or not required as often when herbicides are used. Many perennial species cannot be controlled effectively with hand labor and herbicides are often the only reasonable option. Erosion of cropland declined from about 3.8 billion tons in 1938 to 1 billion tons in 1997 (Gianessi and Sankula, 2003). A billion tons is still way too much, but herbicides help reduce the need for tillage that can lead to soil erosion.

Herbicides save labor and energy by reducing the need for hand labor and mechanical tillage. They can reduce fertilizer and irrigation requirements by eliminating competing weeds. They reduce harvest costs by eliminating interfering weeds and can reduce grain drying costs because green, weedy plant material is absent. Other methods of weed control will, of course, also accomplish these things but not as efficiently and often not as cheaply.

III. DISADVANTAGES OF HERBICIDES

A. Cost

It is often suggested that herbicides reduce crop production costs. Many disagree and suggest herbicides are a net cost because they are expensive, the equipment for applying them is an added cost, and, of most importance, there are large externalized societal costs.[2] The debate continues and its elements vary with different crop production systems.

The cost to manufacturers of developing and introducing a new herbicide has steadily increased. Development costs have become so high that crops that used to be regarded as major markets are now minor due to financial investments required and the increasing possibility that initial costs may not be recovered in sales (Ivany, 2001). Simultaneously, the availability of older her-

[2]An externality is a cost that is not reflected in price, or more technically, a cost or benefit for which no market mechanism exists. In the accounting sense, it is a cost that a firm (a decision maker) does not have to bear, or a benefit that cannot be captured. From a self-interested view, an externality is a secondary cost or benefit that does not affect the decision maker.

bicides is decreasing as more stringent environmental and toxicological requirements result in voluntary removal from the market.

B. Mammalian Toxicity

One of the major concerns about herbicides is their undeniable mammalian toxicity. All have some toxicity to humans and other plant and animal species. Some are no more toxic in terms of their LD_{50} than many common chemicals (e.g., aspirin, mothballs, gasoline, and table salt). Many people are concerned about herbicide toxicity because all must eat and therefore there is no choice about potentially toxic residues in food, especially when one does not know they are present. For example, in 1996, there were 441 definite/probable cases of pesticide intoxication in California and 271 positive cases. Of these only 3 and 22, respectively, were attributed to herbicides. Most (65%) were due to insecticides (http://www.cdpr.ca.gov/docs/whs/1996pisp.htm). Note: Data can be obtained for any state when that state's two letter initial is substituted in this URL. The World Health Organization data show that about 3 million people a year suffer from severe pesticide poisoning (Jordan, 2006).

C. Environmental Persistence

Some herbicides persist in the environment. None persist forever, but all have a measurable environmental life. In some cases, but not all, an herbicide can carry over from one crop season to the next. This restricts rotational possibilities and may injure succeeding crops. Therefore, herbicides can be hazards to plants that are planted *after* the herbicides are used. Plants that are not targets may be affected by drift or inappropriate application. Although weed scientists and farmers are well aware of the problems caused by excessive persistence, they still occur. Greenland (2003) showed that vegetable crops could be injured by flumetsulam (a triazolopyrimidine, injured cabbage and squash) or nicosulfuron (an imidazolinone, injured cabbage and onion), especially when double or higher rates were used. As has been known for many years, warm summer temperatures and adequate soil moisture enhance microbial degradation of the herbicides and reduce injury.

D. Weed Resistance to Herbicides

Herbicide resistance in weeds is defined as the decreased response of a species' population to an herbicide (LeBaron and Gressel, 1982). It is "survival of a segment of the population of a plant species following an herbicide dose lethal to the normal population" (Penner, 1994). The Weed Science Society of America defines resistance as the "ability to withstand exposure to a potentially harmful agent without being injured" (Vencill, 2002, p. 460). Resistance is contrasted with tolerance or the natural and normal variability of response to herbicides that exists within a species and can easily and quickly evolve (LeBaron and Gressel, 1982). Tolerance is characterized by "survival of the normal population of a plant species following an herbicide dosage lethal to other species" (Penner, 1994). The Weed Science Society defines tolerance as the "ability to continue normal growth or function when exposed to a potentially harmful agent (Vencill, 2002, p. 462). The terms are not always clearly distinguished and often are used as synonyms. The ecological effect is the shift of the population to the resistant biotype. The weed species don't change; the ability to control them does. The topic was reviewed by Shaner (1995), who suggested that if the evident trends continued, the number of herbicides effective on several weed species would decline rapidly. Given the evidence available (http://www.weedscience.org/in.asp; accessed November 4, 2005), his prediction has been accurate.

For many years, weed scientists knew that insects developed resistance to insecticides and more of the same insecticide did not solve the problem, nor would new insecticides or new combinations help much. Weed scientists assumed that weeds could become resistant to herbicides but that it was not likely to be a major problem for several reasons. These, however, were the more important reasons (Radosevich, 1983):

1. Weeds, even annuals, have a long life cycle compared to insects.
2. Weeds are not as environmentally mobile as insects.
3. There was a wide range of herbicides in use, and they had several different modes of action. Insecticide resistance, it was assumed, was based on continued exposure to chlorinated hydrocarbons or organophosphate materials. The two groups had different modes of action, but all members of each group shared a mode of action.
4. Crop rotations offered the possibility of using different herbicides in a field.
5. Cultivation and other cultural techniques were used in the same field herbicides were used in and would kill resistant weeds. It was assumed that integration of methods was common.
6. There is, and it was assumed always would be, a large soil seed reserve.
7. Resistant species will probably be less competitive and will not survive well.

These were all logical but incorrect assumptions because herbicide resistance developed and is a serious problem. The wrongness of these assumptions became clear in 1957 when herbicide resistance was reported in Hawaii and Ontario, Canada (Hilton, 1957; Switzer, 1957). The first herbicide-resistant weed was common groundsel that was shown to be resistant to atrazine and simazine after the herbicides had been applied once or twice annually for 10 years in Washington State (Ryan, 1970). In 1986, over 50 weeds were resistant to triazines (Nat. Res. Council, 1986), and over 107 resistant biotypes had evolved around the world. In 1990, 55 weeds were resistant to triazine herbicides in 31 US states, 4 Canadian provinces, and 18 other countries (LeBaron and McFarland, 1990). By the early 1990s, over 100 cases of herbicide resistance had been reported in one or more of 15 herbicide chemical families (Holt and LeBaron, 1990; LeBaron and McFarland, 1990). The most recent compilation (2005) shows 304 resistant weed biotypes from 182 species (109 dicots and 73 monocots). Resistant species have been found in more than 270,000 fields and in 59 countries. The United States has reported more cases of resistance than any other country (http://www.weedscience.org/in.asp; accessed November 4, 2005).

Several examples illustrate the problem and concern. Wild radish collected from northern Australian wheat fields where “typical herbicide-use patterns had been practiced for the previous 17 seasons” exhibited multiple herbicide resistance across at least four herbicide mode-of-action groups (Walsh et al., 2004). This, in the author’s view (and, one presumes, in the farmer’s view), presents a challenge for future wild radish management with herbicides. A randomly collected population of rigid ryegrass from 264 fields in the western Australia wheatbelt found 46% were resistant to diclofop-methyl [inhibits acetyl-CoA carboxylase (ACCase)], 64% were resistant to chlorsulfuron [inhibits acetolactate synthase (ALS)], and 37% were resistant to both herbicides (Llewellyn and Powles, 2001). Only 28% of the tested populations were susceptible to both herbicides. Thus, more rigid ryegrass populations were resistant than susceptible to the herbicides that had been most widely used and successful.

In Nebraska, kochia is widely resistant to most triazine herbicides. Some kochia populations in western Nebraska are also resistant to 2,4-D and dicamba (Gaussoin et al., 2005). Resistance of common broadleaf weeds in wheat to some of the sulfonylurea herbicides has been reported across the western United States. Resistance is real and widely present, but it can be managed. It is well understood that it results from repeated use of the same herbicide or herbicides with the same mode of action in fields. It is not created by the herbicides; it is selected for. The plants that are susceptible are killed. The resistant population survives and comes to dominate. It is a process of evolution by chemical selection.

The time for development of resistance has proven to be short. Shaner (1995) stated that it took 18 years after release for resistance to 2,4-D to be reported. Resistance to triallate and picloram took 25 years; for atrazine and trifluralin it took 10 years; and for diclofop and chlorsulfuron it only took five years. Several species have evolved cross-resistance to more than one herbicide. Since 1982 the number of resistant weeds has more than tripled, and the land area involved has increased 10 times. Multiple resistance has been observed and occurs when resistance to several herbicides results from two or more distinct resistance mechanisms occurring in the same species. Resistant rigid ryegrass in Australia and blackgrass in Europe have limited small grain production. In general, but not always, there are enough alternative herbicides and other control measures (e.g., rotation, tillage) to manage resistant weeds effectively.

The triazines are broad-spectrum herbicides that inhibit photosynthesis and quickly kill a high percentage of emerged seedlings. Because they persist in soil, they continue to kill weeds that emerge after application, and there is a long period when susceptible plants are not present to compete with resistant ones. It was believed that the soil seed reservoir, unique to plant populations, would slow the appearance of resistance because only a small percentage (2–10%) germinates in one year. The large seed reserve slowed but could not prevent expression of resistance.

The sulfonylureas and imidazolinones are active at fractions of an ounce per acre, often persistent in soil, and have a specific mechanism of action. They have important advantages and have replaced some herbicides with multiple sites of action and different soil persistence. Resistance to some of these herbicides has developed in as little as three years (Gressel, 1990).

If one assumes that in the first year of herbicide application there was only one resistant weed in a population of 100,000,000 in a large field, it would not even be noticed, or if it were, the logical assumption would be that it had emerged *after* herbicide application or had been missed. The resistant weed(s) probably would not be noticed after the first year (Table 12.10). It is likely that the resistant population would not be noticed for several years. It would take a person with unusual powers of observation and a keen knowledge of weeds to notice 256 weeds in a large field. If one assumed the 100,000,000 million weeds were all in a 50-acre field, there would be 46 weeds per square foot. That is a dense population, but it is more likely one would be delighted with the excellent weed control achieved rather than notice a few escapes mixed with other weed species the herbicide didn't control. Another way to look at the same problem is to note that concomitant with 90% population reduction of the susceptible species, the resistant species might increase by a factor of 4 each year. So if it were a 10-acre field (435,600 square feet), with 90% control and a 4x annual increase in the resistant population. Table 12.11 shows what would happen. Farmers and weed scientists must anticipate and prevent these problems.

TABLE 12.10. Development of a Population of Resistant Weeds with Repeated Use of a Single Herbicide (Gressel, 1990).

Year	Susceptible population	Resistant population
1	100,000,000	1
2	10,000,000	4
3	1,000,000	16
4	100,000	64
5	10,000	256
6	1,000	1,024
7	100	4,026

TABLE 12.11. Development of a Resistant Weed Population in a 10-Acre Field.

Year	Resistant population	Susceptible population
1	1	4,356,000
2	4	435,600
3	16	43,560
4	64	4,356
5	256	436
6	1,024	44
7	4,096	4
8	16,384	1
9	65,356	0
10	130,712	0

It is incorrect to assume that resistance will occur with all herbicides, although there are several examples (Table 12.12). It is most likely to occur where some or all of the following factors are present:

1. The herbicide has a high degree of control of the target species. It is very active and efficient.
2. The weed's seed has a short life in the soil seed bank.
3. The herbicide has long soil persistence.
4. The herbicide is used frequently: annually for many years or more than once per year for several years.

TABLE 12.12. Examples of Weeds Resistant to Herbicides (LeBaron, 1990, and Other Sources).

Herbicide	Resistant weed(s)	Location
Paraquat	Horseweed	Japan
	Perennial ryegrass	U.K.
	American black nightshade	Florida
Atrazine	Redroot pigweed	Several
	Common ragweed	Pennsylvania
	Downy brome	5 States
	Common lambsquarters	Several
	Velvetleaf	Maryland
	Kochia	12 States
	Wild buckwheat	West Germany and Pennsylvania
	Common groundsel	Several
	Black nightshade	Several
	Barnyardgrass	Several
	Annual bluegrass	Several
MSMA and DSMA	Common cocklebur	North and South Carolina
Sulfonylureas	Kochia	8 States
	Prickly lettuce	Idaho
	Russian thistle	2 States
Trifluralin	Palmer amaranth	South Carolina
	Green foxtail	Canada
Bromoxynil	Common lambsquarters	West Germany
2,4-D	Musk thistle	New Zealand
	Canada thistle	Hungary
	Wild carrot	Ontario
Picloram	Yellow starthistle	Idaho
Pyrazon	Common lambsquarters	Europe
Diuron & linuron	Redroot pigweed	Hungary
	Horseweed	Hungary
Amitrole	Annual ryegrass	Australia
	Annual bluegrass	Belgium
Bromacil	Redroot pigweed	Hungary
	Smooth pigweed	Hungary

5. Annual herbicide rotation is not practiced.
6. The herbicide has a single site of action.
7. The herbicide's rate is high.
8. Herbicides are not mixed in a crop.

It is equally incorrect to assume that the phenomenon of resistance is the death knell for herbicides. Resistant weeds are not super weeds and are often less fit ecologically than their susceptible relatives. It is important to recognize that resistance is possible and to determine the reasons for it. Identification of the cause and mechanism of action of resistance was one impetus for the intentional use of biotechnology to transfer resistance to crops.

The reasons cited at the beginning of this section are good reasons that herbicide resistance will remain an important phenomenon as it is with insects and insecticides. Crop rotation and herbicide rotation for different weed problems are both beneficial and should be used in integrated weed management systems. If the same herbicides, herbicides from the same chemical family, or herbicides with the same action mechanism are used on the same land for several successive years, development of resistance is more likely. Integration of crop rotation and mechanical control in weed management, rather than relying on herbicides to solve all problems, is an important part of the answer to the problem of resistance.

Management includes crop rotation to prevent any one species or weed complex from dominating, including soil tillage, using cultural practices to take advantage of crop competition (e.g., using narrower rows to maximize crop competitiveness), using herbicides with different sites of action in successive years to slow resistance development, and using herbicides with a short rather than a long soil residual life (Gaussoin et al., 2005). Management of herbicide resistance will require reducing reliance on herbicides as the primary tool for weed management and developing integrated weed management systems that require the substitution of human intellect and skill for chemical technology (Shaner, 1995). Mixing herbicides with different sites of action will slow but not prevent resistance development. Long persistence is both advantageous and disadvantageous. Most cases of herbicide resistance involve herbicides with relatively long soil residual lives.

E. Monoculture

American agriculture is characterized by monoculture: large land areas devoted to a single crop. This is ideal for use of selective herbicides, and many have criticized herbicides because they encourage monoculture and discourage diversity. Unquestioned expansion of herbicide technology into developing countries is not always wise because of their existing agricultural plant diversity. There is strength in diversity, and it should not be inhibited or reduced by extensive use of herbicides for weed control, especially where their consequences have not been thoroughly examined.

F. Other

Herbicides are often inconsistent in their control because they are affected by environmental conditions, and the results of these interactions are not always predictable. Herbicide use in many crops may, intentionally or accidentally, eliminate all plants except the crop, and that may lead to excessive soil erosion.

Precision is required when herbicides are used. One must think carefully about what herbicide to use, when to use it, how much to use, and how surplus chemical will need to be disposed of. They cannot be used casually; intelligence is required in their use and in disposal of surplus chemicals and empty containers.

Finally, because herbicides are so good at what they do, they may actually create problems after their use. Herbicides control certain weeds while leaving a crop unscathed. Natural plant communities are usually a polyculture (this is not a universally true generalization). Diversity is the rule. When all plants are eliminated save the crop, other plants (weeds) will move into the environment created, and they may be more difficult to control than the ones just eliminated.

For example, Florida pusley was a common weed in peanut production before herbicides were introduced (Johnson and Mullinix, 1995). When herbicides became integral to peanut production, Florida pusley was controlled, but the previously minor weeds, Florida beggarweed, Texas panicum, and yellow nutsedge, increased. When herbicides were discontinued, even after several years of use, Florida pusley again became the dominant weed (Johnson and Mullinix, 1995). A second example of replacement is from a rice-corn-soybean rotation in Peru. The weeds prior to herbicide use were 60% grass, 25% sedges, and 15% broadleaved. The grasses were large crabgrass and goosegrass. After six years, the weeds were 80% grass, 13% broadleaved, and 7% a species of dayflower; 85% of the grass was itchgrass (Mt. Pleasant and McCollum, 1987). A disadvantage of selective herbicides is their ability to control some weeds that can then create open niches in which other weeds succeed.

Herbicides, like any technology, have advantages and disadvantages that must be weighed carefully to consider intended and unintended consequences prior to use.

IV. CLASSIFICATION OF HERBICIDES

An adequate classification system should be more than an index and should, as much as possible, integrate all dimensions of the objects being classified. Although there are several methods of herbicide classification, no single one is completely adequate. This is because of the great diversity of uses, sites of action, and chemical families. Not many years ago, it was possible to classify herbicides on the basis of chemical structure. That is no longer possible because diversity of structures and sites-of-action have increased. In spite of the inadequacy of all systems of classification, all are used because each has some utility. To become familiar with chemical weed control, one must understand some of the jargon, and much of it is found in the language surrounding herbicides and their classification. The objectives of this section are to understand why herbicides are grouped as they are and to enable use of the several systems of classification to discuss herbicides. Understanding systems of classification will permit explanation of field observations in terms users will understand.

A. Crop of Use

One often hears that a particular herbicide is a corn herbicide or a turf herbicide. This is useful information because it immediately reveals the crop or site of use. Frequently, such statements represent only the narrow geographic or crop perspective of the speaker, and therefore "crop of use: cannot be a complete classification system. To illustrate its inappropriateness, one need only consider herbicides used to control weeds in soybean. Grass weeds can be controlled with a soil-applied herbicide or postemergence. Soil-applied herbicides include representatives of 10 chemical families, and postemergence herbicides include representatives from five chemical families, only one of which is also used as a soil applied herbicide for grass control in soybean. Herbicides from seven different chemical families can be used to control broadleaf weeds in soybeans (for specific information, see Gaussoin et al., 2005, or http://weedscience.unl.edu/weedguide/). These herbicides are from 19 different chemical families, have different modes of action, and are applied at two different times relative to soybean growth. The same case can be made for several crops. Similarly, describing 2,4-D as a "turf herbicide" is accurate but not reflective of its many other uses. Classification by crop is essential knowledge but includes such a diversity of other factors that it is impossible to integrate the subject. Table 12.13 shows different crops or sites in which herbicides are used and the range of chemical groups used on each. If one does not know the crops in which a particular herbicide can be used or,

TABLE 12.13. A Partial Classification of Herbicides Based on Crop of Use.

Herbicide	Crop or Site													
General group	Alfalfa	Aquatic weeds	Dry bean	Soybean	Corn	Cotton	Non-crop areas	Orchards	Peanuts	Potatoes	Perennial weeds	Small grains	Sorghum	Turf or ornamental	Woody plants & brush
Aryloxyphenoxypropionates															
Diclofop												X		X	
Fenoxaprop				X								X		X	
Fluazifop				X		X									
Haloxyfop				X		X			X	X					
Quizalofop				X			X								
Chloroacetamides															
Acetochlor				X	X										
Alachlor			X	X	X				X				X		
Dimethenamid				X	X										
Metolachlor					X	X			X	X			X		
Propachlor					X								X		
Cyclohexanediones															
Clethodim				X		X									
Sethoxydim	X			X		X			X						
Tralkoxydim												X			
Growth Regulators															
Clopyralid					X						X				X
Dicamba					X						X	X	X	X	X
Phenoxy acids			X		X		X				X	X	X	X	X
Picloram							X				X	X			X
Quniclorac												Rice			

(*Continues*)

TABLE 12.13. (*Continued*)

Herbicide	Crop or site														
General group	Alfalfa	Aquatic weeds	Dry bean	Soybean	Corn	Cotton	Non-crop areas	Orchards	Peanuts	Potatoes	Perennial weeds	Small grains	Sorghum	Turf or ornamental	Woody plants & brush
Imidazolinones															
Imazamethabenz												X			
Imazamox	X		X	X											
Imazapyr							X								
Imazaquin				X											
Imazethapyr	X		X	X	X				X						
Trazolinone															
Sulfentrazone				X					X						
P-Nitro Substituted Diphenyl Ethers															
Acifluorfen				X					X			Rice			
Bifenox												Rice			
Fomesafen				X											
Oxyfluorfen				X	X	X									
Lactofen				X		X									
Soil Sterilants															
Sodium chlorate							X				X				X
Sulfonylureas															
Bensulfuron												Rice			
Chlorimuron				X											
Chlorsulfuron									X			X			
Halosulfuron					X								X	X	

(*Continues*)

TABLE 12.13. (*Continued*)

Herbicide	Crop or site													
General group	Alfalfa	Aquatic weeds	Dry bean	Soybean	Corn	Cotton	Non-crop areas	Orchards	Peanuts	Potatoes	Perennial weeds	Small grains	Sorghum	Turf or ornamental	Woody plants & brush
Metsulfuron												X			
Nicosulfuron					X										
Primisulfuron					X										
Prosulfuron					X							X	X		
Sulfometuron												X			
Sulfosulfuron												X			
Thifensulfuron												X			
Triasulfuron												X			
Tribenuron												X			
Carbamothioates-Thiolcarbamates															
Butylate					X										
EPTC	X		X		X	X				X					
Molinate												Rice			
Prosulfocarb												X			
Thiobencarb												Rice			
Triallate												X			
Triazines															
Ametryn					X		X								
Atrazine					X								X	X	
Cyanazine					X	X									
Prometon					X	X	X								

(*Continues*)

TABLE 12.13. (*Continued*)

Herbicide	Crop or site														
General group	Alfalfa	Aquatic weeds	Dry bean	Soybean	Corn	Cotton	Non-crop areas	Orchards	Peanuts	Potatoes	Perennial weeds	Small grains	Sorghum	Turf or ornamental	Woody plants & brush
Prometryn						X									
Simazine					X			X							
Triazinones															
Metribuzin	X		X							X		X			
Hexazinone	X						X								
Triazolopyrimidine															
Cloransulam				X											
Flumetsulam				X	X										
Uracils															
Bromacil							X	X			X				
Terbacil	X														
Ureas															
Fluometuron						X									
Diuron	X				X	X		X		X	X	X	X		
Linuron				X	X					X			X		
Siduron														X	
Tebuthiuron							X								X
Other															
Amitrole							X				X				X
DCPA						X				X				X	
Oxadiazon														X	

conversely, what crops it cannot be used in, one is not conversant with modern weed management.

B. Observed Effect

A second system of classification is based on effects observed after emergence. Some older herbicides, including bipyridiliums, dinitrophenols, and petroleum oils, have a burning effect. This describes what one sees but not how the herbicide actually works. Other herbicides cause chlorosis (amitrole, clomazone) or gradual chlorosis, which is characteristic of photosynthetic inhibitors. Other herbicides cause what is called a hormonal effect or an obvious growth abnormality. Growth abnormalities are so imprecisely defined and so many herbicides affect growth that the category merely serves to distinguish these effects from chlorosis or burning but does not describe what happens. Therein is the problem with observed effects as a system of classification.

C. Site of Uptake

A third, frequently used system of classification is based on site of uptake and distinguishes between foliar and soil-applied herbicides. An herbicide that acts after contact with plant foliage falls in the foliar-active group. Other herbicides can be foliar-active *and* soil-active, with the distinction often based on rate of application. The diphenyl ether herbicides, most of the phenoxy acids, the arsenicals, selective oils, and bipyridilium herbicides act primarily via foliage. Phenoxy acid herbicides and arsenicals translocate readily, whereas bipyridiliums and selective oils do not. The sulfonylureas, imidazolinones, triazines, chloroacetamides, thiocarbamates, and dinitroanilines are taken up by roots. An adequate classification cannot be created for any group as large as the herbicides by dividing the group in two.

D. Contact Versus Systemic Activity

Many herbicides are defined by noting they have contact as opposed to systemic activity. Translocation from point of application to site of action is synonymous with systemic activity. Some herbicides move only upward or acropetally in plants, while others move acropetally and basipetally, or down. This system, like many others, is useful because it reveals how an herbicide is likely to behave, but it does not tell us how it does what it does, nor does it mesh well with any other category.

E. Selectivity

Knowledge of selectivity is essential for wise use of any herbicide because it reveals the plants affected and unaffected. The first herbicides, iron and copper salts and dilute sulfuric acid, were selective because of differential wetting. Droplets of water solutions or suspensions of these herbicides bounced off or ran down upright cereal leaves and tended to stay on broad leaves. Selective herbicides kill or stunt weeds in a crop without harming the crop beyond the point of economic recovery. Nonselective herbicides kill all plants when applied at the right rate. No herbicide belongs rigidly to either group because selectivity is a function of rate. Selectivity is also based on many other factors:

1. Plant age and stage of growth
2. Plant morphology
3. Absorption
4. Translocation
5. Type of treatment (e.g., broadcast vs. band or specific application)
6. Time and method of application
7. Herbicide formulation
8. Environmental conditions

Because selectivity is a function of the combined action of these variables, it is not a precise system of classification. It is essential knowledge but does not integrate the subject.

F. Time of Application

Almost all herbicides must be applied at a particular time to maximize control and selectivity. Therefore, knowledge of when to apply to obtain the desired goal is essential to wise use. Unfortunately, some herbicides can be applied successfully at different times, and this system, like the preceding systems, does not integrate the subject even though it is essential knowledge for wise use. There are three times when herbicides are applied and each can be specified relative to the weed or the crop. The first is prior to planting, or preplanting. Sometimes application is immediately before planting or as early as several weeks prior to planting. Often preplanting applications include soil incorporation or mixing into soil. Incorporation can be combined with any time of application, but it is most common prior to planting. Use of incorporation is a function of the herbicide and control goal. The second application time is preemergence to the crop, the weed, or both. It is after planting, but prior to emergence of the crop or weed. Postemergence applications are after the crop, weed, or both have emerged. Postemergence herbicides are often applied to foliage but can be applied to soil. The exact time for postemergence application varies with the crop, the herbicide, and the weed.

G. Chemical Structure

There is no simple relationship between an herbicide's chemical structure—its chemical family—and its biochemical behavior. Classification based on structural formulas has been used, but with the ever increasing number of new structures, chemical structure no longer integrates the subject. The first edition of the *Herbicide Handbook* (Anonymous, 1967) included herbicides from 29 chemical families. The eighth edition (Vencill, 2002) has 75 chemical families. The structural formula, especially when presented in only two dimensions, is a code that bears little relationship to three-dimensional shape, physical properties, electronic disposition, and steric factors, which determine biological behavior.

To illustrate, there are two chemicals with nearly identical structures, a similar mechanism of action, but quite different outcomes. One is testosterone, the dominant male hormone, which differs from progesterone, the dominant female hormone, by two carbon and two hydrogen atoms. These very similar structures illustrate the lack of desirability of classifying herbicides based only on structure.

H. Site/Mechanism of Action

Why do herbicides affect growth or even kill some plants and not others? What is their mechanism, or mode of action? Knowing an herbicide's site of action may not lead directly to better weed control, but it gives a firmer knowledge base from which to derive conclusions based on field observations. This book does not emphasize detailed knowledge of chemistry or biochemistry, and this edition has removed most chemical structures because as important as they are, they are not essential to understanding the fundamentals of weed science. In addition, structures are readily available in several places, most notably in the 8th edition of the Weed Science Society of America's *Herbicide Handbook* (Vencill, 2002).

This book assumes that readers know the difference between photosynthesis and respiration. Knowledge of the details of the light reactions of photosynthesis or the tricarboxylic acid cycle is not required. Determination of mechanism of action is a complex study of chemistry, biochemistry, and plant physiology. Mechanism of action is defined as the entire chain of events from first contact to final effect, and that detail is beyond the scope of this book.

Site/mechanism of action is another system of classification. However, if one knows only site of action and nothing about the other, albeit incomplete, systems of classification, knowledge of herbicides is incomplete.

The discussion in Chapter 13 on the properties and uses of herbicides uses the several systems of classification mentioned. The primary system is based on site of action with some essential discussion of chemical structure.

THINGS TO THINK ABOUT

1. When did chemical weed control begin? How long is its history?
2. How did herbicides change the practice of agriculture?
3. Do herbicides affect energy use in American agriculture?
4. What do herbicides do that other weed control techniques can't do?
5. What are the advantages and disadvantages of herbicides?
6. How has herbicide resistance affected weed management?
7. What are the attributes of a good classification system?
8. Why are there so many ways to classify herbicides?
9. What is wrong with classifying herbicides based on crop of use or time of application?
10. Can all herbicides be classed as contact or systemic?
11. What is the most important determinant of selectivity?
12. What are the problems with classifying only by chemical structure or mode of action?

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CHAPTER 13

Properties and Uses of Herbicides

FUNDAMENTAL CONCEPTS

- There are many ways to classify herbicides, but because of their chemical complexity, no single way integrates the subject.
- There are several sites of herbicide action in plants.
- Research on herbicide site and mechanism of action progresses rapidly.
- Herbicide site of action and chemical structure can be integrated in a classification system.
- There is great diversity of chemical structures, but there are only six major sites of herbicide action, each with several subsites of action.

LEARNING OBJECTIVES

- To understand the underlying rationale for a classification that integrates herbicide mechanism of action and chemical structure.
- To be familiar with the major groups of herbicides and the six major mechanisms of action.
- To understand and be able to use and expand the classification system with new herbicides.
- To understand the complexity of herbicide chemistry.

I. INTRODUCTION

The classification scheme used herein is based on the site of herbicide action in plants. This method of classification necessarily includes comments on chemical structure. When appropriate, time of use, observed effect, site of absorption, and selectivity are also mentioned. Details of chemical structure and biochemical action are included when essential to understanding, but they are not emphasized.

An herbicide's site or mechanism of action is the precise biochemical (e.g., inhibition of a specific enzyme) or biophysical lesion (e.g., inhibition of electron flow, binding to a protein, or interference with cell division) that creates the herbicide's initial phytotoxic effect (other effects may follow). This text uses the term *site of action* rather than the frequently encountered *mode of action* because the former is more commonly used.

Late in the last century, it was common to speak of herbicides as members of a structurally related, chemical family. The family defined performance characteristics and site of action. This is still possible for some families (e.g., triazines and sulfonylureas), but herbicide chemistry is now so diverse that such generalizations are not as useful as they once were. Many herbicides have a primary site of action and several secondary actions. For example, diphenylether herbicides inhibit protoporphyrinogin oxidase (Protox inhibition) and secondarily affect photosynthetic electron transport, carotenoid synthesis, and ATP synthesis. It is generally true that all herbicides have mutiple actions. However, the primary site of action is known for most herbicides, and that will be emphasized in this chapter.

Without detailed information on the relationship between chemical structure and activity, it is not possible to predict either the site of action from examination of an herbicide's chemical structure or to make reliable recommendations for herbicide-resistance management. Structure and activity are related, but the relationship is often not clear until the necessary research has been conducted and published. Few herbicides developed specifically to target a new site of action (site-directed research) have subsequently achieved commercial success. The site of action of most herbicides has been discovered after identification of activity through mass screening when specific activity and selectivity are determined or after patenting. Study of herbicide site of action is advancing rapidly, as is discovery of activity and selectivity of new chemical structures, but activity has slowed in recent years because of the success of RoundUp Ready™ technology. It is not feasible or wise in a book of this kind to describe all herbicides or all sites of action. The classification scheme used herein is intended to be a framework into which other herbicides can be integrated. This chapter will not attempt to describe structure-activity relationships (SAR) or quantitative structure activity relationships (QSAR). Both are active research areas but are beyond the scope and intent of this book.

The chemical structures of most herbicide groups have not been included, but this is not because they are unimportant but because they are readily available in other easy to find sources (e.g., the *Herbicide Handbook* of the Weed Science Society of America; Vencill, 2002), and, perhaps more important, they are not essential to a comprehension of how herbicides do what they do and how they should be used. This chapter provides a description of most major herbicide activity and structural groups. It is not intended to be a complete description of herbicide action. Books that do this are listed in the chapter's references. This chapter is designed to acquaint students with the diversity of herbicide sites of action and the classification of some important herbicides. Readers should note that supporting evidence for claims in this chapter about activity, selectivity, and rate of use can be found in the *Herbicide Handbook* (Vencill, 2002), which to avoid repetitive citations, is not cited throughout the chapter.

The text divides herbicides into seven site/mechanism of action groups based primarily on the classification scheme developed by Devine et al. (1993). The seven groups have been further subdivided using the sites of action described by Mallory-Smith and Retzinger (2003). The 7 groups and 25 subdivisions follow. In creating these groups, technical language has been minimized, but some terms that may be new to readers are necessary. Clarity, not confusion, is the goal. Some chemical groups included in Mallory-Smith and Retzinger (2003) have been omitted because either they have not achieved full commercialization, there is no commercial product with the site of action, or they are defined only as showing promise for future development. Including these herbicides risks their being eliminated from further development before this book is published. The classification outline follows.

Chapter	Section	Site of Action Group
II		Light-dependent herbicides
	A	Inhibitors of photosynthesis
		1 Inhibitors of photosynthesis at photosystem II, site A
		2 Inhibitors of photosynthesis at photosystem II, site A but with different binding behavior
		3 Inhibitors of photosynthesis at photosystem II, site B
		4 Inhibitors of photosynthesis at photosystem I—electron diverters
	B	Inhibitors of pigment production
		1 Inhibitors of carotenoid biosynthesis
		2 Inhibitors of phytoene desaturase with blockage of carotenoid biosynthesis
		3 Inhibitors of 1-deoxy-D-xyulose 5 phosphate synthatase (DOXP synthase)
	C	Cell membrane disruptors and inhibitors
		1 Inhibitors of protoporphyrinogen oxidase (Protox)
III		Fatty acid biosynthesis inhibitors
	A	Inhibitors of acetyl-CoA carboxylase (ACCase) inhibitors
	B	Inhibitors of lipid synthesis, not ACCase inhibition
	C	Inhibition of biosynthesis of very long chain fatty acids

Chapter	Section	Site of Action Group
IV		Cell growth inhibition
	A	Inhibition of microtubule assembly
	B	Inhibition of mitosis
	C	Inhibition of cell wall synthesis
V		Auxin-like action—growth regulators
	A	Synthetic auxins
	B	Inhibitors of indoleacetic acid (IAA) transport
VI		Amino acid biosynthesis inhibitors
	A	Inhibitors of acetolactate synthase (ALS)—acetohydroxyacid synthase (AHAS)
	B	Inhibitors of 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSP)
	C	Inhibition of glutamine synthatase (GS)
VII		Inhibitors of respiration
	A	Uncouplers of oxidative phosphorylation
VIII		Unknown mechanism of action

II. LIGHT-DEPENDENT HERBICIDES

A. Inhibitors of Photosynthesis

The fundamental achievement of photosynthesis is conversion of light energy to chemical energy, a process on which all life depends. Light quanta falling on green leaves energize electrons in chlorophyll. The energy is converted to chemical energy by reducing (adding an electron) to an acceptor in the plant.

The two photosynthetic light reactions are coupled by the photosynthetic electron transport chain where photophosphorylation (production of ATP) occurs. Photosystem I produces reduced nicotine adenine dinucleotide phosphate (NADP). Herbicides that act in relation to photosystem I divert electrons away from photosystem I *and* generate toxic molecular species. Photosystem II, where most herbicides in this group act, begins with removal of electrons from water and production of oxygen (the Hill reaction). Most of this large and diverse group of chemical structures that inhibit photosystem II block electron transport by binding to adjacent sites on the D-1 quinone protein of the photosynthetic system that functions in the electron transport chain between the primary electron acceptor from chlorophyll and plastoquinone.

These herbicides cause gradual chlorosis in plants. The chemical groups include amide (one herbicide), benzothiadiazole (one herbicide), nitrile, phenyl-carbamate, phenyl-pyridazine (one herbicide), pyridazinone, triazine,

TABLE 13.1. A Summary of Information About a Few Herbicides That Inhibit Photosynthesis.[a]

Herbicide name		
Common	Trade	Applications
TRIAZINES CHLOROTRIAZINES		
Atrazine	Aatrex	Corn, sorghum, sugarcane, conifers
Cyanazine	Bladex	Corn, cotton
Simazine	Princep	Strawberries, trees, citrus fruits
METHOXYTRIAZINES		
Prometon	Pramitol	Noncropland
THIOMETHYLTRIAZINES		
Ametryn	Evik	Banana, corn, pineapple, sugarcane
Prometryn	Caparol	Cotton, celery, pigeon pea
TRIAZINONES		
Metribuzin	Sencor/ Lexone	Potato, soybean, sugarcane, alfalfa, asparagus, tomato
Hexazinone	Velpar	Alfalfa, pineapple, conifers
URACILS		
Bromacil	Hyvar	Citrus, pineapple, brush on noncropland
		Alfalfa, mint, pecan, sugarcane
Terbacil	Sinbar	Alfalfa, cotton, sugarcane, pineapple,
PHENYLUREAS		
Diuron	Karmex/	Grapes, tree fruits, several others
	Diuron	Cotton
Fluometuron	Cotoran	Asparagus, corn, carrot, sorghum,
Linuron	Lorox	potato
Siduron	Tupersan	Turf
Tebuthiuron	Spike	Pasture and rangeland
		Non-crop areas, woody plants

[a]Current herbicide label directions must be consulted for complete use information.

triazinone, uracil, and urea. More herbicide chemical groups act on photosynthesis than on any other physiological process. A summary of selectivity information on some of these herbicides is in Table 13.1.

Inhibitors of Photosynthesis at Photosystem II, Site A

Phenyl-Carbamates. The two, closely related, herbicides in this group may also be called bis-carbamates, desmidipham, and phenmedipham, and they are used for postemergence weed control, especially of broadleaved weeds, in sugarbeets.

Pyridazinone. Pyrazon enters weeds by foliar and root absorption and can be used pre- or postemergence to control a variety of broadleaved weeds in red table and sugarbeets. It has low mammalian toxicity and persists from 4 to 8 weeks in soil, an advantage for use in beets.

Triazines. A large number of herbicides are based on the generalized symmetrical diamine triazine. They all followed the discovery and release of simazine by Geigy Chemical Co. (Switzerland) in 1956. Triazines inhibit photosynthesis following root absorption, although those with higher water solubility also have foliar activity. Translocation is apoplastic after root absorption. There are secondary mechanisms because some seedlings fail to emerge and become photosynthetic. All have relatively low mammalian toxicity. Residues of many persist in soil. This is an advantage where long-term, nonselective weed control is desired. Others [e.g., cyanazine (not available in the United States) and ametryn) have short soil lives. Table 13.1 includes several, but not all, triazines that are now available in the United States.

Chlorotriazines. Chlorotriazines are selective in corn. Simazine was developed for use in corn but was quickly replaced by atrazine. Both can be used as soil sterilants at doses over 20 kg ha^{-1}. The usual selective crop rates are between 1 and 4 kg ha^{-1}. Atrazine is more water-soluble than simazine (33 vs. 6.2 ppm) and is therefore less dependent on, but not completely independent of, rainfall or irrigation for activity. Simazine's low water solubility and high soil adsorption permit use in orchards where deep-rooted trees do not come in contact with it because it leaches very slowly.

Simazine is used for weed control in strawberries, almonds, nectarines, apples, avocados, blueberries, established Christmas trees, lemons, pears, pecans, shelterbelts, oranges, grapefruit, grapes, and walnuts. It can be used preemergence in corn. Because of its persistence and the problem of soil residues affecting a succeeding crop, some uses of atrazine have been eliminated. Atrazine has been combined with several herbicides, as have other herbicides, to broaden the weed control spectrum and shorten total soil life by reducing the amount of each component.

Methoxytriazines. Methoxytriazines (OCH_3) are more water-soluble than their chloro-analogs and have more foliar activity. They are used exclusively for industrial and noncropland weed control. All are more toxic to corn than the chlorotriazines. Prometon is used for soil sterilization on noncropland, industrial sites, and under asphalt paving at 10 to 60 kg ha^{-1}. Without careful application and attention to surrounding vegetation, trees and ornamental plants adjacent to application sites can be killed.

Methylthiotriazines. As a result of higher vapor pressure and higher phytotoxic activity via foliar application, the methylthiotriazines (SCH_3) show high variability in selectivity. Prometryn is selective when applied pre- or postemergence in cotton and celery and preemergence in pigeon peas. Ametryn is selective in pineapple, sugarcane, banana, and plantain. Ametryn can be used as a postdirected spray in corn and has been used, often in combination with other herbicides on noncropland because of its contact activity. Volatility is not a problem but persistence can be. Persistence of the methylthiotriazines is usually shorter than that of the chlorotriazines. Part of their selectivity is related to greater soil adsorption. Banana plants, for example, are sensitive to atrazine because of its mobility but are not sensitive to ametryn, which is far less mobile and does not reach the banana root zone.

Triazinones. Triazinone or asymetrical (*as*) triazine herbicides were first developed in 1971. Metribuzin is selective in potato and soybean and has a shorter soil life than most symmetrical triazines. It is used as a dormant spray for weed control in alfalfa. It can also be used selectively in asparagus, carrots, field corn, garbanzo beans, lentils, and dry field peas. The *Herbicide Handbook* (Vencill, 2002) classifies hexazinone as a symmetrical triazine, but because it has a doubled bonded oxygen on the number 1 and 3 ring carbon atoms, it can be classed as a triazinone. It is a unique chemical structure. It can be applied to dormant or semidormant alfalfa and for weed control in pineapple, sugarcane, some species of Christmas trees, and for weed management on noncropland.

Uracils. The basic uracil structure is identical to the core structure of uracil, thymine, cytosine, and guanine, the building blocks of nucleic acids and therefore of DNA. Two herbicides, bromacil and terbacil, are based on the uracil structure; an asymmetrical ring with two nitrogens. Bromacil is not volatile and moderately leachable. Its phytotoxic residues may persist up to 1 year in soil and it can be used as a soil sterilant. It is excellent for control of perennial weeds at 12 to 24 $kg\,ha^{-1}$, very high rates. It is selective preemergence in some perennial citrus orchards (lemon, orange, and grapefruit) and can be used pre- or postemergence in pineapple. Bromacil is toxic to a wide range of grass and broadleaved species.

Terbacil is used selectively in peppermint, spearmint, sugarcane, small fruits, deciduous tree fruits (e.g., pecans), and as a postemergence, dormant spray in alfalfa. Foliar chlorosis is a normal symptom, but general root and shoot inhibition and leaf necrosis are observed. Both uracils are absorbed primarily by roots.

Inhibitors of Photosynthesis at Photosystem II, Site A, but with Different Binding Behavior

Amide. Propanil is used postemergence to control some annual broadleaved weeds and grasses in wheat and barley and, at higher rates, several annual grasses and barnyardgrass in rice. Propanil is foliarly applied, whereas its older chemical relatives, the substituted acetamides, were soil-applied. It is a photosynthetic inhibitor but also inhibits root and coleoptile growth when applied to those tissues. Propanil causes cessation of growth and gradual leaf necrosis with little or no residual soil activity due to its soil life of one to three days. It has been reported to inhibit anthocyanin formation, RNA, and protein synthesis, but these are secondary effects.

Urea. Urea herbicides, commonly called phenylureas, take their name from the organic compound, urea, the core of all urea herbicides. They are broad-spectrum herbicides applied to soil (see Table 13.1). Most are nonvolatile, noncorrosive compounds, with low mammalian toxicity. They are absorbed by plant roots from soil and translocated to shoots in the apoplast. Leaching is variable. At doses of less than 2 kg ha^{-1}, ureas are selective and control seedling weeds in some crops. At higher doses most are soil sterilants. Soil persistence ranges from two to six months, but they usually do not affect succeeding crops. Ureas are most effective on young germinating seedlings. Because they are photosynthetic inhibitors, death occurs after emergence, as photosynthesis begins. Weeds germinating over time are controlled because ureas persist in soil. Photosynthetic inhibition is the primary mechanism of action but ureas can cause chlorosis and necrosis, which are secondary effects of membrane peroxidation, and they can have a burning effect at higher doses.

Inhibitors of Photosynthesis at Photosystem II, Site B

Benzothiadiazole. Bentazon is the only commercialized herbicide in this group. It inhibits photosynthesis but at a different binding site than those in group II-A-1 and 2, and it is used for selective control of broadleaved weeds in leguminous crops such as soybean, dry beans, pea, and peanut. Postemergence it can be used in corn, sorghum, rice, and in established spearmint and peppermint. It can be used for postemergence control of top-growth of Canada thistle and yellow nutsedge in some crops. Because it does not translocate to roots, it is not as effective for permanent control of Canada thistle as some other herbicides.

Nitrile. Hydroxybenzonitriles were introduced in the early 1960s in the United States and United Kingdom. They are contact herbicides, selective in grasses, with limited translocation in shoots of some species. Due to soil sorption, they have no soil activity. They were developed for control of broadleaved weeds, not controlled by other herbicides, in cereal crops. They are non-mobile photosynthetic inhibitors whose site of action is the D-1 quinone protein of the photosynthetic electron transport system. At doses of 0.21 to 0.56 kg ae ha^{-1} bromoxynil kills a wide range of annual weeds such as chickweed, mayweeds, and members of the polygonaceae without injury to wheat, barley, oats, or triticale. Both bromoxynil and ioxynil can be used for weed management in onions. Bromoxynil can be used for weed control in field and poppable corn, sorghum, peppermint, and spearmint. Ioxynil can be used in rice, sugarcane, flax, and pastures. Both are only effective on seedling weeds. Bromoxynil and ioxynil are often marketed in combination with a phenoxyacid herbicide to broaden the weed control spectrum and reduce cost. Both are moderately toxic to mammals.

A third benzonitrile, dichlobenil, is structurally similar to ioxynil and bromoxynil but has little foliar activity, is volatile, primarily soil-active, and does not inhibit photosynthesis. It inhibits cell-wall synthesis through action on cellulose synthesis.

Phenyl-pyridazine. Pyridate is chemically related to Pyrazon (see section II-A-1-b). It is a rapidly absorbed, postemergence, contact (foliar) herbicide that controls broadleaved weeds and some grasses in peanut and corn. It has short soil persistence (half-life = 6 to 7 days) and does not leach. Susceptible plants turn yellow and necrotic and a rapidly formed metabolite inhibits electron transport in photosystem II.

Inhibitors of Photosynthesis at Photosystem I: Electron Divertors

In some systems of classification these herbicides are called photodynamic, a name that has not achieved universal acceptance. To call an herbicide *photodynamic* is to identify how it acts but only in a general way. The bipyridiliums are photodynamic because they cause photooxidative stress by diversion of photosynthetic energy (electrons) from photosystem I. The specific action of these herbicides is reduction of molecular oxygen to a toxic superoxide radical. Rapid bleaching of photosynthetic tissue occurs. Affected plants initially appear water soaked but rapidly (several hours to a few days) they become necrotic and die. There is severe disruption of cell membranes directly attributable to production of toxic oxygen species.

The bipyridiliums are almost completely dissociated in solution. Their action is due to the positive bypridinium ion, reduced by drawing an electron from photosystem I (the primary site of action) to form a relatively stable, free radical that continues to react and produces hydrogen peroxide, a superoxide radical O^{2-}, a hydroxyl radical (OH^-), and singlet oxygen $^1O_2$ each of which is potentially toxic to cell membranes, where damage occurs.

Diquat and paraquat were discovered by Imperial Chemical Industries of England, and paraquat was released in 1958. They act only when absorbed by foliage and have almost no soil activity due to complete soil adsorption. Both herbicides act quickly; effects are normally seen within several hours and certainly within a few days. Translocation is poor and complete foliar coverage is essential to good weed control. They kill a wide range of annual plants and will desiccate shoots of perennials but are not translocated to roots; the main reason they do not provide permanent control of perennials. The addition of a nonionic surfactant or oil adjuvant improves control of many species because it aids foliar dispersal and cuticular penetration.

Paraquat is more active on grasses and diquat on broadleaves. Paraquat has found extensive use in chemical fallow and for preplanting or preemergence weed control in many crops. It is also used for dormant season weed control in alfalfa, clover, mint, and rhubarb. Diquat is used to control cattails and submersed and floating aquatic species. Both are toxic to humans from skin contact, inhalation, or ingestion. These are nonselective herbicides that kill or affect almost any plant foliage they contact. Because of poor translocation, foliage not contacted directly is not affected. They can be used as preharvest desiccants to speed drying of some crops (e.g., potatoes).

B. Inhibitors of Pigment Production

Inhibitors of Carotenoid Biosynthesis

Carotenoids are essential to plant survival because they protect individual pigment-protein complexes, especially chlorophyll, and ultimately the chloroplast, against photooxidation. With high light intensity or under stressed conditions, chlorophyll molecules receive more light energy than they can transfer effectively into electron transport. The excess energy can be dissipated in several ways including production of singlet oxygen that is destructive of tissue integrity. Carotenoids protect against this by quenching excited chlorophyll molecules and by quenching singlet oxygen. Destruction of carotenoids or their biosynthesis leads to loss of the protective role (Young, 1991). A few herbicides from different chemical groups act to disrupt carotenoid biosynthesis but they act in slightly different ways.

Amitrole, a unique five-membered heterocyclic ring, is structurally unlike any other herbicide. It is unique in that it inhibits accumulation of chlorophyll and carotenoids in the light but exactly how this happens (the specific mechanism or site of action) is not known. It is usually sprayed directly on foliage at 2 to 9 kg a.i. ha^{-1} and is active on many plants but does not have sufficient selectivity to be used in crops. It is applied postemergence to noncrop areas. It can be used postemergence in hardwood tree nurseries, but it must be directed away from foliage. It produces chlorotic, white foliage due to its interference with carotenoid production. The intensity of the effect and extent of recovery depend largely on dose. Chlorosis results, in part, from failure of the chloroplasts to develop from the proplastid stage. Amitrole is readily inactivated in soil with $4\,kg\,ha^{-1}$ normally dissipated in about 7 days. It is very effective for control of poison ivy and poison oak.

Activity of amitrole has been enhanced by mixture with ammonium thiocyanate (Amitrole-T). A 1 : 1 mixture is two to four times as effective as amitrole alone against some weed species. This synergistic mixture kills foliage more slowly than amitrole alone probably because of protection of foliage against rapid contact action and a longer time for absorption and translocation of amitrole.

Inhibitors of Phytoene Desaturase with Blockage of Carotenoid Biosynthesis

Norflurazon, a pyridazinone, and fluridone, a complex pyridone, both block carotenoid biosynthesis by inhibiting the enzyme phytoene desaturase. This means that phytoene, a colorless carotenoid precursor accumulates and that leads to the photodestruction of chlorophyll pigments (Bartels and Watson, 1978). Norflurazon controls many grasses, sedges, and spikerush, and many broadleaved weeds preemergence in soybean, peanuts, and cotton. It is also used for weed control in tree (citrus, apples, apricots), nut (almonds), vine crops, and in blackberries and blueberries.

Fluridone controls submerged and emerged aquatic weeds in lakes, reservoirs, and in irrigation systems. It has little effect on algae and gives partial control of cattails.

Inhibitors of 1-Deoxy-D-Xyulose 5-Phosphate Synthatase (DOXP Synthase)

The chemical group isoxazolidinones has only one active herbicide: clomazone, which was released in 1986. The active molecule is metabolized (created) in plants. It inhibits the action of the enzyme 1-deoxy-D-xyulose 5-phosphate synthatase (DOXP synthase), a key component in plastid isoprenoid synthesis, that is in the biosynthesis of carotenoid pigments. Clomazone selectively controls many annual broadleaved and grass weeds in soybean, cotton, and tobacco. The herbicide is also registered for use in peppers, pumpkin, rice, and sugarcane. It can be applied preemergence or preplanting with incorporation. It has no or limited postemergence activity. It rapidly turns plants white and if more than 75% of the plant foliage is affected, the plant dies. There have been some important instances of drift from clomazone, made readily apparent because of its bleaching symptoms. Drift potential has been significantly reduced by a different formulation.

C. Cell Membrane Disruptors and Inhibitors

Inhibitors of Protoporphyrinogen Oxidase (Protox)

Herbicides in this group are often called photodynamic. They act independently of photosynthesis but require light for activity. These herbicides inhibit the enzyme protoporphyrinogen oxidase, PPO or Protox, a step in the porphyrin pathway that produces half of the chlorophyll molecule. In light, Protox inhibitors cause accumulation of large amounts of the phytotoxic molecule protoporphyrin or proto. Proto accumulation quickly damages lipids and proteins resulting in chlorophyll and carotenoid pigment loss and leaky membranes (e.g., the plasmalemma and tonoplast) that lead to cell dessication and disintegration.

Diphenylethers. The ether or p-nitro substituted diphenylethers were introduced in the 1980s for postemergence broadleaved weed control in broadleaved crops. All require light for their action but are not dependent on photosynthesis; light is required to produce a substrate for their action (Duke et al., 1991). They are sometimes called photobleaching herbicides because a primary symptom is bleaching of plant foliage. All are active on broadleaved weeds and selective in broadleaved crops including: soybean, peanut, bean, and cotton when applied after emergence of crop and weeds. They can be used as post-directed sprays in grass crops. Others are used for postemergence weed control in corn and rice (see Table 13.2).

Acifluorfen is used for postemergence control of broadleaved weeds in soybean, peanut, and rice. Complete foliar coverage assures good activity. Oxyfluorfen controls small annual broadleaved weeds postemergence in soybean, cotton, corn, and several tree and vine crops. The soil life, as

TABLE 13.2. A Summary of Information About P-Nitrodiphenylethers.

Herbicide name		
Common	Trade	Applications
Acifluorfen	Blazer/Galaxy/Tackle	Controls several annual broadleaved weeds and some grasses when in peanut and soybean.
Bifenox	As a mixture = Foxpro D	Used in combination with phenoxy acid or grass herbicides in rice. Not approved in US.
Fomesafen	Reflex/Tornado	Soybean.
Lactofen	Cobra	Cotton, soybean.
Oxyfluorfen	Goal	Cotton, corn, soybean, and several vegetable crops, fruit and nut trees.

with most herbicides in this group, is less than two months. It and its chemical relatives do not leach in soil. Fomesafen and lactofen are selective in soybean; both are most active postemergence and are rapidly absorbed through leaves.

Phenylthalamides. There are a few active herbicides in this group. Flumiclorac is a fast-acting, contact, postemergence herbicide. It controls several annual broadleaved weeds in soybean and corn that have not always been controlled well with other herbicides. Soil degradation is rapid with complete disappearance in ½ to 4 days in a loamy sand soil at pH 7. The herbicides and its metabolites do not leach below 3 inches.

Oxadiazole. Once again, there is only one registered herbicide in this group. It has been available for some time yet no others are being developed. Oxadiazon is of interest because of its ability to control several annual grasses and annual broadleaved species preemergence in bermudagrass, perennial ryegrass, and fescue turf and in some ornamentals. It is strongly adsorbed by soil colloids, rarely leaches, and persists in soil.

Thiadiazole. Fluthiacet-methyl controls velvetleaf (an important broadleaved weed) and some other broadleaf weeds in corn and soybean. Addition of a surfactant or oil is necessary to assure maximum activity.

Triazinone. A few triazinones (e.g., metribuzin, section II-A-1-d) inhibit phtosynthesis. Two commercially available triazinone herbicides act quite differently. Sulfentrazone is a soil applied preemergence herbicide used in soybean, sugarcane, sunflower, and tobacco to control annual broadleaved weeds, some annual grasses and *Cyperus* (nutsedge) spp. It is absorbed by roots and foliage.

The other member of this group is carfentrazone-ethyl, which applied in the range of 4 to 39 grams ha^{-1} has proven to be very effective in corn, sorghum, rice, soybean, and small grains to control weeds resistant to the imidazolinone and sulfonylurea herbicides.

Triazolone. Azafenidin is used for weed control in vineyards, olive orchards, and citrus to control many annual grasses and some broadleaf species.

III. FATTY ACID BIOSYNTHESIS INHIBITORS

Salt and acid herbicides used prior to World War II were contact chemicals that destroyed plant structure by acting on membranes. Their exact mechanism of action has never been determined. Many, presently available, contact herbicides act by modifying membrane structure (Ashton and Crafts, 1981) through effects on lipid biosynthesis or production of toxic radicals. Lipids include fatty acids, neutral fats, and steroids. Plant surfaces are covered with and composed of a complex mixture of lipids, often in crystalline form. These are generally referred to as plant waxes. They form the cuticle or non-cellular outer skin of plants and are integral components of intracellular plant membranes. Six herbicide chemical families are in the general category of inhibitors of lipid biosynthesis, although each family of herbicides acts differently. They are the carbamothioates, acetamides, chloroacetamides, oxyacetamides, cyclohexanediones, and aryloxyphenoxypropionic acids (see Gronwald, 1991b). Carbamothioates and chloroacetamides inhibit growth of emerging seedlings when applied to soil prior to weed emergence. Each herbicide in this group also may secondarily inhibit photosynthesis, and carotenoid biosynthesis. Rate of application and plant species determine the dominant mechanism of action. There are three primary mechanisms of action that result in inhibition of lipid biosynthesis: inhibition of acetyl-CoA carboxylase (ACCase, section III-A), inhibition of lipid synthesis, but not ACCase inhibiton (section III-B), and inhibition of biosynthesis of very long chain fatty acids (section III-C).

A. Inhibitors of Acetyl CoA Carboxylase—ACCase Inhibitors

Aryloxyphenoxypropionic acids and cyclohexanediones are commonly called "fops" and "dims," respectively. Each is used for postemergence selective control of annual and perennial grasses in some dicotyledonous crops and in some cereal crops. They are often referred to as graminicides (Gronwald, 1991b). Herbicides in these groups are foliar applied, readily absorbed, and translocated to meristems, where they are toxic to grasses (Gronwald, 1991b) and have similar selectivity. Observed symptoms in susceptible plants are also similar because both inhibit activity of the enzyme acetyl-CoA carboxylase (ACCase), the enzyme that catalyzes the first step in fatty acid synthesis. Tables 13.3 and 13.4 list representatives of these two chemically different but mechanistically similar families.

Aryloxyphenoxypropionates

Aryloxyphenoxypropionates (fops) are foliar graminicides that selectively remove annual grasses from grass crops such as wheat and barley. They are used for selective grass control in many broadleaved crops. Diclofop is a phenoxyphenoxy derivative, as are all "fops." Its selectivity is due to differential rates of metabolism to inactive products in susceptible and tolerant species. Control of wild oats and other grasses is growth stage dependent, with the best control when grasses have two to four leaves. Clodinafop (more accurately clodinafop-propargyl) is a broad spectrum graminicide that controls

TABLE 13.3. A Summary of Information About Aryloxyphenoxypropionate Herbicides (the Fops).[a]

Herbicide name		
Common	Trade	Applications
Clodinafop	Discover/Horizon	Rice
Cyhalofop	Clincher	Rice
Diclofop	Hoelon/Hoe-Grass	Wheat, barley, lentils flax, and sugarbeet
Fenoxaprop	Acclaim/Whip/and Several Others	Soybean, wheat, and turf
Fluazifop	Fusilade	Cotton, soybeans, and several horticultural crops
Haloxyfop	Galant/Verdict	Soybean, sunflower, rape, potato, bean, flax, and peanut
Quizalofop	Assure	Soybean

[a]In all cases only annual and some perennial grasses are controlled.

TABLE 13.4. A Summary of Information About Cyclohexanedione Herbicides (the Dims).

Herbicide name		
Common	Trade	Applications[a]
Clethodim	Select	Cotton and soybeans
Sethoxydim	Poast and several others	Soybean, peanut, alfalfa, sugarbeet, sunflower, and cotton
Tralkoxydim	Achieve	Wheat and barley

[a]In all cases, only annual and some perennial grasses are controlled.

many annual and perennial species in wheat. Cyhalofop-butyl is a newer member of the group. It controls grass weeds in upland (dry) and lowland (water seeded) rice.

Fluazifop is also a postemergence grass herbicide that is selective in broadleaved crops including cotton, soybean, stone fruits (e.g., cherry), coffee, and several others. It, and other members of this group, controls young (three to six leaves), actively growing grasses best. Quizalofop-P controls annual and perennial weeds in soybean. Fenoxaprop controls nearly all annual and perennial grasses in soybean, wheat and turf. If it is applied alone to wheat it kills it. Selectivity is achieved when it is applied in combination with phenoxy acid herbicides or one of the sulfonylureas that is selective in wheat. All of the fops are selective in many important broadleaved crops.

Cyclohexanediones

Among the cyclohexanediones (dims), sethoxydim and clethodim, applied postemergence, selectively control nearly all annual and perennial grasses in all broadleaved crops. Sethoxydim is also selective in many ornamental trees, shrubs, flowers, and ground covers. These are unique structurally because they are based on a hexane rather than a benzene ring. Rate of application varies with the grass species to be controlled; higher rates are needed for larger plants and perennials. Combination with cultivation often improves control of perennials.

B. Inhibitors of Lipid Synthesis, Not ACCase Inhibition

Older literature uses the now largely abandoned name thiocarbamate for the herbicides that are now called carbamothioates that inhibit fatty acid elongation and thereby, production of lipids. Cuticles protect plants against water loss, injury from wind, physical abrasion, frost, radiation, pathogens, and chemical entry. Loss of one or more of these functions due to the inability to synthesize cuticular lipids may lead to death. Interference with the integrity of internal plant membranes also leads to death. The primary mechanism of action of these herbicides is inhibition of fatty acid biosynthesis and lipid and fatty acid elongation, although present evidence is inconclusive. Secondarily, they may play a role in gibberellin biosynthesis (Wilkinson, 1983, 1986).

The primary visual symptoms of carbamothioate injury are shoot inhibition (aberrant morphology), abnormal growth, and emergence of leaves in grasses, often seen as the leaf's inability to emerge or unfurl and formation of loops as leaves fail to emerge properly. Many carbamothioates are volatile and must be incorporated to prevent loss. Soil persistence is short and residue carryover problems have not occurred. In general, they are much more effective against annual grass weeds than against annual broadleaved weeds. Table 13.5 summarizes some information about these herbicides.

Triallate is soil applied specifically for control of wild oats in small grains, lentil, and pea. Triallate is very selective in small grains and has been used widely. It is not effective postemergence, except in some cases with granular application, and must be incorporated into soil. Incorporation throughout the top 4 to 5 inches (10 to 13 cm) of soil often leads to crop injury whereas incorporation in the top 1 to 3 inches (2.5 to 7.5 cm) does not. This selectivity is because of the different growth habits of the mesocotyl of small grain and wild oats. In small grains, the mesocotyl, the primary area for absorption of these herbicides, and the apical meristem remain near the seed as the seedling

TABLE 13.5. A Summary of Information About Carbamothioate Herbicides.

Herbicide name		
Common	Trade	Applications
Butylate	Sutan	Preplant incorporated application controls several annual grasses, yellow and purple nutsedge, and a few broadleaved species in corn
Cycloate	Ro-Neet	Preplant incorporated application controls annual grasses and some annual broadleaved species in sugarbeet, table beet, and spinach
EPTC	Eptam	Preplant incorporated application controls weeds in several crops including alfalfa, bean, flax, potato, sugarbeet, sunflower, citrus, pea, walnut, almond, and tomato
	Eradicane	EPTC formulated with a safener for preplant incorporated weed control in corn
Pebulate	Tillam	Preplant incorporated or preemergence in tobacco, sugarbeet, and tomatoes for annual grass and some broadleaf weed control
Triallate	Avadex B-W	Pre- or postplant incorporated control of wild oats in spring wheat, barley, lentil, and pea

emerges. In wild oats, these regions are pushed toward the surface and more herbicide is absorbed.

EPTC was released in 1954. In the 1980s it was discovered that after use, its activity could completely disappear within a matter of days. This enhanced degradation in soil occurs after repeated use on the same site. Microorganisms adapt to EPTC, and other carbamothioates, and are able to degrade them quickly. The problem can be avoided by identifying soils where enhanced degradation is likely, by rotating crops, using different herbicides, diverse weed management techniques, or, if the same crop must be grown, by rotating herbicides.

EPTC is used in alfalfa, birdsfoot trefoil, clover and beans, flax, potatoes, sugarbeets, sunflowers, citrus, cotton, tomatoes, and some other crops. It is used in corn to control grassy weeds, not controlled well by other herbicides. If it is used alone, it injures corn. A safener that permits higher rates and crop tolerance is required. The mechanism of action is enhanced metabolism. EPTC is not an active herbicide until it is converted in plants to EPTC-sulfoxide, which interferes with vital plant processes. Resistant plants detoxify sulfoxides by converting them to a glutathione derivative via conjugation. The safener increases levels of the necessary enzyme and of glutathione. It is also possible that there is a direct competition between the safener and EPTC for sites of action. The safener expanded the selectivity range of EPTC in corn. The combination is sold as Eradicane.

Other carbamothioate herbicides illustrate the diversity of uses found in this group. Cycloate is soil incorporated for control of weeds preemergence in sugarbeets, table beets, and spinach. EPTC can be used in sugarbeet, but cycloate controls as many annual grass weeds and some broadleaf weeds with less crop injury. Pebulate is used in tobacco, sugarbeets, and tomato with soil incorporation primarily to control annual grass weeds. Butylate is the only carbamothioate herbicide selective in corn without a safener. It is primarily effective on annual and some perennial—seedling johnsongrass, nutsedge (properly a sedge)—grasses and some broadleaved weeds. It has a relatively short (about two weeks) soil persistence. Thiobencarb controls some grasses, rushes, sedges, and some broadleaf weeds in rice. Molinate is also used in rice with incorporation by flooding to control annual grass weeds. It is volatile from aqueous solution but not after sorption to soil and thus can be applied without soil incorporation. Prosulfocarb, a carbamothioate that is not especially volatile, is used to control several annual broadleaf weeds in winter wheat, winter barley, and rye.

Chemically, bensulide, a phosphorodithioate, does not belong with the carbamothioates, and it illustrates why classification by chemical family is essential but is not sufficient to integrate all herbicides. Bensulide is not as volatile as most carbamothioates. It is used preplanting with incorporation or preemergence in vegetable crops [e.g., squash and pumpkins (preplant incorporated only), broccoli, cabbage, lettuce, onions, and peppers. Irrigation soon after application is required for maximum activity.

C. Inhibition of Biosynthesis of Very Long Chain Fatty Acids

The chloroacetamide herbicides inhibit shoot growth of emerging seedlings and produce abnormal seedlings that may not emerge from soil. There is contradictory evidence of their effect on de novo (new, fresh) fatty acid biosynthesis and thus on membranes. The primary site of action is presently regarded as inhibition of synthesis of very long chain fatty acids and functionally related structures (Böger et al., 2000).

These herbicides are important because of their widespread use in several major crops (Table 13.6). They are relatively water soluble, soil applied, readily degraded, and not hazards to succeeding crops. They affect germinating seedlings but do not affect seed germination. Alachlor is used preemergence to control many broadleaved and annual grass weeds in a wide range of crops including corn, sorghum, soybean, and peanut. Alachlor can be applied prior to planting, preemergence, or early postemergence. It is chemically similar to metolachlor and used in the same crops. S-Metolachlor is also used in cotton, potato, and safflower. When it is used, it must be applied with a safener (corn) or after seed treatment with a safener (sorghum). Metolachlor has longer soil persistence and a slightly different weed control spectrum. Other than Roundup, more pounds of Metolachlor are used annually than any other herbicide. Metolachlor and dimethenamid have been formulated as about a 50 : 50 mixture of the active and nonactive isomers. Both manufacturers improved the manufacturing process to increase the ratio of the active isomer and the herbicides are sold as Dual II Magnum (Syngenta) or Outlook (BASF). This resulted in the rate of both herbicides being reduced up to 40% and a significant reduction in total herbicide applied; it was an environmentally good achievement.

Propachlor is applied preemergence in corn and sorghum. It was one of the first members of this group released. The range of activity in the group is illustrated by comparing butachlor (not currently marketed in the United States; Vencill, 2002), which controls many annual grasses and some broadleaved weeds selectively in rice, with the other herbicides in Table 13.6.

TABLE 13.6. A Summary of Information About Chloroacetamide Herbicides.

Herbicide name		
Common	Trade	Applications
Acetochlor	Harness	Controls most annual grasses, yellow nutsedge, and certain small-seeded broadleaved weeds in corn and soybean.
Alachlor	Lasso/Micro-Tech	Control of many annual grasses, yellow nutsedge, and certain broadleaved weeds in soybean, corn, dry bean, peanut, and grain sorghum.
Butachlor	Machete	Controls many annual grasses, some broadleaved weeds, and many aquatic species in transplant, dry, and wet seeded rice. Not marketed in the US.
Dimethenamid	Frontier	Controls yellow nutsedge, many annual grasses, and some broadleaved weeds in corn and soybean.
Flufenacet	Define/Axiom	Selective in corn, soybean, cotton, peanut, wheat, and other crops.
Metolachlor	Dual	Controls many annual grasses, yellow nutsedge, and some broadleaved weeds, soybean, cotton, corn, potato, peanut, safflower, sorghum, and in nursery and landscape plantings.
Propachlor	Ramrod	Controls many annual grasses and some broadleaved weeds in corn and grain sorghum.

The chemical nature of chloroacetamides is not constant, as illustrated by dimethenamid, which has a five-member thiophene (sulfur containing) ring instead of the six-member benzene ring common to the other chloroacetamides. Crop selectivity has not changed (it is used in corn and soybean) but the weed control spectrum is similar.

The usefulness of chloroacetamides has been expanded by the development of safeners. These chemicals, also called antidotes or protectants, were developed to broaden the range of crop selectivity for particular herbicides. The compound flurazole, sold under the trade name Screen by Monsanto Chemical Co., when applied to sorghum seed makes it possible to use some chloroacetamides selectively in sorghum. Acetochlor is selective in soybean but requires a safener when used in corn. Oxabetrinil (Concep II) and fluxofenim (Concep III) are seed treatments to protect sorghum seed from injury. None of the safeners has phytotoxic activity.

Flufenacet, an oxyacetamide, is selective in many of the crops in which the chloroacetamides are. It appears to act in the same way as the chloroacetamides but is chemically dissimilar.

IV. CELL GROWTH INHIBITION

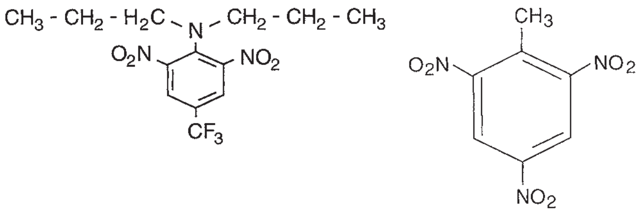
All herbicides that inhibit cell division are effective on seedlings. Many herbicides affect mitosis and directly or indirectly affect microtubules (Vaughn and Lehnen, 1991). In general, they act preemergence and are absorbed by roots and shoots from soil. Many herbicides inhibit cell division as a secondary mechanism of action. The precise mitotic site of action is disruption of microtubule assembly during mitosis and cell wall formation between daughter cells (Vaughn and Lehnen, 1991).

A. Inhibition of Microtubule Assembly

Dinitroanilines

The dinitroanilines or toluidines at one time held 8 to 10% of total US herbicide sales. They are based on para-toluidine. The herbicide trifluralin (Figure 13.1A) is related chemically but not functionally to the explosive TNT or trinitrotoluene (Figure 13.1B). The dinitroaniline herbicides bind to alpha tubulin, the protein from which microtubules, required for cell division and wall formation, are composed (Duke, 1990). The binding inhibits tubulin polymerization, a process essential to cell division.

As a group, these herbicides control grasses and some small-seeded broadleaved weeds in cotton, soybean, dry bean, potato, canola (rapeseed), and



A B

FIGURE 13.1. Structure of trinitrotoluene = TNT (A), and trifluralin (B).

TABLE 13.7. A Summary of Information About Dinitroaniline or Toluidine Herbicides.

Herbicide name		
Common	Trade	Applications
Benefin	Balan	Controls grasses and several annual broadleaved species in lettuce, alfalfa, tobacco, and established turfgrasses.
Ethalfluralin	Sonalan	Applied preplant and incorporated it controls most annual grasses and many annual broadleaved weeds in cotton, soybean, peanut, edible bean, pea, and sunflower.
Oryzalin	Surflan	Several annual grass and broadleaved species in soybean, tree fruits and nuts, and some ornamentals.
Pendimethalin	Prowl	Weed control in corn, soybean, cotton, barley, rice, sunflower, potato, pea, and onion.
Prodiamine	Barricade	Controls many annual grasses and some broadleaved species in established turf and ornamentals.
Trifluralin	Treflan and other names	Controls most grasses and many broadleaved weeds in a wide range of agronomic and horticultural crops.

many horticultural crops (Table 13.7). The compounds all yield a yellow, liquid formulation and have low water solubility, little leaching, and dominantly preemergence activity. Soil persistence varies and soil residue problems have occurred. Dinitroanilines are usually applied prior to planting with incorporation, but some can be used postplanting but are effective only when applied prior to seed germination. They are often classified as root growth inhibitors. They cause stunting, and plants generally don't emerge from the soil. Affected plants have short, thick lateral roots with a swollen root tip. Grass shoots are short, thick, and commonly red or purple. Broadleaved plants have swollen, cracked hypocotyls.

Volatility varies among the dinitroanilines and is not a problem if recognized and controlled, usually by soil incorporation. Incorporation is essential for most dinitroanilines (not for oryzalin or pendimethalin) to prevent loss by volatilization and photodecomposition. They are poorly translocated in plants and not leached in soil. Good incorporation places them in the weed seed germination zone, which enhances their effectiveness.

Other

Chemically, dithiopyr is a pyridine. It is used in rice and for weed control in turf. It does not bind to tubulin as the dinitroanilines do but to microtubule-associated proteins (MAPs) associated with stabilizing tubulin molecules. Dithiopyr inhibits mitosis in late prometaphase. It is used for weed control in direct-seeded and transplanted rice and in turf. Thiazopyr, also a pyridine, acts similarly to dithiopyr and causes multipolar mitosis. It is available for use in several crops.

DCPA is a dibenzoic or terephthalic acid. It is actually the dimethyl ester of terephthalic acid and another illustration of the diversity of herbicide chemistry. Polymerization of ethylene glycol terephthalic acid yields Dacron, a textile. Dacthal is a turf herbicide and 12 to 17 kg ai ha^{-1} give excellent preemergence control of crabgrass and other seedling annual grasses and some seedling broadleaved weeds. It is active only on germinating seedlings and affects growth of root and stem meristems. It is used in horticultural crops and nurseries and in several vegetable crops.

Dacthal does not interfere with seed germination, only with seedling growth. Therefore, to be effective, it must be applied before plants emerge; it is exclusively a preemergence herbicide and its site of action is disruption of the microtubule array and cell wall formation and thereby cell division (Vaughn and Vaughn, 1990).

B. Inhibition of Mitosis

There is one herbicide (carbetamide) that directly inhibits mitosis. It is not presently sold in the United States.

C. Inhibition of Cell Wall Synthesis

Cell wall synthesis is inhibited at two sites referred to as A and B. Two herbicides are known and each inhibits one of the two sites. Action at site A disrupts production of UDP (uredine diphosphate) glucose from sucrose. UDP glucose is crucial to the biosynthesis of uronic acids, the backbone of pectic polysaccharides in the cell wall matrix, which ultimately interferes with cellulose synthesis. Site B occurs later in the same sequence when UDP glucose is prevented from being converted to cellulose. The nitrile herbicide, dichlobenil, inhibits site A and the benzamide, isoxaben, inhibits site B. Dichlobenil has little to no foliar activity, is volatile, primarily soil-active, highly adsorbed, with little leaching, and a soil life of two to six months; almost the exact opposite of the other substituted benzonitriles. It may exert its toxic action by inhibition of cellulose synthesis (Corbett et al., 1984; Duke, 1990). Cellulose is unique to plants and interference with its synthesis offers avenues for herbicide development. Dichlobenil is effective on a wide range of annual and perennial weeds and is particularly effective preemergence on germinating seedlings. Primary uses are in ornamentals, turf, cranberries, and as an aquatic herbicide. Dichlobenil can be applied to soil with or without incorporation in late fall or with incorporation in spring in fruit and nut orchards, woody ornamentals, vineyards, and nursery stock containers. Isoxaben is chemically very different, but its uses and action are similar.

V. AUXIN-LIKE ACTION— GROWTH REGULATORS

A. Synthetic Auxins

There are at least six classes of hormones that affect plant growth: auxins, cytokinins, gibberellins, ethylene, abscisic acid, and polyamines. Plant hormones are chemicals that are produced in one location and act, in very low concentration, at another location. Auxins stimulate plant growth, particularly growth of excised coleoptile tissue. The name auxin generally refers to indoleacetic acid (IAA), but there are other active molecules. Gibberellins have varied effects on plant growth that differ between organs and between plants. They influence internode extension and thus can change dwarf to tall plants, affect cell division, induce fruit development, and can substitute for cold or light treatments required to induce sprouting or germination. There are no known herbicides whose primary mechanism of action is interference with gibberellin synthesis or action, but, as just noted (see section III-B), some carbamothioates may interfere with gibberellin biosynthesis as a secondary action.

Ethylene is a plant hormone involved in many aspects of growth. There are no herbicides whose primary mechanism of action is interference with ethylene action although some non-herbicidal compounds have been developed to stimulate fruit ripening and stem growth of flowers. Auxin-like herbicides often increase ethylene production that is linked to development of injury symptoms. There are no herbicides based on cytokinin's or abscisic acid's structure, and there are no known herbicides that interfere with their action.

It is difficult to assign a specific physiological role to a compound within one of the six major hormone groups because they interact with each other and with other factors that influence plant growth. In a similar way, we do not know precisely how all herbicides mimic auxin action but we know enough about them to use them intelligently. In this text and in most classifications, herbicides that interfere with plant growth are the phenoxyacetic acids, benzoic acids, and the picolinic acids. These growth regulator or hormone herbicides act at one or two specific auxin-binding proteins in the plasma membrane. They disrupt hormone balance and also affect protein synthesis to yield a range of growth abnormalities.

Phenoxy Acids

The chloro substituted phenoxyacetic acids, 2,4-D and MCPA, were developed in 1942 in the United States and the United Kingdom, respectively. When they were introduced widely after World War II, they revolutionized weed control because of their ability to kill many annual and perennial broadleaved weeds without harming cereals and other grass crops. They were revolutionary because they were the first of many selective herbicides that made modern chemical weed control possible. Grass tolerance is related to different morphology but more importantly to rapid, irreversible metabolism to nontoxic molecules. Susceptible dicotyledons metabolize these herbicides to reversible conjugates. Farmers readily accepted the new technology because it was inexpensive and easy to apply. The inorganic salt herbicides that preceded them were not expensive but large amounts had to be applied, in large volumes of water, cost could be high, and poor weed control was common. The phenoxyacetic acids are absorbed by roots and shoots and readily translocated in plants. They have low mammalian toxicity, are nonstaining, nonflammable, and do not persist long in the environment.

Auxin-like herbicides are effective because high tissue concentrations are maintained. They affect proteins in the plasma membrane, interfere with RNA production, and change the properties and integrity of the plasma membrane. The rate of protein synthesis and RNA concentration increases as persistent auxin-like materials prevent normal and necessary fluctuation in auxin levels required for proper plant growth. Sugars and amino acids in reserve pools are mobilized by the action of auxin mimics. This is followed by, or occurs concurrently with, increased protein and RNA synthesis and degradation and depolymerization of cell walls. There are chemical structural requirements that must be satisfied for an herbicide to interfere with auxin activity. These include a negative charge on a carboxyl group, which must be in a particular orientation (spatial configuration) with respect to the ring and a partial positive charge associated with the ring that is a variable distance from the negative charge. These spatial and charge requirements enable herbicide molecules to interact precisely with the receptor proteins.

Growth regulator herbicides are not metabolically stable in plants and are metabolized to a variety of different products. They are not resistant to metabolism but plants cannot control their concentration as they can control concentration of natural plant hormones. This is an important reason for their activity. Physically, their action blocks the plant's vascular system because of excessive cell division and excessive growth with consequent crushing of the vascular transport system. External symptoms include epinastic (twisting and bending) responses, stem swelling and splitting, brittleness, short (often swollen) roots, adventitious root formation, and deformed leaves. All or a few of these symptoms may appear in particular plants and activity is often due to two or more actions at the same time.

Use of these translocated, auxin-like herbicides offers significant advantages but they have limitations. Advantages include the need for only small quantities and foliar application that can kill roots deep in soil because of phloem translocation. Low doses keep residual problems to a minimum; however, limitations are just as real and important. Only roots attached to living shoots in the right growth stage are killed. A uniform stage of growth is often required and very difficult to achieve with a variable plant population whose individuals emerge over time and grow at different rates. Residual effects can be important if soil remains dry after application.

2,4-D (Figure 13.2) is a white, crystalline solid, slightly soluble in water. Soon after it and its many relatives were developed, it became obvious that substitution for hydrogen in the carboxyl group affected activity. Therefore, a great deal of research was done on formulation to develop the dominant, ester, and amine formulations (Figure 13.2).

These forms are important because of their ability to penetrate plant cuticles and differences in volatility. In general, esters are more phytotoxic on an acid equivalent basis than are the amine or salt forms. Technically, amines are also salts but have been distinguished because of their different chemical properties. Amines are, in general, soluble in water and used in aqueous

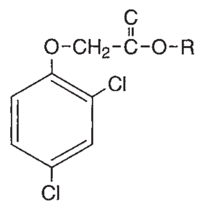


FIGURE 13.2. Salt, amine, and ester groups substitute for R in phenoxy acids.

concentrate formulations. Esters are oil-soluble but may be applied as water emulsions with a suitable emulsifying agent. They are more toxic to plants because they are more readily absorbed by plant cuticle and cell membranes. The methyl, ethyl, and isopropyl esters are no longer commercially available because of high volatility. The butoxyethyl ester and propylene glycol butylether ester have low volatility and thereby reduce, but do not eliminate, volatile movement.

Symptoms often appear within hours of application, and usually within a day. The most obvious symptom is an epinastic response resulting from differential growth of petioles and elongating stems. Leaf and stem thickening leading to increased brittleness often appear quickly. Color changes, cessation of growth, and sublethal responses occur. Plants often produce tumor-like proliferations and excessive adventitious roots. The effective dose varies with each weed species, its stage of growth at application, and the formulation applied. As plants mature, they can still be controlled by growth regulator herbicides, but higher rates are required.

MCPA, developed in England, differs from 2,4-D by the substitution of a methyl (CH_3) group for chlorine at the 2 position of the benzene ring. Uses are similar and performance is nearly identical. MCPA is more selective than 2,4-D in oats but less 2,4-D is required to control many annual weeds. MCPA persists two to three months in soil whereas 2,4-D persists about one month. Formulations are the same. MCPA is used more in the UK and in Europe than 2,4-D. MCPA is used in peas and flax in the United States because they are more susceptible to injury from 2,4-D.

The herbicide 2,4,5-T is no longer available in the United States. It is more effective against woody plants than 2,4-D. 2,4,5-T was developed for brushy rangeland weeds and tree control. It was formulated as an amine and ester but it was more persistent than 2,4-D or MCPA. For several years, it was marketed in combination with 2,4-D for broad-spectrum control of broadleaved weeds. It has low mammalian toxicity but is no longer registered because of a dioxin contaminant found during its use for defoliation during the Vietnam War.

It didn't take long after activity was found with an acetic acid derivative for researchers to examine the activity of the propionic (3 carbon), butyric (4 carbon), pentyl (5 carbon), or longer chain derivatives. Very early in the development of these compounds, it was found that a chain with an even number of carbons had herbicidal activity but a chain with an odd number did not. The even number carbon chain is broken down through beta oxidation (cleavage of 2 carbon units) to produce 2,4-D, MCPA, or the appropriate analog with a 2-carbon chain. A 3, 5, 7, and so on, chain will also be broken down by beta-oxidation but the final product is an alcohol that has no herbicidal activity. Thus, it is only the even-numbered carbon chains that are of interest as herbicides. However, as is true for many generalizations about herbicides, this one is wrong. Straight chains follow the rule but iso- or branched chains do not. The alphaphenoxypropionic acids are widely used in Europe for weed control in small grains. Their structure has 3 carbons in a branched chain, which acts like a 2-carbon chain. These compounds are dichloroprop (the analog of 2,4-D), or mecoprop (the analog of MCPA). Mecoprop was introduced in Europe as a complement to MCPA because of its ability to control catchweed bedstraw and common chickweed. Previously, these weeds could only be controlled by sulfuric acid or the substituted phenols. Dichloroprop is effective against weeds in the Polygonaceae.

Another interesting part of the history of phenoxy acid herbicides is the phenoxybutyrics. MCPB and 2,4-DB [or 4-(2,4-DB)] were used widely. MCPB is selective postemergence to the crop for annual broadleaved weed control in peanut, soybean, and seedling forage legumes. Plants, through their enzyme composition, determine selectivity of 2,4-DB. Young alfalfa is less susceptible than older alfalfa, because older plants have a more efficient and widespread beta oxidation system and are able to break down 2,4-DB to 2,4-D, which is immediately toxic.

Arylaliphatic or Benzoic Acids

Figure 13.3 shows the structure of the benzoic acid, aspirin, and the structure of the herbicide, dicamba, also a benzoic acid. These structures illustrate that herbicide chemistry is not strange or unique and that herbicides are related chemically, but not in terms of activity, to other common chemicals. Dicamba is a growth regulator, with a weed control spectrum similar to 2,4-D, but it is more effective on many weeds at lower rates and more effective on perennial weeds, which 2,4-D does not control well. It has more foliar activity than 2,4-D and the other phenoxy herbicides, and is often used in combination with one or more of them for weed control in small grains and turf. It does not control mustards well, but it is very effective on Polygonaceae species, which the phenoxy acids do not control well. This is part of the rationale for combinations. It is approved for use in cereals, corn, and sorghum and persists in soil longer than phenoxy acids.

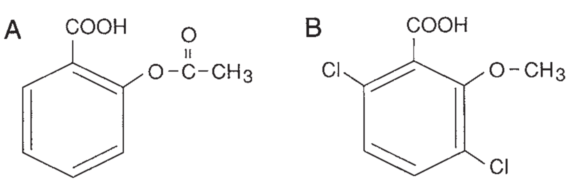


FIGURE 13.3. Structure of aspirin (A) and dicamba (B).

Pyridinecarboxylic or Picolinic Acids

The final group of synthetic auxin or growth regulator herbicides is based on the pyridine ring. By adding a carboxyl group, picolinic acid is created. Moving the carboxyl group creates nicotinic acid, the basis of the essential B vitamin, niacin.

The development of the picolinic acid herbicides is an interesting tale. Scientists at Dow Chemical Co. were working with a pyridine-based structure to inhibit nitrification—the conversion of ammonia in soil to nitrate, the form available to plants. This is the general process:

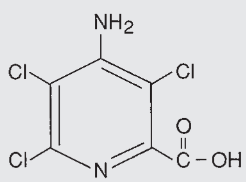
NH_4^+ *Nitrosomonas* ⟶ NO_2^- *Nitrobacter* ⟶ NO_3^-

↑ Common form in fertilizer

↖ Responsible microorganism ↗

↑ Readily available to plants and leachable

Nitrification occurs readily in many soils and is desirable. Nitrate ions are readily available to plants but leachable. Therefore, if nitrification can be slowed but not stopped, leaching will be reduced and plant availability maintained or increased. Scientists were working with the structure shown here and applying it in combination with ammonium fertilizers. The presence of the ammonia fertilizer made it possible for microorganisms to aminate the 4 position, and subsequent or simultaneous carboxylation of the trichloromethyl group was also carried out by soil microorganisms to yield picloram.



The scientists saw plants dying where they weren't supposed to, and by examining their work, they discovered an herbicide when they had been looking for an inhibitor of nitrification.

Picloram gives excellent control of woody plants and many annual and perennial broadleaved species. It is not effective on grasses, nor is it particularly effective on members of the Brassicaceae. It is chemically similar to but not directly related to other growth regulator herbicides. Picolinic acids produce epinastic and other effects typical of growth regulators and are active after absorption through foliage and through roots. Picloram is effective on many perennial broadleaved plants, including field bindweed and Canada thistle. It is translocated in plants after pre- or postemergence application. Doses as low as $0.25\,kg\,ha^{-1}$ are effective. Grasses, even seedlings, are relatively resistant. Picloram is very persistent and lasts for several months up to one year or longer to affect succeeding crops. It is water soluble, not highly adsorbed, and therefore susceptible to leaching. These characteristics are undesirable, although its high activity is desirable for control of perennial weeds.

Clopyralid is less persistent and less leachable than picloram and effective for control of broadleaved species. It is selective in Christmas trees, sugarbeets (a crop picloram kills), and corn and is not effective on grasses or mustards. It is especially effective on Polygonaceae and Asteraceae in field crops and turf. A primary advantage is its high activity against Canada thistle.

Triclopyr is effective on woody plants and broadleaved weeds and has been used for control of ash, oak, and other root-sprouting species. Most grasses are tolerant and while it is not used in many crops (it is used in rice), it is used as a turf herbicide.

Other

Quinclorac, a quinolinecarboxylic acid, is a unique chemical structure among herbicides. It controls some annual grasses, and a few annual and perennial broadleaf weeds when applied pre- or postemergence in rice. It also has good activity on some annual and perennial broadleaved weeds including field bindweed. According to the *Herbicide Handbook* (Vencill, 2002), its action in broadleaf weeds is as a growth regulator; however, in grasses it appears to inhibit cell wall (cellulose) biosynthesis. Exactly what it inhibits and how it does it are not clear, but its selectivity and activity are known and these enable its uses.

B. Inhibitors of Indoleacetic Acid (IAA) Transport

Naptalam is a selective, preemergence herbicide for control of a wide range of annual broadleaved weeds and grasses in dicotyledonous crops, including soybean, peanut, cucumber, musk and watermelon, and established woody ornamentals. It has a unique antigeotropic property. Because microbial breakdown is slow it provides weed control for three to eight weeks. Chemically it is a phthalmic or benzoic acid, but it can also be regarded as a substituted amide. It is not used widely but is interesting because of its ability to interfere with auxin transport.

This ability is shared with compounds known as morphactins. These materials have specific antigeotropic activity and prevent the normal downward movement of roots in soil and of shoots toward light. Their herbicidal activity is minimal to non-existent but they have been used to promote activity of growth regulator herbicides.

Diflufenzopyr is an auxin transport inhibitor that inhibits polar transport of natural auxin. It is formulated with the benzoic acid, dicamba, and increases its activity in plants susceptible to dicamba. Many regard this compound as a growth regulator rather than strictly as an herbicide.

VI. AMINO ACID BIOSYNTHESIS INHIBITORS

When a cell divides, the information necessary to form new cells is carried in genes by DNA and is subsequently expressed in structural and enzymatic proteins. Information in plant cells flows from nucleic acids (via mRNA) to proteins but not in the opposite direction. Any disruption of this information flow leads to growth inhibition. Protein synthesis is necessarily preceded by amino acid synthesis. Three sites for amino acid biosynthesis that include three different enzyme systems are important sites of herbicide action (Duke, 1990):

1. Inhibitors of branched chain amino acid synthesis, specifically inhibition of acetolactate synthase (ALS) = acetohydroxyacid synthase (AHAS).
2. Inhibition of aromatic amino acid synthesis, specifically inhibition of 5-enolpyruvyl-shikimate-3-phosphate synthase = EPSP.
3. Inhibition of glutamine synthetase.

Plants synthesize all essential amino acids and, in theory, blocking biosynthesis of any one will kill the plant. These three enzymes above are firmly established as primary sites of action of three herbicide families and some other herbicides.

A. Inhibitors of Acetolactate Synthase (ALS)—Acetohydroxyacid Synthase (AHAS)

Sulfonylureas

In the 1980s the sulfonylureas were introduced by the DuPont Co. The core structure for the sulfonylureas combines the photosynthetic inhibitors ureas and triazines, but the primary mechanism of action is inhibition of amino acid synthesis not photosynthesis. Secondarily, they inhibit photosynthesis, respiration, and protein synthesis. Plant symptoms include chlorosis, necrosis, terminal bud death, and vein discoloration. The site of action for the sulfonylureas catalyzes the first step in the biosynthesis of the three branched chain aliphatic amino acids valine, leucine, and isoleucine. A secondary effect is cessation of plant growth (stunting) due to cessation of cell division and slow plant death. Tolerance is related to a plant's ability to detoxify the herbicide.

Table 13.8 shows the range of selectivity of sulfonylureas and the primary crop of use for 17 sulfonylurea herbicides sold in the United States. Several others are available in other countries. A notable attribute of these herbicides is that they are active at rates in the range of 8 to 80 g (grams) ha^{-1}. This is as significant a reduction in the quantity of herbicide required as that which occurred when 2,4-D was introduced and replaced the heavy metal inorganic salts. However, older herbicides in this group tend to be persistent (newer ones, thifensulfuron, triflusulfuron, and nicosulfuron, are not) and very active

TABLE 13.8. A Summary of Information About Some Sulfonylurea Herbicides.

Herbicide		
Common	Trade name	Primary uses
Bensulfuron	Londax	Rice
Chlorimuron	Classic	Soybean, peanut
Chlorsulfuron	Glean/Telar	Wheat, barley, oats
Ethametsulfuron	Muster	Canola (rapeseed)
Halosulfuron	Permit	Corn, grain sorghum
Metsulfuron	Ally/Escort	Wheat, barley
Nicosulfuron	Accent	Corn
Primisulfuron	Beacon	Corn
Prosulfuron	Peak/Exceed	Corn, grain sorghum, wheat, barley
Rimsulfuron	Titus/ Matrix	Corn, potato
Sulfometuron	Oust	Noncrop, conifer plantings
Sulfosulfuron	Maverick	Wheat
Triasulfuron	Amber	Wheat, barley
Tribenuron	Express	Wheat, barley
Trifloxysulfuron	Enfield	Cotton, sugarcane
Triflusulfuron	Upbeet/Debut/Safari	Sugarbeet
Thifensulfuron	Pinnacle/Harmony	Wheat, barley, soybean

on several crops. Wheat is not affected by chlorsulfuron until soil concentrations approach 100 ppb. Lentil and sugarbeet, on the other hand, are affected by soil concentrations of 0.1 ppb. This thousandfold range in activity is unprecedented in herbicide chemistry. Great care is required to use these herbicides so that their activity and weed control potential are exploited, but untoward environmental problems are avoided. Several weed species have developed resistance to these herbicides, some in as little as three years, after annual use.

Imidazolinones

The imidazolinones, also developed in the 1980s, are active at low rates. Their site of action is the same as the sulfonylureas, but their activity is lower. At this writing there are six imidazolinones available in the United States. Imazamethabenz is a selective, postemergence herbicide for control of some annual grasses and broadleaf weeds in wheat, barley, and sunflowers. Imazamox is used postemergence to control annual broadleaf and annual and some perennial grass weeds in alfalfa, edible legumes (e.g., dry beans), soybean, and crops tolerant of imidazolinones (e.g., canola). Imazapic controls a wide range of annual broadleaf and annual and perennial grass weeds in peanuts. Imazapyr is not selective in crops, does not leach vertically or laterally, and is used for weed control on non-cropland and in imidazolinone tolerant corn. Imazaquin is not limited to postemergence application as most imidazolinones are. It is used to control annual grass and broadleaf weeds in soybean. Imazethapyr is used for pre- or postemergence control of annual grass and broadleaved weeds in soybean, edible legumes, alfalfa, and peanut. It has a relatively long soil persistence, and while small grains and rice can be planted within four months of its use, corn, dry beans, and sorghum should not be. There can be problems with soil, effects on rotational crops, and development of weed resistance.

Pyrimidinylthio-Benzoate

Chemically, pyrithiobac is a benzoate and the only herbicide in this group available in the United States. When used pre- or postemergence, it controls several annual broadleaved weeds in cotton. Although chemically distinct from other ALS inhibitors it acts in the same way.

Sulfonylamino-Carbonyltriazolinone

The two herbicides in this chemical group, flucarbazone-sodium and propoxycarbazone, are both active against different annual grass weeds when applied postemergence in wheat.

Triazolopyrimidines

The second edition of this book reported only one triazolopyrimidine, flumetsulam, that had been approved for use in the United States. It is still available, and three new herbicides have been added to the group. Cloransulam-methyl is applied pre- or postemergence to control broadleaf weeds in soybean. Diclosulam is soil-applied to control broadleaf weeds and perennial nutsedge in peanuts. Florasulam is used in spring or winter cereal crops. Flumetsulam is used pre- or postemergence in combination with at least one other herbicide in soybean and corn to control a range of broadleaved weeds. It has little activity against grasses. Soil life is short so rotation for each of these herbicides and injury to rotational crops is not a problem. Low use rates minimize leaching in soil. The four herbicides in this chemical group possess a diversity of activity against weeds and selectivity in crops. They illustrate why site of action is a better system of classification than chemical group or crop of use.

B. Inhibitors of 5-Enolpyruvyl-Shikimate-3-Phosphate Synthase (EPSP)

Glyphosate was released by Monsanto Chemical Co. in 1971. It is now sold under several trade names by Monsanto and other companies. Its discovery and release were as revolutionary in weed science as the discovery of 2,4-D. The structure of the amino acid glycine is underlined in Figure 13.4; glyphosate, the N-phosphonomethyl derivative of glycine, is a nonselective, foliar herbicide with limited to no soil activity because of rapid and nearly complete adsorption. It controls perennial grasses and has an advantage over paraquat, because glyphosate translocates. It is the only available herbicide that inhibits EPSP synthase. The enzyme is common in the synthetic pathways leading to the aromatic amino acids phenylalanine, tyrosine, and tryptophan. These amino acids are essential in plants as precursors for cell wall formation, defense against pathogens and insects, and production of hormones (Duke, 1990). The enzyme is not found in animals. Glyphosate has very low mammalian toxicity. Secondarily glyphosate affects respiration, photosynthesis, and protein synthesis. It is active only postemergence because it is completely and rapidly

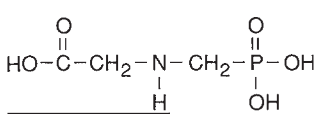


FIGURE 13.4. Structure of glyphosate with glycine underlined.

adsorbed on soil colloids. Its nonselectivity means that it will affect, if not kill, almost any green plant it contacts. Low application volume is more effective than high volume, and small plants are more readily controlled than large ones. Paraquat, a photosynthetic inhibitor, acts quickly (one or two days) on most plants. Glyphosate activity usually cannot be detected as quickly and may take several days to appear after application. One glyphosate formulation is used as an aquatic herbicide. Transgenic crops resistant to glyphosate have been created and marketed. At least eight species have been reported to be resistant to glyphosate (www.weedscience.org/Summary/UspeciesMOA.asp?1stMOAID = 12; accessed March 2006). Resistant species include Palmer amaranth, common ragweed, hairy fleabane, goosegrass, Italian ryegrass, rigid ryegrass, and buckhorn plantain. Resistance has been found in Australia, Chile, South Africa, Spain, and in 15 US states.

C. Inhibition of Glutamine Synthetase (GS)

Glutamine synthetase (GS) is essential for assimilation of organic nitrogen as ammonia (Duke, 1990). Its lack leads to very high ammonia levels. Glufosinate (phosphinothricin) is the only available herbicide that inhibits GS. It is available in the United States for complete weed control in noncrop areas and as a directed spray in field- and container-grown nursery stock. It is rapidly degraded in soil with a half-life of seven days. Even though it is not adsorbed tightly, it does not leach because it is degraded quickly. Glufosinate is nearly nonselective. It has been made selective in corn because a gene coding for phosphinothricin acetyl transferase activity was isolated from the soil bacteria, *Streptomyces hygroscopicus*, and cloned into corn. The acetyl transferase enzyme converts glufosinate to its nonphytotoxic acetylated metabolite, enabling crops to achieve resistance by rapidly metabolizing glufosinate.

VII. INHIBITORS OF RESPIRATION

Plants obtain energy by transforming the electromagnetic energy of the sun into stored chemical energy of carbohydrate molecules through photosynthesis. They must transform that energy to a form suitable for driving life processes. That transformation, called respiration, is analogous to the conversion of fossil fuel to electric power. Respiration is the removal of reducing power from carbohydrates, fats, or proteins, and its transfer to oxygen with the concomitant trapping of released energy in ATP. The few herbicides in this category are of historical interests because they are no longer readily available for use.

A. Uncouplers of Oxidative Phosphorylation

Herbicides interfere with respiration by uncoupling oxidative phosphorylation. Uncoupling is like braking while continuing to press a car's accelerator. Energy is released as electrons pass down the electron transport chain to oxygen and is trapped by converting ADP to ATP (oxidative phosphorylation). If you uncouple and keep the accelerator down, the motor will race and overheat (Corbett, 1974).

Arsenites

Arsenic has been known as a biological poison for many years. Arsenic-based insecticides were used in orchards in the late 1800s. Arsenic trioxide, an insoluble soil-sterilant, was used at 400 to 800 kg/ha, but is no longer registered for US use. Its residues remained for many years, and weed control could be effective up to five years. Livestock were attracted to, and could be poisoned by, plants sprayed with arsenic trioxide due to the release of aromatic compounds.

The acid arsenicals such as sodium arsenite were more effective because they were translocated in plants. They are nonspecific inhibitors of sulfur-containing enzymes and also precipitated proteins and disrupted membranes. Sodium arsenite was used as a preharvest desiccant in cotton. Inorganic arsenicals are poisonous to mammals and are generally regarded as nonselective, foliar-contact herbicides with soil sterilant activity. They persist in soil, and arsenic is no longer used except in combinations for soil sterilization.

Phenols

The first synthetic organic herbicide that achieved success in the field was 2-methyl-4,6-dinitrophenol, released in 1932. Several other substituted phenols followed but all are no longer approved for use in the United States and are only of historical interest. They are intensely yellow staining compounds, toxic to mammals, and poisonous to humans by ingestion, inhalation, or skin absorption. They were used for selective broadleaved weed control in cereals, and their activity increased directly with temperature.

DNBP [(2-(1-methylpropyl)-4,6-dinitrophenol] was used in several salt forms as a selective broadleaved weed herbicide in pea, legumes, corn, and flax. It was used, with less success, in small grains and for preemergence weed control in bean and cotton. Its selectivity depended on selective retention and absorption by foliage, and good coverage was essential. The phenol derivatives have short soil persistence. They also, secondarily, inhibit other plant processes, including photosynthesis and lipid, RNA, and protein synthesis. Pentachlorophenol was a widely used wood preservative.

VIII. UNKNOWN MECHANISM OF ACTION

All present systems of herbicide classification have imperfections because the site/mechanism of action is unknown for some herbicides. Some older herbicides are described as having a nonspecific action. An unknown mode of action may mean that it is truly unknown, the herbicide has not been studied completely, or the herbicide is too new to know and it is being studied.

The mechanism of action is unknown for most inorganic herbicides. Available studies are old and were done with far less sophisticated analytical techniques and less knowledge than modern studies. Most of these herbicides were used for many years, but their use has declined as organic herbicides have been discovered to provide better weed control at much lower rates. Some are still used in mixtures with organic herbicides for soil sterilization.

Chemical weed control began with inorganic herbicides. Ammonium sulphamate ($NH_2SO_3NH_4$) was patented in 1942. It is a water-soluble contact herbicide used for brush and weed control in industrial and residential areas. It is nonstaining and has low mammalian toxicity. Rates of 100 to 200 $kg\,ha^{-1}$ applied in 400 liters of water are required for effective brush control. Rates of 60 $kg\,ha^{-1}$ in 400 liters of water control poison ivy. These rates illustrate the great change that occurred when the phenoxy acid herbicides were introduced and rates dropped from over a hundred to a few kilos per hectare.

Sodium tetraborate ($Na_2B_4O_7$) and sodium metaborate ($Na_2B_2O_4$) are nonselective, taken up by roots, and have an unknown mechanism of action. Boron accumulates in reproductive structures after translocation from roots. Boron compounds are used for long-term, nonselective weed control in industrial and power line areas in combination with triazine and urea herbicides.

Sodium chlorate ($NaClO_3$) is a nonselective soil sterilant used on noncrop land or in combination with triazines, ureas, or other organic herbicides for soil sterilization. It leaches, has foliar contact activity, and in the past, was used widely along railroads. It is flammable when dried on foliage, and many railroad fires occurred when sparks from coal-fired engines landed on sprayed plants. Sodium chloride (table salt) is an example of an herbicide that desiccates and disrupts a plant's osmotic balance. It has been used for nonselective weed control for centuries.

Sulphuric, phosphoric, and hydrochloric acid all have burning, contact activity, but because of high toxicity to users, corrosion of equipment, and the availability of safer alternatives, they are no longer used.

Among the metallic salts, copper sulphate is one of the few still used as an herbicide. Its toxicity is due to a nonspecific affinity for various groups in cells leading to nonspecific denaturation of protein and enzymes. It is used as an algicide.

There are several organic herbicides with presently unknown sites/mechanisms of—action. The organic arsenicals are metallo-organic herbicides that interfere with general plant growth and may affect cell division. These chemicals, based on arsonic or arsenic acids, are strong acids that decompose carbonates. They have postemergence contact activity on plant foliage, are rapidly adsorbed by soil, and do not have soil activity. They are most effective at high temperatures, but rapidly lose selectivity above about 27°C. Organic arsenicals are more phytotoxic than inorganic arsenic herbicides. The most toxic form of arsenic to mammals is the AS^{+3} state; the form in inorganic arsenic compounds. Organics have arsenic in the +5 state, and because it is not normally reduced to AS^{+3}, organic arsenicals are less toxic to mammals.

The principal organic arsenicals, first released in the United States in the 1950s, are monosodium methane arsenate (MSMA) and disodium methane arsenate (DSMA), both derivatives of arsonic acid. Cacodylic acid, an arsinic acid, is less selective than arsonic acids. Organic arsenicals are water soluble, rapidly absorbed by soil, and do not leach except in sandy soils, and even then they don't leach beyond 20 cm. They are much more toxic to annual than perennial grasses. DSMA has been used for selective weed control in turf and cotton. Arsenicals have been used in forest weed control. They do not persist in soil because they are rapidly and completely absorbed by soil colloids. They may affect mitosis, but the Weed Sci. Soc. *Herbicide Handbook* (Vencill, 2002) lists the mechanism of action of all three as "not well understood," and Mallory-Smith and Retzinger (2003) categorize them as having an unknown site of action.

Difenzoquat, a pyrazolium salt, is used for the selective control of wild oats in barley and wheat. Its primary mechanism of action is unknown, but it inhibits photosynthesis, ATP production, potassium absorption, and phosphorus incorporation into phospholipids and DNA. It is a postemergence herbicide that, like other bipyridiliums, has only contact foliar activity and no soil activity. It has fungicidal properties and controls powdery mildew (*Erisiphe graminis* f.sp. *Hordii*) in barley. In contrast to diquat and paraquat, it does not cause rapid burning and desiccation of plant foliage.

Chemically ethofumesate is a benzofuranyl that controls several annual grass and broadleaf weeds in grass seed production fields and in sugarbeets. It is readily absorbed by emerging shoots and translocated to foliage, but its specific site of action is unknown.

Pelargonic was introduced in 1995 as a contact, nonselective, broad-spectrum foliar herbicide. Because it is not selective, it is used only in noncrop locations, and retreatment is required for plants that emerge after treatment from seed, roots, or rhizomes and other vegetative reproductive structures. It is a naturally occurring, nine-carbon fatty acid found in several plants and animals. Translocation doesn't occur, so it is not effective for long-term control of biennial or perennial weeds. There is no soil residual activity. The bipyridyliums are fast acting, but pelargonic acid is faster. Rate of kill is related to temperature, but even in cool conditions, plants begin to exhibit damage 15 to 60 minutes after application and die within one to three hours. Foliage darkens and begins to look water-soaked followed by rapid wilting. The site of action is unknown, but it causes rapid cell death, bleaching of chloroplasts, and general ion leakage. The primary effect may be a sudden drop in intracellular pH that causes rapid membrane deterioration and leads to cell death.

IX. SUMMARY

The precise molecular site of action of most herbicides is known. Research is advancing rapidly, and more precise classification will be possible with more knowledge. Any classification of a group as chemically complex as herbicides creates problems because of disagreement about (1) the best way to classify herbicides and (2) the relative importance of primary and secondary sites of action. Classification systems are complex and necessary and, when adequate, will assist classification of new herbicides and integration of knowledge. This chapter has used a scheme based on site of action to classify many of the presently available herbicides. It is not, nor is it intended to be, a catalog of all presently available herbicides. It should be possible to integrate any herbicides that are not mentioned herein into the classification system.

This chapter does not make any attempt to cover herbicide mixtures, which for good reasons, are used commonly. The reasons include broadening the spectrum of weed control, reducing the required amount of one herbicide, enhancing selectivity, or fitting a particular market niche. Nearly all mixtures will be classified in one or more of the groups mentioned herein. Therefore, determination of the site of action can be done with the classification scheme presented.

There are many herbicides and a great deal of information about uses, environmental fate, and mechanism of action is available for each one. The amount of information, even in a brief chapter, can be overwhelming. Table 13.9 lists the herbicide families included in this chapter and combines their primary site of action with the major plant function modified or irreversibly changed by the herbicide's activity. It is included to assist organization of the abundant information in this chapter.

TABLE 13.9. Summary of Herbicide Mechanism of Action (Adapted from Corbett et al., 1984).

Herbicide family	Primary action	Major function modified or disrupted	
Aryloxyphenoxypropionate, cyclohexanedione, carbamothioates, chloroacetamide	Fatty acid biosynthesis (ACCase action) →	Structural organization →	DEATH
Dichlobenil, isoxaben	Cell wall synthesis →	Structural organization	
Oxadiazole N-phenylthalamide thiadiazole, triazolone diphenylethers, triazinone	Protox inhibitors →	Structural organization	
Bipyridylliums	Photosynthetic electrons diverted from photosystem I →	Structural organization	
Urea, triazine, triazinone, Uracil acylanilide, Amide nitrile, pyridazinone, Benzothiadiazole, phenyl pyridazine	Photosynthetic electron transport (Hill reaction) →	Energy supply →	DEATH
Organic-arsenicals Dinitrophenols	Oxidative-phosphorylation uncoupled →	Energy supply	
Isoxazolidone, Amitrole, norflurazon	Carotenoid synthesis →	Chlorophyll destruction → ; Low carotenoid level →	DEATH
Imidazolinones, pyrimidinylthio benzoate, Sulfonylureas, triazolopyrimidine, Sulfonylamino-carbonyltriazolinone	Amino acid synthesis →	Growth and reproduction	
Glyphosate	EPSP synthase →	Growth and reproduction	
Glufosinate	Glutamine synthesis →	Growth and reproduction	
Dinitroanilines, dithiopyr	Cell division inhibited →	Growth and reproduction →	Growth; DEATH
Phenoxyacids, Benzoic acids, Picolinic acids, quniclorac	Synthetic auxins →	Growth →	Growth
Naptalam	IAA transport →	Growth	

THINGS TO THINK ABOUT

1. What is the primary site/mechanism of action of the herbicides in a particular chemical group?
2. Does chemical structure always predict an herbicide's site of action? Is it a reasonably good predictor?
3. What are the major plant processes affected by herbicides?
4. Are herbicides unique chemical molecules that are unrelated to other common chemicals?
5. What are the major sites/mechanisms of herbicide action?
6. Is it likely that the next edition of this book will have a modified system of herbicide classification? Why?
7. Why do herbicides have so many different mechanisms of action?
8. Why aren't more herbicides designed to inhibit specific plant biosynthetic processes?
9. Why don't we have a complete understanding of the precise mechanism of action of all herbicides?

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NOTE: Some of these sources were not in the text, but they were used extensively to prepare this chapter.

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CHAPTER 14

Herbicides and Plants

FUNDAMENTAL CONCEPTS

- There are several environmental, chemical, and physiological factors that affect an herbicide's activity and selectivity.
- The most important determinants of herbicide selectivity are the rate of absorption and the amount absorbed, translocated, and metabolized by two species.
- Several plant and environmental factors interact to determine selectivity.
- Sprayer calibration is one of the most important and neglected aspects of herbicide application.
- Forward speed, pressure, and nozzle tip orifice size are the primary things that can be adjusted to change a sprayer's calibration.

LEARNING OBJECTIVES

- To understand the difference between herbicide drift and volatility and the importance of each.
- To know techniques to control drift and volatility.
- To understand the fundamental importance of sprayer calibration.
- To know the external factors that influence spray retention and herbicide absorption.
- To know the effect of moisture, temperature, and light on herbicide action.
- To know the relative advantages and disadvantages of foliar and soil-applied herbicides.
- To understand the difference between shoot and root absorption of herbicides.
- To understand the role of absorption, translocation, and metabolism as determinants of selectivity.

I. FACTORS AFFECTING HERBICIDE PERFORMANCE

This discussion of factors affecting herbicide performance in plants assumes that users have an applicator appropriate to the task and that it has been calibrated to apply the correct volume and the proper amount of active ingredient per acre. The discussion also assumes that the correct herbicide has been selected and that it will be applied at the right time. If these things are not ensured, they will nearly always negatively affect herbicide performance and environmental quality, but because human errors and their results are not precisely predictable (we can't plan our accidents), the discussion herein assumes human error has been avoided.

This chapter discusses factors that affect performance from the time an herbicide molecule leaves the applicator (usually this means the nozzle tip) until it hits a plant target and acts.

II. GENERAL

A. Sprayer Calibration

It is important to understand the equipment required to apply herbicides properly. Although size and reliability of equipment have changed, it remains basically the same (McWhorter and Gebhardt, 1987). More than 90% of all herbicides are still applied with hydraulic sprayers that have the same four basic components: a tank, pressure regulator, pump, and spray nozzles. The conventional hydraulic sprayer continues to be the most acceptable and most widely used method of herbicide application whether herbicides are applied to plants or soil. Great advances in herbicides and formulations have been made, but while application technology has improved, it has not advanced at the same pace. Most herbicides are still broadcast as an aqueous mixture from a hydraulic sprayer that uses simple nozzles to break the pressurized liquid stream into droplets. As long as the fuel, the herbicide, and the farmer's time were inexpensive and environmental contamination was a minor concern, a cheap method of herbicide application was appropriate. These conditions have changed, and more effort is now being expended to improve herbicide application.

In most cases herbicides are applied as broadcast sprays to an entire area, whether the area is an entire field or a band over the crop row. Not all of the area sprayed may have weeds, but it is all sprayed. This means that herbicide is commonly applied where there are no weeds. This, while appearing inefficient, has been efficient because it has been easier and less expensive to spray an entire area and the technology to spray just the weeds has not been available. There has been no way to detect each weed. Weed scientists know that weeds usually exist in patches in a field, not as uniform stands, and spraying the entire field is not necessary. Recent research (Felton, 1990) makes it possible to apply one herbicide to one species and another herbicide to a second species in one pass across a field. Weed species are detected because the leaf tissue of each species differs in reflectance. Microprocessors turn the sprayer on only when weeds are sensed. The system reduces total spray, herbicide use and cost, doesn't waste herbicide, reduces environmental presence, and reduces the likelihood of off-target movement and nontarget effects. When morphological and foliar reflectance characteristics of different species are incorporated, specific weed control will be possible. These advances combined with global positioning system (GPS) technology will allow an applicator to know and the machine to remember where species are and be very precise with herbicide application.

Several years ago, there was great interest in controlled droplet applicators (CDA technology), but that has waned. In principle CDA technology produces droplets over a narrow size range. The principle holds for low-volume applications, and CDAs are quite effective for drift reduction (see the following section on drift).

Herbicides can be, but usually are not, applied as granules with applicators capable of being calibrated. Granule application can often be combined easily with crop planting. Because of its exclusive foliar activity, glyphosate led to the development of wiper application. Wipers could be nylon ropes that act as wicks but do not drip the herbicide on nontarget species. Weeds that emerge above a crop canopy receive a lethal dose of glyphosate when wiped by the rope. Shag carpet–covered rollers have been used, but they were replaced by rope wicks. Both technologies are now rarely used and are primarily of historical interest.

Each kind of herbicide applicator can be calibrated with the same basic technique. The applicator is driven over a known area, and output is measured, or output is measured for a certain time with the applicator stationary. Special devices are available to assist with calibration by direct reading during spraying or while stationary. No technique is difficult or complex but each takes time before herbicide application.

Even with sophisticated, specialized knowledge of herbicide chemistry, mechanism of action, application timing, rate of application, selectivity, and activity, herbicides may fail to control the weeds they should control, achieve desired crop selectivity, and may leave undesirable environmental residues. A major reason for failure is not a lack of knowledge about how the herbicide acts, but rather that herbicides are frequently not applied properly. A Nebraska study (Reichenberger, 1980) found that two of every three pesticide applicators made application errors due to inaccurate calibration, incorrect mixing, worn equipment, or failure to read and understand the product label. These mistakes caused over- and underapplication and cost farmers between $2 and $12 per acre in added chemical expense, potential crop damage, and lost weed control. When results were extrapolated to the entire United States, a billion-dollar application blunder was made each year. Other studies of farmer's sprayers have shown similar problems (Ozkan, 1987).

It is not totally inaccurate to say that a major problem with agricultural chemicals is the people who apply them. In spite of all the specialized research and technology required to develop and market an herbicide, the end result is often dependent on decisions made by a user, just prior to use. These quick decisions are frequently wrong. The reason more accidents haven't occurred is that herbicides are developed to be reasonably foolproof, but they are not completely so; all mistakes are not tolerable.

Because of application blunders and concern for human and environmental safety, government regulation of herbicides has increased. No legislative body can enforce a law against stupidity, but all can pass laws that make penalties for stupidity greater and encourage use of reasonable intelligence. Such laws become more likely when reasonable intelligence is not the norm.

The metallic salts, the first selective herbicides, were applied at 100+ lbs/A in at least 100 gallons of water per acre. Some may also have been applied in relatively low volume by brushing or wiping (Gebhardt and McWhorter, 1987). Invention of the compressed air sprayer in the early 1900s improved application (Gebhardt and McWhorter, 1987) but didn't reduce the amount of herbicide required for weed control. Early weed sprayers were high-volume sprayers with wooden tanks. Later sprayers, capable of applying lower volumes, had steel tanks. As mentioned, the first sprayers and modern sprayers have basically the same parts: a tank, pressure regulator, pump, and nozzles. Today, 90% of all herbicides are applied with low-pressure ground sprayers drawn by a tractor (Felton, 1990). Herbicides are also sprayed by airplane and with large, self-propelled ground implements.

Spraying may be followed by soil incorporation to reduce or control volatility, put the herbicide in position to maximize plant uptake, and promote control of emerging seedlings, or root uptake. Failure to incorporate well is a frequent reason for poor herbicide performance. Power rototillers are the best incorporation implements but are not used on most farms. Disking is probably the most common incorporation technique and works best if done twice with the second pass at right angles to the first. A single disking produces zones of high herbicide concentration and other areas with virtually no herbicide because of the tendency of the disk to ridge soil.

Herbicides can be applied by injection into water flowing in furrows or ditches and through sprinklers. This technique, called herbigation, is effective for herbicides taken up by plant roots from soil, but is not effective for all herbicides.

B. Reaching the Target Plant

Drift

Spray drift is movement of airborne liquid spray particles. It is often unseen and may be unavoidable. It can be minimized. Drift increases with wind speed and the height above the ground at which drops are released and decreases as spray droplet size increases. Ideally, uniform drops between 500 microns (moderate rain) and 1 mm (1,000 microns = heavy rain) in diameter are desired. Drops of this size minimize, but do not eliminate, drift, especially if spraying is done when wind speed is less than 5 mph. It is not uncommon, especially in arid environments, for water to evaporate within 200 to 300 feet of the point of delivery, so only the herbicide and associated organic solvents remain to drift. Table 14.1 shows spray droplet size, droplet lifetime, and the potential effect on drift (Brooks, 1947; Hartley and Graham-Bryce, 1980). For comparison, a number 2 pencil lead is about 2,000 microns, a paper clip is 850, a toothbrush bristle 300, and a human hair is about 100 microns in diameter.

Nozzle tips give pattern to sprays and break up the liquid stream into small particles. Hydraulic nozzles produce a range of droplet sizes rather than just one. Droplet size is a function of orifice size, operating pressure, and surface tension of the spray solution. Smaller nozzle orifices, higher pressures, and lower surface tensions produce more small drops. All hydraulic nozzles produce a normal (Figure 14.1) distribution of spray drop sizes. As size decreases and pressure increases a greater percentage of small droplets is produced.

The influence of wind on droplets is illustrated in Table 14.1. Small droplets will drift a long way in a light breeze. Large drops decrease drift problems. Spraying in strong wind should be avoided, but it is difficult when large areas must be sprayed with herbicides that require application at particular growth stages or before crop emergence. Farmers and other applicators must apply herbicides at the proper time. However, if other considerations take precedence over drift avoidance, problems may ensue when the applicator's or a neighbor's crops are injured or the environment is contaminated by improper application. Sprayer boom height is normally fixed. However, as illustrated (Table 14.1), release height influences drift potential simply by allowing drops to remain suspended longer.

TABLE 14.1. The Effect of Spray Droplet Size on Evaporation and Drift.

				Evaporating water			
Droplet diameter (microns)	Type of droplet	Precipitation (in./hr)	Drops (No./in.^{2})	Drop life (sec)	Lifetime fall distance (in.)	Time to fail 10 feet (sec)	Distance traveled while falling 10 feet in a 3 mph wind
5	Dry fog	0.04	9,220,000	0.04	<1	3,960	3 miles
20	Wet fog	—	144,000	0.7	<1	—	—
100	Misty rain	0.4	1,150	16	96	10	409 feet
200	Light rain	—	144	65	1,512	—	—
500	Mod. rain	3.9	9	400	>1,500	1.5	7 feet
1,000	Heavy rain	39	1	1,620	≥15,000	1.0	4.7 feet

Source: Adapted from Bode, L.E. and R.E. Wolf. Techniques for applying postemergence herbicides. Univ. Illinois, Urbana, IL. 5 Pp. Undated.

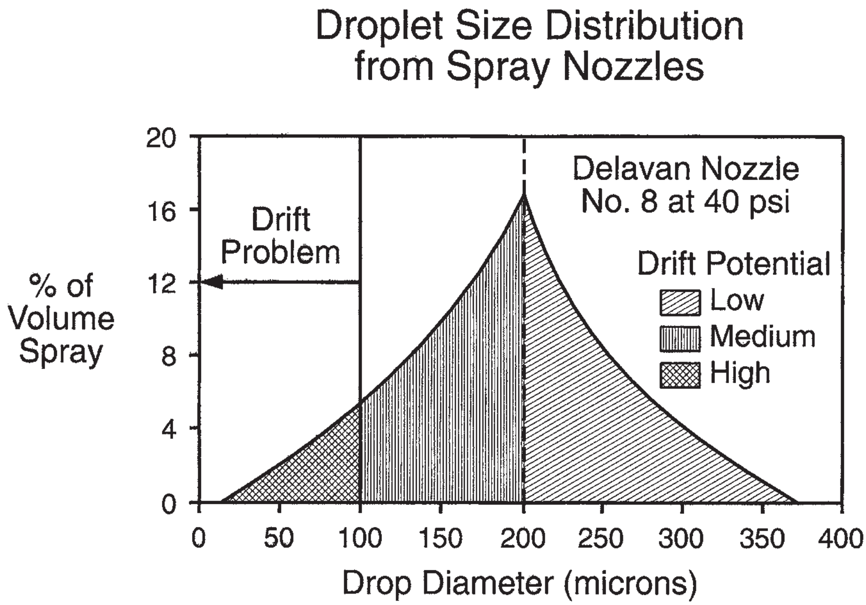

FIGURE 14.1. Normal distribution of spray drop size from a hydraulic nozzle.

Because drift is an inevitable problem, several techniques have been developed to control it. The first, and simplest, is to reduce spray pressure and create fewer small drops. Increasing drop size from 20 to 200 microns decreases coverage 200 times and increases drop lifetime from 0.7 to 65 seconds (Table 14.1). Small drops attain a horizontal trajectory quickly, and water may evaporate before the drop contacts a plant. After water evaporation, pesticides can become airborne aerosols that fall out with rain or sprinkler irrigation, but one cannot be sure where they will fall. Droplets larger than 150 microns normally resist evaporation long enough to reach the target.

Low-volume applicators that use a rotary atomizer reduce water requirements and equipment weight and are known as ULV (ultralow volume) or CDA (controlled drop) applicators. Drop size is usually controlled between 150 and 300 microns, and total volume can be as low as ½ gal/A. CDA applicators have been available for several years but have not achieved a high level of commercial acceptance due to high cost, frequent performance failures, and the widespread acceptance and availability of hydraulic nozzles.

Nozzles that incorporate air or facilitate use of a foaming adjuvant are available. They produce coarse droplets, but up to 5% loss is still possible within 1,000 feet of the point of application. Foam adjuvants increase spray volume two to three times and may also act as wetting agents and increase phytotoxicity. Water-soluble thickening agents (thixotropic agents) increase average droplet size. These are water-imbibing polymers that create a particulated gel spray. The smallest droplet size is predetermined by the polymer's particle size. There is usually no phytotoxic benefit, but drift is reduced. Chapter 16 discusses use of the limited, and now largely abandoned, invert emulsions to increase spray solution viscosity and reduce drift.

A recirculating sprayer was developed (McWhorter, 1970) to apply herbicides. The hypothesis was that environmental contamination could be reduced without loss of weed control if spray that did not strike a target plant was captured, recirculated, and reused. This was done by spraying horizontally above the crop's foliar canopy. The system was only successful with foliar applied, postemergence herbicides. The recirculating sprayer eliminated vertical spraying. The sprayer successfully applied glyphosate to control weeds above the canopy of cotton and soybeans in the southern United States, but was never a commercial success.

Wax bars impregnated with 2,4-D (McWhorter, 1966) were once used to control weeds in crops and in turf. They were not satisfactory because 2,4-D was hard to impregnate uniformly, bars tended to self-destruct, and wax melting was not uniform because temperature was not uniform or hot enough, so herbicide application was not uniform and successful. They are no longer manufactured.

The development of glyphosate led to renewed interest in the question "Why spray." As just mentioned, wiper technology was developed (Derting, 1987) first with shag carpet and eventually with rope wicks. When the ropes were moved horizontally above the crop, weeds, growing above the crop, contacted the herbicide in the rope and, through control of solution concentration, sufficient herbicide was applied to kill them without affecting crops. This was an excellent way to eliminate drift, but the system is no longer used widely and, with a few exceptions, is only of historical interest.

Drift is not just a problem of historical interest. In the late 1980s, clomazone drift affected many nontarget plants after application to soybeans in the midwestern United States. More recently, the US Environmental Protection Agency has expressed concern about drift from sulfonylurea herbicides that can damage flowers, seeds, and fruits of grapes, alfalfa, cherries, and asparagus. The state of Washington prohibited use of sulfonylurea herbicides within 14 miles of nontarget crops because of drift potential and requires 24 hours' notification of intent to spray (Anonymous, 1996).

Volatility

Volatility measures the tendency of a chemical to vaporize—that is, to move from the liquid to the gaseous state. Drift is movement as a liquid, whereas

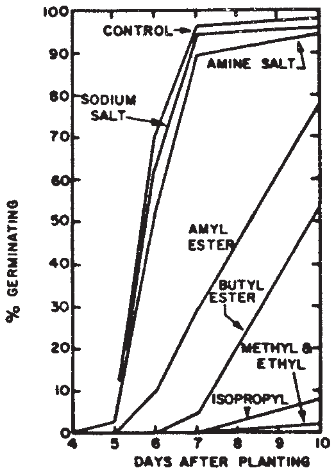

FIGURE 14.2. Percent germination of pea seeds after exposure to 2,4-D formulations (Mullison and Hummer, 1949).

volatility determines movement as a gas. Volatility is related to an herbicide's vapor pressure and ambient temperature. Volatilized herbicides may cause damage in another place or reduce effectiveness at the point of application. The most common example of volatilization is found with some esters of phenoxyacetic acids (e.g., 2,4-D). Figure 14.2 shows the effect on germination of pea seeds after exposure to volatile 2,4-D (Mullison and Hummer, 1949). Because of the experiment's design, only volatility could have caused the observed effects. Methyl and ethyl (1- and 2-carbon) esters are more volatile than the 5-carbon amyl ester, and all esters are more volatile than amine or sodium salts. Because of the high volatility of short-chain esters of 2,4-D, it is no longer possible to purchase and use them. Volatility is not limited to phenoxyacetic acids. Some carbamothioates and dinitroanilines are volatile and can be lost from the area of application if not incorporated into soil. Volatility problems are not going to go away, and intelligent herbicide use demands continuing attention to the risk.

III. FOLIAR ACTIVE HERBICIDES

A. Spray Retention

If herbicides do not drift or volatilize, the next factor that affects performance is retention on plant surfaces. A foliar herbicide must remain on leaves long

TABLE 14.2. Spray Retention by Different Species (Blackman et al., 1958).

Species	Number of leaves	Height cm	Water retained ml/g shoot weight
White mustard	2	5–7	2.5
Sunflower	2	6	2.0
Flax	2	5	1.1
Pea	2	5–7	0.4
Barley	3	15–20	0.3

TABLE 14.3. Retention of Propanil by Wheat and Green Foxtail Plants at the Three-Leaf Stage of Growth (Eberlein and Behrens, 1984).

	Propanil retained	
Species	mg/Plant	mg/g Fresh weight
Green foxtail	0.69	19.09
Wheat	1.20	2.49

enough for absorption to occur. Plants differ in their ability to retain water on leaf surfaces (Blackman et al., 1958; Table 14.2). Barley has upright leaves disposed nearly perpendicular to the soil surface, and liquid droplets run off easily. Peas have a waxy cuticle that makes it difficult for liquids to remain on the leaf surface. Flax is an upright plant with small vertical leaves, but sunflowers and white mustard are large plants with broad leaves. Broadleaved species with large, flat leaves disposed parallel to the ground retain liquid droplets more easily than grass leaves.

The use of propanil for selective control of green foxtail in hard red spring and durum wheat (Eberlein and Behrens, 1984) illustrates the influence of spray retention on herbicide activity (Table 14.3). The data show that wheat has a slightly higher concentration in terms of mg of propanil retained per plant but green foxtail absorbs and retains more. Propanil is used in rice and is selective because of rapid metabolism rather than differential retention (Yih et al., 1968a and b).

Leaf Properties

The ability of an herbicide to control weeds selectively can depend on morphology (shape) and chemical variations between plant surfaces (see Harr and

Guggenheim, 1995, for detailed descriptions of leaf surfaces of major crop plants). Large, broad leaves disposed parallel to the soil surface are easier to hit with spray solutions applied by most field sprayers. Herbicide molecules are more likely to contact and remain on the broad leaves of dicots than on grass leaves, which are often disposed perpendicular to the soil surface.

Velvetleaf, crabgrass, and some species of mallow have hairy leaf surfaces that prevent direct, quick contact of spray droplets with the leaf surface. But when a hairy surface becomes saturated, herbicide entry may be promoted because hairiness delays evaporation.

Because leaves are one of the principal entry points for herbicides, their structure and function are important. The primary leaf tissues are epidermal, mesophyll, and vascular. The epidermis is present on upper and lower leaf surfaces and consists of a single layer of interlocked cells with no chloroplasts. It is covered by the cuticle that is often layered with waxes. These constitute a varnish-like layer or film that retards movement of water in and out of leaves.

All leaves have cuticles, a formidable barrier to herbicide entry, yet herbicides do enter plants. Surface active agents (surfactants) are used in some formulations to assist entry, and they often determine the amount of herbicidal activity obtained because of their effect on leaf surface penetration. Water is not compatible with many plant surfaces, especially those with thick or very waxy cuticles. Surfactants lower surface tension of liquid systems, increasing their tendency to spread and their ability to wet leaf surfaces. Surfactants aid penetration.

It is incorrect to assume that plants with thick, waxy cuticles absorb less herbicide or absorb the same amount more slowly than plants with thin cuticles. The reason is that cuticle hydration and composition are more important factors in herbicide absorption than cuticle thickness. Plant leaves that are growing in shade generally have thinner cuticles than those growing in full sun, and young leaves have thinner cuticles than old ones. Thinner cuticles are one reason, but not the only reason, that young plants are more susceptible to herbicides than old plants.

Stomata appear to be obvious entry points, but most herbicides enter plants through leaf surfaces. Liquid spray droplets or volatile gases can enter stomata, but even after stomatal entry, herbicides must penetrate the thin cuticle present in substomatal chambers. Stomata vary in number, location, and size among different plant species, and while they can be located on upper and lower surfaces, most agricultural plants have the majority of stomata on lower surfaces. There may be as much as tenfold variation among species in stomatal number.

Another problem with entry through stomatal openings is the surface tension of spray solutions. It is possible, but not very likely, for a droplet of a liquid with high surface tension to bridge a stomatal opening and not enter it. Surface tension is a more important determinant of the tendency to spread than it is of stomatal entry.

Often stomata are not open during the day when herbicides are most commonly applied; they close during the heat of day and open during cool mornings and evenings. To achieve easy stomatal penetration, an herbicide spray must have low surface tension and high wetting power; a difficult combination.

Other Factors

The location of growing points or plant meristematic areas can determine herbicide selectivity. In grasses growing points are usually at the base of plants and are protected from foliar herbicides by surrounding leaves. In some plants, growing points are actually below the soil surface and not exposed to direct contact by foliar applied herbicides. In contrast, broadleaved plants usually have terminal, exposed growing points that may be more readily contacted and susceptible to herbicide action.

Selectivity can be obtained through herbicide placement. An herbicide can be applied to plant foliage, only to soil, only to soil and weeds between crop rows, or only over the crop row. A nonselective herbicide can be used selectively by controlling where it is applied. Selective placement can also be obtained by using granular herbicides that have little or no foliar activity because granules do not adhere to foliage.

The stage of plant growth at application is an important determinant of herbicide activity. It is a good generalization that seedling plants are more easily controlled by an herbicide than mature plants. An example of this was given earlier (see 2,4-D, in Chapter 13).

Characteristics of Spray Solution

Composition of the spray solution is a very important aspect of selectivity and activity. A spray solution with little or no surfactant may have high surface tension and just bubble up on a cuticular surface as water does on a newly waxed car. In this case, there is less opportunity for absorption because the contact area between the applied herbicide and the plant surface is limited. On the other hand, a spray solution with a surfactant decreases liquid surface tension, spreads out water droplets, increases surface coverage, and wets the surface thereby promoting penetration. Frequently, nonphytotoxic crop oils are included in spray mixtures to promote herbicide penetration and activity. Diesel fuel has been included as an adjuvant in a water-based spray system for control of plants on rangeland because it promotes penetration of leaves and is phytotoxic.

TABLE 14.4. Dry Weight of Oat Seedlings Selectively Exposed to Diallate (Appleby and Furtick, 1965).

Plant part exposed	Dry weight (mg)
Coleoptile	0
Root	205.2
Coleoptile and root	0
Untreated control	303.8

Another factor, often not controlled, influencing herbicide activity is drop size. For a given amount of herbicide per unit area, activity usually increases as droplet size decreases (McKinlay et al., 1972) (Table 14.4). For a fixed droplet size, effective dosage can be increased equally well by increasing herbicide concentration in each drop or by increasing the number of drops per unit area. If a spray solution has 0.86 grams of 2,4-D per liter, three 400-micron drops per sq cm will apply 64 times more spray volume and active ingredient per sq cm than three 100-micron droplets (McKinlay et al., 1972). Drop size is difficult to control in most hydraulic sprayers, but is fixed, in a narrow range, in controlled drop applicators (CDA).

B. Environmental Factors

The influence of environmental factors on herbicide phytotoxicity is almost always related to differential absorption, translocation, or metabolism. These are affected by morphological characteristics imposed on plants by the environment. Altered plant susceptibility to herbicides can often be traced to environmental stress that alters a plant's ability to absorb or metabolize herbicides.

Moisture

If an herbicide molecule doesn't drift or volatilize, reaches its target, and is retained on the plant surface, its activity can still be affected by environmental factors. Herbicide users want to know the likely effects of weather (rain, snow, cold, hot, dry, wet, etc.) on herbicide performance. If the sun comes out immediately after application or even during application, as opposed to application on a gray, cloudy day, does that affect an herbicide's activity and selectivity? Phenoxy acids formulated as esters are more fat-soluble than water-soluble. Therefore, on a warm day, leaf cuticles may be more fluid and more readily penetrated by fat-soluble compounds such as esters. Warm days aid penetration and activity. It is a good generalization that the warmer it is, the better herbicide activity will be. For noncontact or soil-active herbicides, temperature at time of application is less important. Temperature influences a plant's metabolic rate and physiological activity. If a plant is rapidly metabolizing and photosynthesizing, it will translocate herbicides rapidly enhancing their activity.

What if an herbicide is applied and it rains soon after? With phenoxy acids, penetration occurs within an hour and it is rain fast after one hour, so rain several hours after application does not affect activity. On the other hand, some herbicides are not rain fast for up to 6 hours after application. Atrazine is a soil-applied herbicide and is rarely applied to plant foliage because it penetrates poorly and rain will wash some off even if it rains as many as seven days after application. Weed scientists in the University of Nebraska system annually publish a guide to weed management (Gaussoin et al., 2005) that includes a table (p. 116) showing how long it takes after application for more than 80 herbicides to become rain-fast. The time ranges from ½ to 8 hours. The best recommendation for foliar herbicides is that they should be applied on warm, sunny days with little chance of rain within 24 hours after application. Product labels should be consulted when questions arise. Activity of soil-applied herbicides may be enhanced by a light rain shortly after application that moves them into upper soil layers.

In general, high temperatures and low humidity are detrimental to cuticular absorption. Plants growing under these conditions may produce thicker, less penetrable cuticles or have thin, poorly hydrated cuticles that are not easily penetrated. Sprays dry rapidly, and water stress may cause stomatal closure. High relative humidity reduces water stress, delays drying, and favors open stoma. Plants sprayed with an herbicide under warm, dry conditions may die more quickly if they are moved to warm, moist conditions. Warm temperatures that are not excessive (above 100°F) usually promote herbicide penetration and action. Rain and hard winds before treatment may weather (break and crack) cuticle and more spray may be trapped and taken up by weathered leaves.

Temperature

Weed control is best when temperatures before and at the time of herbicide application favor uniform plant germination and growth. High temperatures during application generally increase herbicide action by favoring more rapid uptake, but the effect may be offset by rapid drying of applied herbicide on leaf surfaces.

Light

Light is an important, but uncontrollable, environmental factor. It is essential for photosynthesis but photosynthetic inhibitors do not have to be sprayed during the day. Many photosynthetic inhibitors are taken up by roots and can be applied at any time of day. Good light conditions may open stomates, increase photosynthetic rate, and increase transport of photosynthate and herbicide.

IV. PHYSIOLOGY OF HERBICIDES IN PLANTS

A. FOLIAR ABSORPTION

If an herbicide avoids all of the preceding problems and resides on a plant surface long enough, it must be absorbed for activity to follow. Very few herbicides are true contact materials that solubilize cuticles and membranes and enter plants without absorption through the cuticle to achieve activity.

Most herbicides must enter plants and reach an appropriate site of action before toxicity is expressed. Successful herbicide action requires herbicide absorption, translocation in the plant, and avoidance of detoxification (loss of activity) prior to an attack at the molecular level on some process vital to plant growth.

No general description of the entire process of herbicide action is applicable to all herbicides any more than such a description can be provided for all antibiotics or general pharmaceuticals. How does aspirin work? We don't know precisely. However, the fact that we don't know does not mean that we can't use it intelligently.

Absorption of an herbicide can be regarded as passage through a series of barriers, any one of which may limit or prohibit action. With crops and weeds, functioning of such barriers can be the basis of selectivity. Modern herbicide formulations have been created with full knowledge of absorptive barriers and while selectivity is most often explained by metabolism, absorption must still occur (see section IV-D).

The terms symplast and apoplast are helpful when thinking about uptake and distribution. The essence of the concept of symplast is that all living cells of an organized, multicellular plant form a functionally integrated unit. The apoplast is the continuous nonliving cell wall structures that surround and contains the symplast. The xylem, nonliving tissue that conducts water and solutes from roots to shoots, is part of the apoplast. The apoplast varies in composition from the highly lipid cuticle to aqueous pectin and cellulose cell walls. It is interposed between the symplast and the external environment. All herbicides that enter plants do so via the apoplast and bring about death by action on the symplast.

There are several barriers to apoplastic penetration. The role of each barrier varies with each herbicide-plant-environment combination. These barriers include stomata, cuticle, epidermis, and cell walls.

Stomatal Penetration

As we said before, stomatal presence, exposure, and distribution vary between plants and between plants of the same species grown in different environments. Stoma are an obvious port of entry but are not very important because stomatal openings vary under field conditions and the maximum opening may be different than the time of application. Rapid drying of solutions (Table 14.1) also allows little time for stomatal penetration. Cuticular penetration is often easier and occurs regardless of stomatal presence or aperture size when herbicides are properly formulated and applied.

Cuticular Penetration

The cuticle is a waxy layer on the leaf surface; the thickness and composition of which varies between species. The composition and thickness of cuticle varies when plants of the same species are grown in different environments. Apart from root absorption (to be discussed) and some stomatal entry, cuticular penetration is the way most foliar herbicides enter plants. Cuticular entry is possible when stomates are closed and occurs under a range of environmental conditions. There are aqueous and lipid routes of entry through the cuticle. Both are available for simultaneous entry of herbicides, and the relative rate of entry depends on the molecule entering and the environment.

Cuticles are somewhat open, sponge-like structures made up of a lipid frame with interspersed pectin (water-soluble) strands and possibly open pores. Pores can fill in a water-saturated atmosphere to provide an accessible water diffusion continuum. Herbicides concentrate as solution dries and gather in depressions, commonly over anticlinal (sloping downward) walls, prior to absorption. Cuticular penetration is by diffusion through a water or lipid continuum. When a plant is under stress, pores fill with air, which acts as a barrier to water penetration, but lipoidal routes are still available.

Fate of Foliar Herbicides

There are five possible fates of herbicides applied to plant foliage:

1. Volatilization from foliar surfaces and loss to the atmosphere
2. Retention on leaves in a viscous liquid or crystalline form
3. Penetration of the cuticle and retention there in lipid solution

4. Adsorption by the cuticle
5. Penetration of the cuticle

While the first four fates are theoretically possible, for all practical purposes they can be neglected because manufacturers are aware of these fates and strive to develop formulations that eliminate the possibilities.

Penetration of the cuticle is what is intended. Desirably that is followed by penetration of the aqueous portion of the apoplast (epidermal cell walls) and migration via anticlinal walls to the vascular system. If an herbicide is not phloem mobile, it will remain in the apoplast and move with the transpiration stream to acropetal leaves. Some herbicides that move this way cannot cross the plasmalemma barrier, and they translocate only acropetally in xylem. Many others cross easily to phloem. Because xylem translocation is much more rapid than phloem, the herbicide may appear to be translocated only or dominantly in xylem, even though phloem translocation occurs.

Finally, after penetrating the cuticle via the aqueous phase of the apoplast, molecules are absorbed into the living cellular system (symplast) and translocated in phloem out of leaves in the assimilate stream. These molecules can become systemic and move throughout the plant to sites of high metabolic activity (e.g., meristematic regions). Many herbicides follow this route.

Advantages and Disadvantages of Foliar Herbicides

There are obvious advantages to foliar herbicides. Foliage is a readily available site of entry. There is often a high efficiency of foliar absorption and treatments can be designed and scaled to control specific, observable weed problems. There are equally important disadvantages. Application timing is often critical because the herbicide may be most effective when applied at a certain stage of plant growth (e.g., herbicides active only postemergence). Some herbicides are not absorbed well by foliage and are also readily absorbed by roots. Wetting plant surfaces is difficult and weather conditions at the time of application affect performance. Herbicides control small plants better than large ones but small plants do not have many leaves and contact and absorption may be inefficient. It often takes several days or even weeks for some plants (e.g., perennials) to grow enough foliage so good absorption and activity can be obtained.

B. Absorption from Soil

General

Some herbicides are directed at soil without any intention of foliar entry. Most foliar herbicides are applied as broadcast sprays, and much of the spray hits soil because it necessarily misses plant foliage. Because many herbicides are applied when plants are young, most of the soil surface is exposed. Thus, soil becomes an unavoidable target and repository for much of what is applied. Herbicide fate in soil becomes a significant determinant of performance and environmental affect (see Chapter 15).

Advantages and Disadvantages of Soil-Applied Herbicides

Application timing of soil-applied herbicides may be convenient and economical because it can be combined with other operations. The effectiveness of preplant or preemergence soil-applied herbicides is not dependent on stage of plant growth or physiological condition at time of application. Positional selectivity can be obtained by placing soil-applied herbicides at a particular depth relative to the crop plant or seed.

Soil-applied herbicides have important disadvantages. There is a tremendous dilution by soil and soil water following application and the amount available to plants is low. There is fixation by soil colloids (adsorption) that reduces the amount of herbicide available for plant absorption. Foliar herbicides are affected by weather conditions at application whereas soil-applied herbicides are more affected by weather subsequent to application, especially dry conditions. There is often dependence on rainfall, irrigation, or soil incorporation for distribution and action. Persistent residues that may injure subsequent crops can occur after use of some soil-applied herbicides.

Root Absorption

It is generally conceded that herbicides enter roots via root hairs and the symplastic system—the same pathway that inorganic ions (plant nutrients) follow. Passive and active uptake occurs but most uptake is passive with absorbed water, and movement is with water in the apoplast. Active uptake involves respiration energy, oxygen, entry into cells, and movement in the symplast. There is accumulation of herbicides at points of activity in the symplast, and selectivity is expressed in the symplast. Most phenylureas, sulfonylureas, triazines, and uracils are absorbed by roots and move upward apoplastically. Root absorption is highly dependent on an herbicide's lipophilicity (solubility in lipids).

Influence of Soil pH

For weak aromatic acids such as dicamba and 2,4-D, phytotoxicity increases as soil pH increases and reaches a maximum at pH 6.5 (Corbin et al., 1971). The same is true for weak bases such as prometon and amitrole. Soil pH between 4.3 and 7.5 had no effect on phytotoxicity of picloram, weak aromatic acids, and the nonionic herbicides dichlobenil and diuron. The conclusion is that no generalizations can be made about effects of soil pH on herbicide absorption (Corbin et al., 1971). There is an influence, and the effect of pH cannot be ignored, but there is no basis for predicting what it will be in every case.

Many soil-applied herbicides, including the triazines atrazine and simazine, the assymetrical triazine metribuzin, the phenylurea linuron, and several of the sulfonylureas show increased activity when soil pH is above 7.5. This is often seen on areas of exposed calcareous soil where more plant injury occurs and selectivity is reduced. This is because there is less herbicide adsorbed at high pH and more is biologically available.

When soil pH was raised from 5 to 7, soil microflora and degradation rate of EPTC increased and phytotoxicity was shortened two to three weeks. A similar increase in rate of degradation of EPTC was found when manure was added (Lode and Skuterud, 1983). Therefore, EPTC and presumably other herbicides are less effective on soils with high effective microbiological activity and high pH. These examples further illustrate the point that phytotoxicity is affected by soil pH, but no generalizations can be made.

C. Shoot Versus Root Absorption

Different plants absorb herbicides at different sites. Grasses vary in seedling morphology, location of the mesocotyl, and depth of seed germination. Selectivity of diallate and triallate between wheat and wild oats is due to differences in location of the site of herbicide uptake (Appleby and Furtick, 1965). In wild oats, the mesocotyl elongates into herbicide treated soil where the herbicide is absorbed after seed germination. Wheat and barley have a short mesocotyl that does not elongate into the herbicide treated zone. Depth of the herbicide zone in soil can be controlled by incorporation depth and positional selectivity can be obtained when these herbicides are used to control wild oats in wheat or barley (Table 14.4). Root exposure has an effect but wild oats survive. Coleoptile exposure results in plant death because of absorption by mesocotyls of emerging seedlings.

Parker (1966) confirmed these results and demonstrated preferential root or shoot absorption by sorghum with five herbicides (Table 14.5). Dichlobenil and trifluralin are dependent on root absorption whereas EPTC and diallate depend on absorption by shoots of emerging seedlings. Triallate was equally effective on sorghum when absorbed through roots or shoots.

Studies with yellow nutsedge have shown that most tuber (often called nutlets) sprouts come from below 2 in. because tubers in the top 2 in. of soil

TABLE 14.5. Herbicide Dose Required to Cause 50% Reduction in Root or Shoot Dry Weight of Sorghum (Parker, 1966).

Herbicide	Equally effective concentration (ppm) Root	Shoot	Ratio
	Exposure		
Diallate	>8	2.5	1 : 0.33
Dichlobenil	0.055	1.25	1 : 23
EPTC	>16	0.8	1 : 0.05
Triallate	>4	4	1 : 1
Trifluralin	0.065	2.7	1 : 42

often winter kill. When tubers sprout they develop a crown meristem about 1½ to 2 in. below the soil surface; roots, and new rhizomes arise from this crown. It is important to have herbicides in this area for absorption from soil. Many herbicides that have activity on nutsedge are soil incorporated at least 2 in. deep to assure crown meristems come in contact with the herbicide.

The area near or above the shoot of green foxtail is the primary area for herbicide uptake. Placement of soil active herbicides in the top 1–2 in. of soil is essential for good control. Corn and sorghum have a different site of uptake because of deeper planting. This provides an opportunity to achieve selectivity through herbicide placement.

D. Absorption as a Determinant of Selectivity

Selectivity is a function of three factors: absorption, translocation, and metabolism. In some cases, absorption can explain why an herbicide affects one plant and not another.

Peas are tolerant to 2,4-D and tomatoes are susceptible because peas absorb 2,4-D for only 24 hours after exposure, while tomatoes absorb greater quantities over 7 days (Fang, 1958). Wheat and corn absorb 2,4-D more slowly than beans, and the low rate of absorption into monocots is a factor in selectivity.

For many modern herbicides, absorption is not a major barrier to activity. Studies of herbicide selectivity frequently find metabolic ability or rate of application to be the defining difference between species. But not all differences in selectivity of new herbicides are due to metabolism. Differences in

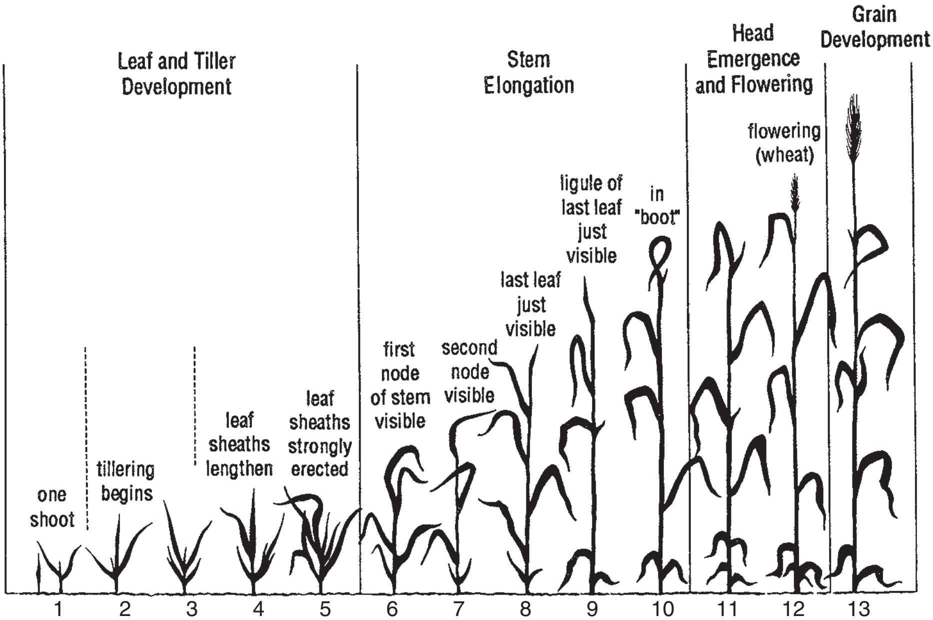

FIGURE 14.3. Growth stages in wheat, oats, barley, and rye.

activity of glufosinate on tolerant barley and sensitive green foxtail were explained by differences in foliar absorption and translocation but not by metabolism (Mersey et al., 1990). Improved control of common milkweed and poor glyphosate activity on hemp dogbane were attributed to improved foliar absorption of glyphosate by milkweed when surfactants were used (Wyrill and Burnside, 1977).

A major determinant of herbicide selectivity is the plant's growth stage when the herbicide is applied. Some plants show maximum susceptibility in early seedling stages and greatly reduced susceptibility after fruiting. Much of this can be traced to absorption. Figure 14.3 shows the growth stages for wheat, oats, barley, and rye. Each is susceptible to growth regulator herbicides when they are applied during stages one to three. A growth regulator herbicide applied between stages three and nine has little effect. When they are applied during stage ten, susceptibility increases but it is not as high as it was in stages one through three. All of this cannot be explained by absorption. Much is due to greater absorption by young seedling plants and direct access to floral structures in stage ten. Susceptibility of small grains follows a consistent general pattern during various stages of growth. Thus, growth regulator herbicides should not be applied to small grain crops before tillers are formed. After tillering, susceptibility decreases and application is safe.

E. Translocation

Translocation is important because, to be effective, most herbicides must move to sites of action. Translocation takes place through phloem and xylem, the transport systems in plants. It is common to find a direct correlation between foliar absorption and phloem transport and root absorption and xylem transport.

It is helpful to think of phloem translocation as movement from source to sink. Movement from source to sink often occurs with photosynthate transport from regions of high carbohydrate synthesis to regions of high use. Sources are points of entry of herbicides and sinks are sites of high metabolic activity where herbicides express their toxicity.

Herbicide movement in plants is determined frequently by patterns of photosynthate distribution and by the relative activities of sources and sinks. For example, movement from cotyledons and young leaves is predominantly to roots. From lower leaves of mature plants there is either no movement or movement to roots. From later formed leaves there is transport to roots and shoot tips and meristematic areas. From upper, mature leaves transport is to shoot tips, flowers, and fruits.

Herbicides that enter phloem can pass from it to xylem and are systemic. The reverse is rare but occurs. Herbicides that move symplastically and migrate to xylem can move up or down, whereas those that move only apoplastically (root uptake dominates) translocate only acropetally in the transpiration stream. Table 14.6 shows the primary translocation pathway for several herbicides (Ashton and Crafts, 1981). Rate of translocation for one herbicide varies between species and with different environmental conditions for one species. Many patterns are possible and no absolute generalizations can be made.

F. Translocation as a Determinant of Selectivity

A few old experiments illustrate the role of translocation. 2,4,5-T, is more mobile than 2,4-D in burcucumber (Slife et al., 1962), but burcucumber is resistant to 2,4-D and susceptible to 2,4,5-T. Translocation of 2,4-D is initially slow, and there is no movement after 24 hours. Slow continual movement occurs in domestic cucumbers over eight days. Burcucumber avoids 2,4-D injury by immobilizing it, whereas 2,4,5-T is translocated to sites of action.

Bean leaves absorb 2,4-D and it seldom moves elsewhere. It is strongly absorbed by roots but moves in stems at low concentrations but not into leaves after root absorption (Crafts, 1966). Bean roots absorb 2,4-D but translocate

TABLE 14.6. Mobility and Primary Translocation Pathways of Some Herbicides in Plants (Adapted from Ashton and Crafts, 1981).

Free mobility		Limited mobility				
Apoplast	Symplast	Both	Apoplast	Symplast	Both	Little mobility
Chloroacetamides	Glyphosate	Amitrole	Chloroxuron	Phenoxy acids[b]	Endothall	Bensulide
Desmedipham		Dicamba	Diquat		Naptalam	Diphenylethers
Diphenamid[b]		DSMA	Fluridone[b]		Nitriles	DCPA
Methazole		MSMA			Phenoxy acids	Dinitroanilines
Napropamide[b]		Picloram			Propanil	
Norflurazon[b]		Glyphosate				
Phenmedipham		Imidazolinones				
Pronamide		Sulfonylureas				
Thiolcarbamates						
Triazines						
Uracils						
Ureas[a]						

[a]Except chloroxuron, limited apoplast.
[b]Translocation rate varies widely between species.

little into stems and none into leaves. After foliar absorption there is no apoplastic movement and no re-transport. Barley leaves, on the other hand, absorb 2,4-D and translocate it symplastically but not apoplastically. Barley roots absorb it but transport very little. Thus, translocation may partially explain bean's susceptibility to 2,4-D and barley's low susceptibility.

Two-year-old white ash trees treated for four weeks with 10 ppm picloram in nutrient culture were only slightly injured, but young red maple, treated in the same way, died in two weeks (Mitchell and Stephenson, 1973). Rate of root uptake, acropetal translocation, and leaf accumulation was lower in red maple and would explain what happened, except red maple died. Foliar penetration was similar in both species, and absorption could not explain selectivity. Picloram was metabolized at equal rates in both species, and metabolism did not explain selectivity. Tolerance of white ash was not related to lower rates of uptake or faster metabolism. Red maple's high susceptibility was due to blockage of xylem by undifferentiated callus growth caused by picloram activity. Death was caused by lack of normal translocation and subsequent desiccation of leaves and stems. Picloram's activity prevented necessary translocation.

Glasgow and Dicks (1980) asked why beans and peas differed in their tolerance to dimefuron (a substituted urea). Beans are susceptible to dimefuron applied to roots, but peas are tolerant. Dimefuron was translocated from roots to shoots in beans but not in peas. Beans are therefore tolerant to preemergence field applications because there is root absorption but no shoot absorption. When only roots are exposed, absorption is low and poor translocation explains selectivity.

G. Herbicide Metabolism in Plants

Modification of a known herbicide's chemical structure usually eliminates phytotoxicity. This is not always true but is a good generalization. An example of the opposite case is the phenoxybutanoic acid 2,4-DB, which, among other uses, controls broadleaved weeds in peanuts. It is chemically altered by plant metabolism through a process called beta-oxidation that produces the 2-carbon phytotoxic derivative, 2,4-D (Chapter 13).

Once an herbicide is absorbed by plants, it is susceptible to metabolism and loss of biological activity. The faster an herbicide is metabolized, the less there is available for translocation and activity at the site of toxic action. An example of plant metabolism is conversion of simazine to hydroxysimazine, a derivative with no herbicidal properties (Figure 14.4).

Many metabolic reactions occur in plants but the most important are oxidation, reduction, hydrolysis, and conjugation (Hatzios and Penner, 1982).

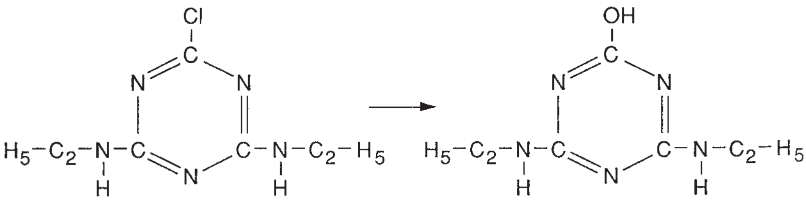

FIGURE 14.4. Conversion of simazine to hydroxysimazine.

TABLE 14.7. **Plant Metabolic Reactions and the Herbicide Chemical Groups Affected.**

Chemical reaction	Affected chemical groups
Hydroxylation	Triazines, phenoxy acids, imidazolinones
Oxidation	Phenoxy acids
Decarboxylation	Benzoic acids, picolinic acids
Deamination	Ureas, dinitroanilines
Dethioation	Carbamothioates
Dealkylation	Dinitroanilines, triazines
Hydrolysis	Carbamates, sulfonylureas, imidazolinones
Conjugation with plant constituents, e.g., glucosidation	Benzoic acids, Imidazolinones

Plant metabolic reactions have been separated into three phases (Hatzios and Penner, 1982; Shimabukuro et al., 1981). Phase one includes nonsynthetic, generally destructive processes such as oxidation, reduction, and hydrolysis. Phase two reactions are conjugations that result in synthesis of a new molecule. Phase one reactions add OH, NH_2, SH, or COOH functional groups that usually change phytotoxicity, increase polarity, and lead to a predisposition for further metabolism. Phase one reactions can be enzymatic or nonenzymatic. An example of the latter is photochemical reduction (detoxification) of bipyridyllium herbicides.

Phase two metabolism is conjugation that yields metabolites with reduced or no phytotoxicity, higher water solubility, and reduced plant mobility. Conjugations occur with glutathione, amino acids, and glucose and other sugars. Phase three metabolism is unique to plants because plants cannot excrete metabolites as animals can. Conjugated metabolites must be compartmentalized in plant cells or somehow removed from further metabolic activity. Herbicides become more water soluble as they are metabolized from phase one to two and they remain water soluble or become insoluble in phase three. Phytotoxicity is reduced with each phase and herbicides metabolized to phase three are no longer toxic. Table 14.7 shows some reactions and the herbicide groups affected. A complete discussion of these reactions is beyond the scope of this text (see Ashton and Crafts, 1981; Corbett et al., 1984; Hatzios and Penner, 1982).

H. Metabolism as a Determinant of Selectivity

Herbicide activity and selectivity are often directly attributed to differences in plant metabolism. For example, black currant is susceptible to 2,4-D and decarboxylates only 2% of applied 2,4-D. Red currant is tolerant and decarboxylates 50% of applied 2,4-D in the same time (Luckwill and Lloyd-Jones, 1960). The different rate of metabolism accounts for observed selectivity. Catchweed bedstraw is selectively controlled by MCPP but not by MCPA, and there is no difference in absorption or translocation. Ten days after treatment, MCPP was not metabolized at all and MCPA was completely metabolized (Leafe, 1962). Rapid metabolism of MCPA explains its lack of effect and no metabolism of MCPP leads to the plant's death.

Broadleaf plantain, common chickweed, and strawberry are resistant to the phenoxyacids, especially 2,4-D. Dandelion, cucumber, soybean, pea, common lambsquarters, and wild buckwheat are moderately sensitive and sunflower, mustards, and cotton are very sensitive to the same herbicides (Hatzios and Penner, 1982). These differences are explained by differences in rate of metabolism among the plants.

A portion of atrazine's selectivity can be explained by differential metabolism (Negi et al., 1964). Data in Table 14.8 show the amount of atrazine

TABLE 14.8. The Amount of Atrazine in Shoots of 8 Plant Species 10 Days After Preemergence Application (Negi et al., 1964).

Species	Susceptibility	ppm Atrazine
Johnsongrass	none	19
Grain sorghum	none	8
Corn	none	10
Cotton	intermediate	222
Peanuts	intermediate	97
Oats	high	376
Soybean	high	322
Bean	high	227

remaining 10 days after preemergence application to eight different plants. Nonsusceptible species have a low concentration because they metabolize atrazine to a nontoxic form. Species intermediate in susceptibility have a higher concentration than nonsusceptible species but a lower concentration than susceptible ones. Susceptible species, especially oats and soybeans, have the highest concentration and are, in part, susceptible because of their inability to metabolize atrazine. But beans and cotton differ by only 5 ppm; hardly a significant amount. The reason cotton is intermediate in its susceptibility is not related solely to metabolism. Atrazine accumulation in lysigenous (oil-bearing) glands of cotton is an isolating, protective mechanism. Higher concentrations exist but the plant isolates atrazine, and a lower active concentration is present. This research illustrates the complexity of explaining selectivity.

Metabolism is the basis for differential atrazine tolerance among warm-season forage grasses (Weimer et al., 1988). Big blue stem and switchgrass are not very susceptible to atrazine, and yellow Indian grass and side oats grama are susceptible in the seedling stage. Atrazine metabolism in big bluestem and switchgrass occurred primarily by glutathione conjugation. Conjugation by big bluestem and switchgrass occurred faster than N-dealkylation of atrazine in yellow Indian grass and side oats grama. Differential tolerance to atrazine among these four grasses is due to the metabolic route by which atrazine is detoxified and the rate and type of metabolism that dominated in susceptible and resistant species.

Propanil has been used for selective control of green foxtail in hard red spring and durum wheat. Green foxtail moved into niches created when broad-leaved species were controlled by growth regulator herbicides. Other research has shown that propanil was selective in rice because it is rapidly metabolized (Yih et al., 1968a and b). Green foxtail retained more spray solution than wheat but less propanil (Table 14.3), and retention is important. Both plants had rapid absorption during the first 12 hours after treatment. Green foxtail absorbed about 10% more, but differences in absorption after 48 hours did not account for selectivity. Because over 95% of applied propanil remained in leaves, translocation was not a major factor in selectivity.

Retention was important, but the most important determinant of propanil selectivity was metabolism (Table 14.9). Propanil was metabolized by wheat but not by green foxtail. Only 34% of the amount applied remained active 72 hours after application to wheat, whereas over 90% remained in green foxtail. Propanil is selective in wheat and rice through rapid metabolism, and wheat has the added advantage that it does not retain the amount of spray solution green foxtail does.

Many studies include absorption, translocation, and metabolism because it is generally recognized that all must be considered if selectivity is to be under-

TABLE 14.9. Rate of Propanil Metabolism by Wheat and Green Foxtail (Eberlein and Behrens, 1984).

Hours after application	Percent applied propanil remaining	
	Wheat	Green foxtail
24	69.8	93.7
48	42.8	93.5
72	34.2	93.5

stood. Results of two studies are summarized above to illustrate their scope and complexity. Wilcut et al. (1989) studied selectivity of the sulfonylurea herbicide, chlorimuron, among soybean, peanut, and four broadleaved weeds. Absorption was similar in five species after 72 hours but lower in Florida beggarweed. There was slight symplastic and apoplastic translocation in all species. Peanut showed more tolerance with age because of reduced absorption by older plants and faster metabolism. Neither absorption nor translocation differences explained differential selectivity among the two crops and four weeds. Further experiments showed tolerance was directly correlated with the amount of unmetabolized chlorimuron. Rate of metabolism was greatest in soybean and lowest in common cocklebur. After 24 hours, nearly two times as much unmetabolized chlorimuron was found in the four weeds compared to the two crops. After 72 hours, 16.7% of the applied chlorimuron was present in soybean, and peanut had 25.6%. Prickly sida, classified as intermediate in susceptibility, retained 29.6% of applied chlorimuron unmetabolized after 72 hours. Sicklepod and common cocklebur, susceptible species, had 39.9 and 60.6%, respectively. Florida beggarweed is susceptible to chlorimuron even though only 16.6% of the herbicide remained after 72 hours. This was equal to soybeans and should have made the weed tolerant if metabolism was the only factor. Florida beggarweed actually had over five times as much chlorimuron compared to soybean when chlorimuron was calculated as amount per gram dry plant weight. Its susceptibility occurred in spite of the fact that it absorbed less than half as much as soybean and seemed to metabolize rapidly. Chlorimuron concentration remained very high in Florida beggarweed even though the total amount was low (Wilcut et al., 1989).

Field violet is controlled by terbacil, but only when it is applied to emerging seedlings with fewer than three leaves. Established plants with 12 leaves are not controlled by terbacil applied to control weeds in strawberries. Doohan et al. (1992) demonstrated that field violet with 12 leaves absorbed less terbacil per gram fresh weight than three-leaf plants. Young plants translocated twice as much terbacil to foliage after root uptake. Metabolism studies showed 79% of terbacil was still intact after 96 hours in three-leaf plants, whereas in resistant 12-leaf plants only 40% of terbacil remained. Young plants were susceptible because although they absorbed less they translocated twice as much of what was absorbed and metabolized it more slowly than 12-leaf plants. A similar explanation was offered for the selectivity of fluroxypyr among four species. More fluroxypyr was recovered in susceptible wild buckwheat and field bindweed (about 70%) than in tolerant Canada thistle and common lambsquarters (about 30%) 120 hours after application (MacDonald et al., 1994). Fifteen and 10% of applied fluroxypyr was translocated in Canada thistle and common lambsquarters, respectively, whereas 40% was translocated in the two susceptible species. Selectivity was due to limited translocation in tolerant species and more rapid metabolism (MacDonald et al., 1994).

One of the most striking features of herbicides is selectivity; the ability to kill or affect the growth of one plant without affecting another. These factors affect selectivity:

1. Distribution as affected by drift, volatility, soil incorporation, and selective placement.
2. Retention by plants as affected by leaf morphology, herbicide formulation, and the herbicide's chemical and physical properties.
3. Absorption by plants as affected by site of uptake (root vs. shoot), cuticle, weather, soil, and the herbicide's chemical and physical properties.
4. Immobilization versus translocation in plants as affected by plant age, weather, the specific herbicide, herbicide formulation, and soil.
5. Metabolism or molecular change of herbicides in plants and soil as affected by the herbicide, and soil microorganisms.
6. Plant age.
7. Weather.
8. Physiological factors including translocation and inactivation without molecular change.

In general, for maximum effectiveness the ideal herbicide should have the following:

1. Ability to enter plants at various sites.
2. Ability to enter plants without local damage.
3. Activity or ability to affect plant growth that is not confined to a particular stage of plant development or plant size.
4. Ability to translocate in plants to appropriate sites of action.
5. Metabolism or degradation to inactivity in target plants should be slow enough to permit full expression of activity.

6. Moderate soil absorption to decrease leaching.
7. Reasonable stability in soil except for foliar active, contact herbicides where soil persistence is of no consequence to plant action but may nevertheless have environmental consequences.
8. A wide weed control spectrum or specific activity against target weeds.

There are no ideal herbicides. Some come close, but none meet all of these criteria. Herbicide selectivity means that all plants do not respond in the same way to all herbicides. Their use in agronomic and horticultural crops, lawn and turf, forestry, or aquatic sites is dependent on selective activity. Herbicide selectivity is dependent on morphological and metabolic differences between weed and crop. For most herbicides, selective action occurs over a relatively wide dose range. This gives users some assurance of selectivity and avoids catastrophe if small errors in sprayer calibration or application are made. The selective action and effectiveness of herbicides depends on differences in their toxicity at the cellular level. Selective action also depends on all the factors that influence the amount of herbicide that reaches sites of toxic action in cells.

For herbicides, dose is the most important determinant of selectivity. All herbicides have a recommended dose for particular tasks and applicators need to know and apply the correct dose for each weed-crop situation.

THINGS TO THINK ABOUT

1. Can drift and volatility be eliminated?
2. How can drift and volatility be controlled?
3. Are drift and volatility current problems. Why? What are appropriate solutions?
4. How does plant morphology affect selectivity?
5. How can spray solutions be modified to affect selectivity?
6. How does weather affect performance of foliar applied herbicides?
7. How does weather affect performance of soil-applied herbicides?
8. What can happen to foliar applied herbicides after they contact plants?
9. Foliar and soil-applied herbicides each have advantages and disadvantages. Compare and contrast them.
10. How do absorption, translocation, and metabolism interact to determine selectivity?
11. What are the phases of herbicide degradation in plants, and what is the significance of each?
12. What factors determine an herbicide's selectivity?
13. What characteristics should an herbicide have to maximize activity?

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CHAPTER 15

Herbicides and Soil

FUNDAMENTAL CONCEPTS

- The three important concerns about herbicides in soil are (1) concentration equilibrium among the soil's gaseous, liquid, and solid phases; (2) susceptibility to degradation; and (3) possible effects on soil flora and fauna.
- Soil is a living medium with a vast adsorptive surface that plays a major role in determining an herbicide's activity and environmental fate.
- Several physical and chemical factors interact to determine an herbicide's activity and fate in soil.
- Herbicides are degraded in the environment by soil microorganisms, nonenzymatic, and photochemical processes.
- When used in accordance with label directions, herbicides do not accumulate in the environment.

LEARNING OBJECTIVES

- To understand the effect of soil colloidal surfaces on an herbicide's activity and environmental fate.
- To know the physical and chemical factors that affect herbicide activity and performance in soil.
- To understand the importance of adsorption to an herbicide's fate in soil.
- To know the relationship between herbicide adsorption, leaching, volatility, and degradation.
- To understand the role of soil microorganisms in herbicide degradation.
- To understand the role of chemical or nonenzymatic and photodegradation of herbicides.
- To understand the role of herbicides that persist in soil and their effect on weed management.

Independent of method of application, some of any applied herbicide reaches soil. Foliar applications may be washed off foliage to soil, and other herbicides are applied directly to soil. Understanding the interactions of herbicides and soil is thus an essential aspect of proper herbicide use and environmental care. Soil is not an instrument of crop production similar to a tractor, fertilizers, or pesticides. It is a complex, living, fragile medium that must be understood and protected because it can be destroyed. It is a living medium for plant growth and a myriad of biological and chemical activities occur in soil. The thin mantle of soil on the earth's surface is properly regarded as humankind's most essential and least appreciated resource. The earth's diameter is about 8,000 miles. The thin soil mantle is about 7×10^{-5} of the earth's total thickness or 3 to 4 feet thick in the world's temperate zones. That thin mantle is where our food grows; it is definitely not just dirt.

There are three major concerns about herbicides in soil. The first is the reciprocal equilibrium of exchange and distribution of any material in the liquid, solid, and gaseous phases. The second is an herbicide's susceptibility to degradation and its rate of degradation. The third involves possible influences of herbicides on soil, soil fertility, and soil microorganisms.

After soil application, there is no immediate, direct contact between an herbicide and plant roots or emerging shoots. The physical processes of diffusion in and mass flow of water bring herbicides to plant roots. These processes are necessarily weather dependent (especially on rainfall) and the dose that creates a biological response is a function of weather, soil properties, and rate of application. Some control of these factors is possible, especially in irrigated agriculture. An essential property of a successful soil applied herbicide is activity over a fairly wide range of environmental conditions with reproducible reliability.

I. SOIL

Soil contains many heterogeneous organic and inorganic compounds. It is a dynamic system in which components are constantly displaced mechanically or chemically or biochemically transformed. It contains gaseous, liquid, solid, and living phases. The solid phase, what is seen, is present in a finely distributed form that creates large surface areas. This is of great importance to the soil behavior of herbicides. Table 15.1 shows how surface area increases with decreasing particle diameter. The fine, colloidal clay minerals with their large surface area determine behavior primarily because of the properties of their surfaces rather than because of their chemical composition. Small particles with huge surface areas play an important role in herbicide behavior in soil. Figure 15.1 (Dubach, 1971) shows the basic structure of kaolinite and

Table 15.1. Increase of Soil Surface Area with Decreasing Particle Diameter.

Size fraction	Particle diameter (mm)	Approximate surface cm^2 per gram
Stones	>200	—
Coarse gravel	200–20	—
Fine gravel	20–2	—
Coarse sand	2–0.2	21
Fine sand	0.2–0.02	210
Silt	0.02–0.002	2,100
Clay	<0.002	23,000

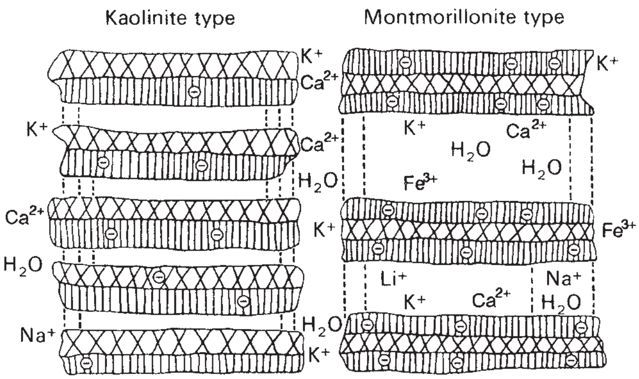

FIGURE 15.1. Structure of two clay minerals (Dubach 1970).

montmorillonite clays. The thin molecular layers of clay minerals are held together by chemical attraction in layers. In kaolinite, there is 1 silicon tetrahedral layer and 1 aluminum octahedral layer in a fixed lattice. Attraction between the two layers is so strong that water molecules and chemical ions cannot penetrate between the nonexpanding, fixed layers. In montmorillonite clay, there are 2 silicon tetrahedral layers and 1 aluminum octahedral layer in an expanding lattice structure. Individual layers are held together weakly in a lattice structure capable of expanding and molecules and ions can penetrate between layers. Internal and external surfaces are available for chemical activity in expanding lattice clays whereas only external surfaces are available in nonexpanding (fixed) lattice clays.

TABLE 15.2. Comparison of Cation Exchange Capacities and Surface Area for Three Clay Minerals and Soil Organic Matter.

Exchange surface	Exchange capacity (cmols (+)/kg)	Surface area (m^2/g)
Organic matter	100–300	500–800
Montmorillonite	100	600–800
Illite	30	65–100
Kaolinite	10	7–30

The molecular lattice of clay colloids interacts with positively charged ions and molecules, from the soil solution, on the clay's predominantly negatively charged surfaces. These molecules and ions are exchangeable between surfaces and soil solution. Most do not become permanently fixed to clay surfaces. The sum of negative charges, the cation exchange capacity, varies between clays (Table 15.2).

Soils also contain negatively charged organic colloids that have large internal and external surfaces, and an exchange capacity equal to or greater than that of expanding lattice clays (Table 15.2).

Herbicides in soil are subject to electrostatic attractive forces from soil colloidal surfaces and are thus adsorbed on surfaces. When adsorbed, it is difficult, often impossible, for them to be taken up by plants or microorganisms and they are at least partially protected from attack by microbes and nonenzymatic chemical reactions in soil. If an herbicide is sorbed by action at one moiety (part), an exposed or nonadsorbed portion can be susceptible to microbial or chemical attack but the entire herbicide molecule cannot be absorbed by plants until it is desorbed from the soil surface.

There is a well-established, negative correlation between an herbicide's soil activity and the soil's clay and organic matter content. Soil pH and soil water content are also important. In the field, rainfall, temperature, clay, and organic matter content (sorptive capacity) are important determinants of activity, but each alone and all collectively can be affected by temporary, significant, alterations of their interaction (e.g., drought). Great differences in an herbicide's activity are determined by whether application is on dry soil and rain falls afterwards, or whether soil is moist and there is or is no precipitation or irrigation afterwards. Interaction of factors is important. Most soil interactions are well understood, and good generalizations, based on laboratory and field experiments, permit accurate prediction of field behavior. Such predictions of herbicide activity are qualitatively accurate although they are not always quantitatively precise.

II. FACTORS AFFECTING SOIL-APPLIED HERBICIDES

A. Physical Factors

Five physical factors: placement, volatility (evaporation), adsorption, leaching, and soil moisture affect herbicides in soil. Table 15.3 shows the points of entry for any pesticide, the active environmental processes, and the interacting pesticide processes that affect movement and environmental fate.

TABLE 15.3. Pesticide Entry into the Environment and Processes Affecting Movement and Loss.

			Processes affecting pesticide fate	
Environmental zone	Environmental	Processes	Addition	Loss/immobilization
Atmosphere	Evaporation	Precipitation	Application Drift	Photodegradation Condensation
Above ground	Transportation Evaporation	Precipitation Irrigation	Foliar application Volatilization Drift Condensation	Plant absorption Photodegradation Drift Wash-off
On the soil surface	Irrigation/ rainfall	Leading to runoff		
Unsaturated soil to root depth	Evaporation	Leaching Root uptake	Surface—sub- Surface appl. Seed appl. Wash-off Transport	Degradation (chem/bio.) Adsorption Root absorption Transport
Unsaturated soil (below root depth = Vadose zone)	Movement Upward Lateral Downward	Transport	Degradation	(chem./bio.) Adsorption Transport
Saturated zone (groundwater)	Movement Upward Lateral Downward		Transport Transport	Degradation (chem./bio.) Adsorption

Adapted from Figure 1 in Cheng and Koskinen (1986).

Placement

Some herbicides are taken up more readily by roots than by shoots and vice versa (see Chapter 14). This knowledge permits placement in soil to enhance or reduce uptake. Herbicides can be placed in or on soil to contact specific weeds or avoid crops. This seems obvious and easy, but it is difficult because control of movement after application is impossible.

Time of Application

Time of herbicide application can determine residual activity and soil persistence. Late summer or fall and early spring applications normally yield good phytotoxic activity but decrease the possibility of leaching due to lower soil temperatures, reduced evapotranspiration, and a higher probability of rainfall. Application when soil is dry may lead to no or reduced activity and extend soil life.

Volatility

Volatility or evaporation affects location. It changes a molecule's physical state from liquid to gas, but does not cause chemical change or molecular degradation. All herbicides have a vapor pressure, although for many it is negligible. The vapor pressure of mothballs, gasoline, and ether is high and their scent is easy to detect. Vapor pressure, the tendency to volatilize, increases with temperature and is measured in millimeters (mm) of mercury (Hg) at a specific temperature, usually 25°C. Volatilization of herbicides with low phytotoxicity does not create an obvious hazard, but it affects environmental quality. Volatilization of herbicides that are toxic to other plants or other species is undesirable and should be avoided.

Volatility can occur from soil or plant surfaces. Herbicides that volatilize from the soil surface move through the atmosphere, the easiest and most available route. Herbicides that volatilize in soil move laterally and toward the surface. Incorporation in soil decreases atmospheric volatility and is required for some dinitroaniline and carbamothioate herbicides.

Application of herbicides to a dry soil surface followed by surface wetting and then hot, low humidity, drying weather can move volatile herbicides to the soil surface and increase volatility. Some lateral and upward movement of volatile herbicides occurs after incorporation in soil and is desirable.

Measures should be taken to reduce or eliminate volatility after application. Formulation of phenoxyacetic acids as long chain esters or complex ester chains with an ether linkage reduces volatility (see Chapter 14). Soil incorporation reduces volatility, by burial that increases adsorption, and puts

TABLE 15.4. Relative Volatility of Some Herbicides.

Volatility	Herbicides
High Vapor pressure 10^{-2} to 10^{-4} mm Hg	most carbamothioates—butylate, EPTC clomazone, trifluralin, short chain esters of phenoxy acids
Medium Vapor pressure 10^{-5} to 10^{-6} mm Hg	alachlor, benefin, bromoxynil, butachlor clopyralid, DCPA, dicamba, ethalfluralin, linuron, napropamide, oxyfluorfen, pendimethalin, pronamide, long chain esters of phenoxy acids
Low Vapor pressure $>10^{-7}$ mm Hg	acetochlor, atrazine and most triazines, amitrole, bentazon, bromacil, cyanazine, diclofop, bipyridilliums, ethofumesate, fluazifop, fluometuron, glyphosate, hexazinone, most imidazolinones, oryzalin, picloram, sethoxydim, most sulfonylureas

herbicides near plant roots to enhance their activity. The relative volatility of some herbicides is shown in Table 15.4. The herbicides have been divided into high, medium, and low volatility groups according to their vapor pressures (in mm Hg @ 25°C). Herbicides with high volatility have low vapor pressure (10^{-2} to 10^{-4} mm Hg) and a high tendency to change state from liquid to gas at normal atmospheric pressure. High volatility is a caution but not an automatic hazard. Most herbicides have low volatility (10^{-7} mm Hg or less).

Adsorption

Adsorption is a process of accumulation at an interface and is contrasted with absorption, or passage through an interface. In soil, clay and organic matter surfaces are interfaces between the solid soil surface and soil's gaseous and liquid phases. Through cation exchange and physical attraction, herbicides can be concentrated at adsorptive surfaces and removed from the soil solution, from which plant uptake occurs. Adsorption is one of the most important mechanisms that reduces herbicide concentration in soil solution and few herbicides completely escape adsorptive interactions. Manufacturers develop application rates to compensate for adsorption and to keep enough desorbed (in solution) for activity. The organic arsenicals, dipyridiliums, and glyphosate are adsorbed quickly and extensively and because of this they have no soil residual activity.

Adsorption affects movement and availability in soil and rate of degradation. It regulates degradation by soil microorganisms and chemical reactions. The adsorption-desorption equilibrium determines the amount adsorbed and the amount in solution and available for plant absorption. The equilibrium is the ratio of adsorbed herbicide to solution concentration and can be expressed mathematically given specific herbicide-soil combinations.

TABLE 15.5. Adsorption Strength for Several Herbicides.

Adsorption strength	Herbicide
Very strong K_{oc} >5,000	benefin, bipyridilliums, bromoxynil, DCPA diclofop, DSMA, fluazifop, glyphosate, MSMA, oxyfluorfen, pendimethalin, prodiamine, trifluralin
Strong K_{oc} 600 to 4,999	bensulide, butachlor, cycloate, desmedipham ethalfluralin, fluridone, napropamide, norflurazon, oryzalin, oxadiazon, thiobencarb
Moderate K_{oc} 100 to 599	aciflurofen, alachlor, amitrole, bensulfuron, butachlor, clomazone, dichlobenil, diuron, EPTC, fluometuron, glufosinate, isoxaben, quizalofop, most triazines, vernolate
Weak K_{oc} 0.5 to 99	acrolein, bentazon, bromacil, chlorsulfuron, clopyralid, dicamba, haloxyfop, hexazinone, most imidazolinones, mecoprop, metribuzin, nicosulfuron, picloram, primisulfuron, sodium chlorate, sulfometuron, tebuthiuron, terbacil, tribenuron, triclopyr

In adsorption, there are two factors to consider, strength of binding, and extent of binding. It is not true that the most extensively bound chemical will be the most strongly bound; both must be determined. Table 15.5 compares strength of adsorption for several common herbicides. The groups, from very strong to weak, were created by using each herbicide's K_{oc}. Expressed in ml/g, K_{oc} is the soil-organic carbon sorption coefficient. It is the herbicide's K_d (distribution coefficient) divided by the weight fraction of organic carbon in a soil.

$$K_{oc} = k_d/\text{weight fraction of organic carbon in soil}$$

K_d, usually expressed in L/Kg or ml/g, is the ratio of sorbed to dissolved herbicide at equilibrium in a soil-water slurry.

$$K_d = \text{herbicide sorbed (mg/kg)/herbicide in solution } (\mu\text{m/L})$$

These are standard measures available for most herbicides (Vencill, 2002).

Bipyridilium herbicides are susceptible to cation exchange. But they are cations that are adsorbed tightly and extensively by negatively charged surfaces. Imidazolinones and sulfonylureas are both acidic herbicides and are not adsorbed extensively or tightly. Their sorptive interactions are governed by soil pH and their sorption increases as soil pH decreases. With acidic pHs, soil adsorption is higher because the molecules are more negatively charged. As pH becomes more basic the molecules are neutral and not sorbed extensively.

Soils high in clay and organic matter usually require higher concentrations of herbicide for equal activity compared to soils low in clay and organic

TABLE 15.6. The Influence of Soil Texture and Organic Matter on Trifluralin Rate.

	Pints of treflan (EC) required per acre for		
Soil texture	Dry beans	Cotton in fall in eastern/western United States	
Coarse	1	2	1.5
Coarse with 2–5% organic matter		1.5	
Medium	1–1.5	2	2
Fine	1.5–2	2.5	2.5
Fine with 2–5% organic matter		2	
Soil with 5–10% organic matter		2–2.5	

matter. Clay soils require more herbicide than sandy soils. High levels of organic matter and clay adsorb herbicides and residues persist longer than in sandy soils. To illustrate, Table 15.6 shows the recommended change in trifluralin rate with increasing organic content of soil, which is true for many crops on which the herbicide is used (specific label instructions should be consulted prior to use).

Leaching

Leaching is movement of an herbicide with water—usually, but not always, downward. It is of environmental concern because of the possibility of offsite movement and ground water contamination. It can determine an herbicide's effectiveness by moving it into or out of the zone of action.

Leaching can be thought of as a chromatographic process where soil is the stationary phase and water the moving phase. Given the correct soil and herbicide information, leaching can be predicted mathematically. It is inversely related to percent organic matter and percent clay, and therefore to adsorption. The greater the adsorption of an herbicide and the adsorptive capacity of a soil, the less leaching will occur.

The extent of leaching is determined by the following:

1. Adsorptive interactions between herbicide and soil.
2. Water solubility. The greater an herbicide's water solubility, the greater the leaching potential.
3. Soil pH. Because they are weakly charged, sorption and leaching of imidazolinone and sulfonylurea herbicides is governed by soil pH. Adsorption increases as pH decreases and at low pH more of the herbicides will be sorbed and leaching is reduced.

4. pKa. This is a measure of alkalinity and is a property of the herbicide, not the soil. The higher the pKa, the greater the leachability. At the pKa, one-half of a molecule is neutral and one-half is ionized. For example, small amounts of acidic herbicides (phenoxyacetic acids, dicamba, picloram) are adsorbed on clay colloids when the pH equals the pKa and molecular and anionic species occur in relatively equal amounts. For acidic herbicides, when the pH is above the pKa, anionic species dominate and adsorption will be lower. When soil pH is below the pKa, molecular species dominate and adsorption can increase. Basic molecules (e.g., triazines) have a high pKa and adsorption is greatest at low pH.
5. The amount of water moving through the profile. The more water moving due to rainfall or irrigation, the more likely it is that leaching will occur.
6. Temperature. In theory, leaching will be greater at higher temperature but this is very difficult to measure in the field. Sorption is an exothermic reaction so with increasing temperature sorption will decrease and leaching can increase.

If an herbicide is very water soluble, it is more likely to leach. But water solubility is not the sole determinant of leaching. A 4½-inch rain or irrigation weighs about 1 million pounds. That's enough water to leach most herbicides out of the soil profile because their water solubility is greater than 1 ppm, but that doesn't happen. Even after 10, 15, or 20 inches of water as rain or irrigation, some herbicide remains in upper soil layers in spite of the fact that the water is capable of dissolving much more than was applied. The reason is adsorption. Table 15.7 shows the relative mobility of herbicides in soils. The table is approximately the inverse of Table 15.5 because adsorption and leaching are inversely related: The greater the adsorption, the lower the amount leached. Herbicides with weak adsorption are in mobility class 5, and those with very strong adsorption are in mobility class 1. There is no question that herbicides or their transformation products are present in ground and surface water in the United States. A US Geological Survey study (http://water.wr.usgs.gov/pnsp/gw/gw_4.html, USGS fact sheet FS-244-95; accessed March 3, 1999) found pesticides or their transformation products in ground waters of more than 43 states.

In general, leaching is movement downward, but it can occur laterally and upward. Upward movement occurs when, after application, there is movement of water upward by capillary action owing to a high rate of water evaporation from the soil surface. Herbicides can move up with evaporating water.

Interactions with Soil Moisture

If soil is wet and air is dry, plants transpire more. Roots absorb water from soil to replace transpired water and herbicides in soil move to roots by mass

TABLE 15.7. Relative Mobility of Herbicides in Soil.

Mobility class[a]				
5	4	3	2	1
Bromacil	Amitrole	Atrazine	Acifluorfen	Benefin
Clopyralid	Chlorsulfuron	Alachlor	Bensulide	Bromoxynil
Dicamba	2,4-D	Ametryne	Butachlor	DCPA
Haloxyfop	Metribuzin	Bensulfuron	Clomazone	Diclofop
Mecoprop	MCPA	Dichlobenil	Diuron	Difenzoquat
Picloram	Nicosulfuron	Fluometuron	EPTC	Diquat
Sodium chlorate	Tribenuron	Glufosinate	Imazapyr	Fluazifop
		Isoxaben	Imazaquin	Glyphosate
		Prometon	Imazethapyr	MSMA
		Quizalofop	Linuron	Paraquat
		Simazine	Napropamide	Trifluralin
		Terbacil	Norflurazon	
			Oxyfluorfen	
			Prometryn	
			Propanil	
			Pyrazon	
			Siduron	

[a]Class 5 = very leachable; Class 1 = essentially immobile.
Table compiled from Helling (1971) and published K_{oc} values in Vencill (2002).

flow. More herbicide will be absorbed and phytoactivity will increase. Sometimes dry air and wind cause rapid foliar water loss and when not enough water is taken up by roots, plants wilt. Stomata then close, water movement in plants slows, and herbicide uptake decreases. Soil drying can increase soil adsorption and decrease root uptake.

Rainfall or irrigation is essential to move herbicides into the top soil layers where most weed seeds germinate. Some rain (perhaps an inch) may be essential to activate herbicides such as the triazines, which are taken up by roots. No moisture for 10 to 14 days after application can cause weed control failures. Heavy rains, on the other hand, may move herbicides below the zone of activity. Excess rainfall can leach herbicides through a zone of action unless they are adsorbed.

The effect of soil moisture cannot be generalized for all herbicides, crops, or application times. Pendimethalin controlled itchgrass in upland rice irrespective of soil moisture after preemergence application (Pathak et al.,

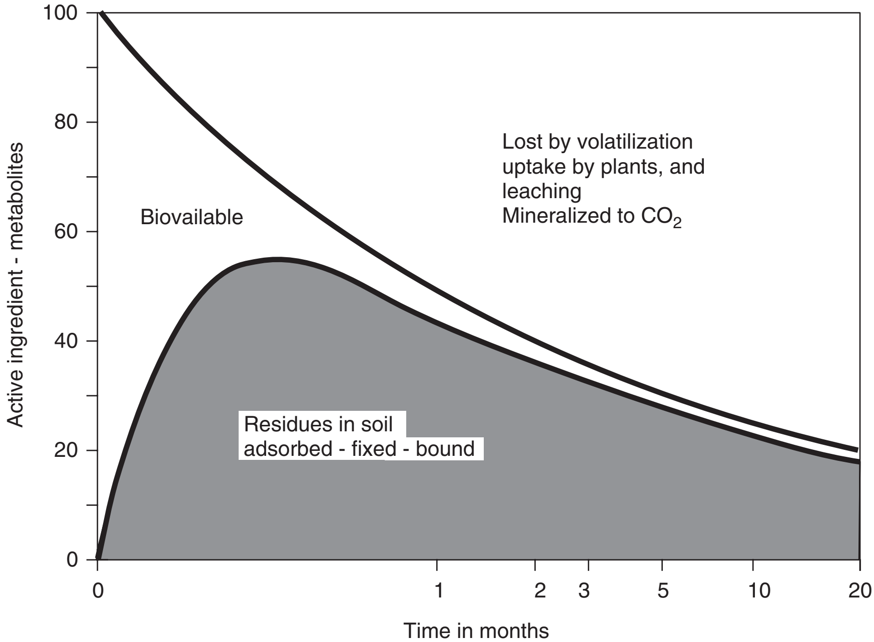

FIGURE 15.2. A general description of the fate of any organic chemical in soil (source unknown).

1989). When bentazon or 2,4-D was applied postemergence it controlled purple nutsedge well but only when soil moisture was above the demands of plant evapotranspiration (Pathak et al., 1989). Figure 15.2 integrates the several environmental fates of an herbicide and clearly shows that little of the amount applied remains available for weed control after two to three weeks.

B. Chemical Factors

Microbial or Enzymatic Degradation

An enduring lesson of the study of soil microbiology is that things in soil do not just rot or disintegrate. They are decomposed by active chemical processes. It is the large (really very large) heterogeneous microorganism population of soil that mediates much of pesticide decomposition in soil. If one scoops up a handful of forest soil (any forest) that handful will contain ten billion bacteria, a million yeast cells, perhaps 200,000 mold fungi, 10,000 protozoans, and assorted other creatures known as crytozoa (Bryson, 2005,

p. 460). A single handful of agricultural soil contains hundreds of different species (not just hundreds of creatures) and billions of microorganisms all together in a complex food web. That handful will contain algae, fungi, actinomycetes, and bacteria. For soil degradation of herbicides, bacteria and fungi are most important.

Herbicides in the soil solution can be adsorbed by soil colloids or be degraded by microorganisms. Many herbicides provide a carbon source from which microorganisms derive energy. Some herbicides (perhaps most) are degraded as an incidental process as microorganisms degrade soil organic material. Herbicide degradation is enhanced by warm, moist, aerobic conditions that favor microbial growth. Under similar temperature and moisture conditions, herbicide degradation occurs more rapidly in soils that are rich in organic material and have high microbial activity. In general, with high adsorptive capacity herbicides persist longer and are less available for microbial activity. Soil adsorption and microbial action as influenced by environmental conditions determine rate of degradation.

Microbial degradation proceeds by many pathways, none of which are unique to herbicide degradation in soil:

Dehalogenation	Loss of a halogen atom
Dealkylation	Loss of a methyl or methylene group
Decarboxylation	Loss of COOH = carboxylic acid group
Oxidation	Structural change by addition of oxygen
Hydrolysis	Attack by water
Hydroxylation	Addition of an OH group
Ether cleavage	Breaking the R-O-R linkage
Conjugation	Usually with a sugar or amino acid, sometimes with a protein
Ring cleavage	Breaking ring integrity

In a few cases, decomposition leads to activity, but in most cases it results in loss of phytotoxic activity.

Chemical or Nonenzymatic Degradation

Several herbicides are degraded nonenzymatically by chemical reactions not mediated by soil microorganisms. Some triazines (e.g., atrazine) are degraded by hydroxylation and removal of chlorine at the 6-position that converts them to the nonphytotoxic hydroxy derivative through a purely chemical, nonenzymatic process. In many other cases, herbicides are decomposed by nonenzymatic *and* enzymatic processes that work, in concert and at different points on a single molecule.

The sulfonylurea herbicides are degraded in soil by simple hydrolysis if pH is acidic. As pH approaches neutrality, or under basic conditions, enzymatic degradation by microorganisms dominates. Degradation in acidic soils is more rapid because of the high rate of acid hydrolysis. Imazaquin (an imidazolinone) persists longer and is more active at low pH (5.1) (Marsh and Lloyd, 1996). Studies have been done to determine the influence of soil pH on herbicide degradation and activity. For most herbicides, rate of degradation is slower as soil pH rises.

Photodegradation

Photodegradation, the effect of radiation on internal chemical bonds, is a form of chemical degradation. It is well established that many herbicides, particularly heterocyclic molecules (with carbon and nitrogen in a ring), and nitrogen-containing compounds undergo photodecomposition. Photochemical reactions have been reported for many herbicides, including phenoxy acids, dinitroanilines, propanil, benzoic acids, and others. Absorption of electromagnetic radiation at wavelengths between 290 and 450 nanometers affects the excitation states of electrons and leads to bond rupture and can energize several common reactions including oxidation, reduction, hydrolysis, substitution, and isomerization. While there is no question that photodecomposition occurs, its importance as a determinant of activity or selectivity under field conditions is usually minor. Photooxidations are important environmental reactions because of the abundance of oxygen in air, soil, and water. Reactions can occur in a matter of hours and can affect any herbicide during its time in air or on an exposed surface. Photooxidations are important especially for herbicides that remain in the atmosphere or move back into the air after application. Once a compound is incorporated in soil, the importance of photodecomposition is negligible.

III. SOIL PERSISTENCE OF HERBICIDES

Table 15.8 shows the rate range, crop of use, and expected soil life for several herbicides. Soil persistence is agriculturally important because residual herbicides control weeds over time but may also injure crops. Soil residues can become contaminants in the edible portions of crops and water and affect nontarget species. Residues may cause temporary or permanent effects on soil microorganisms. It would have enormous agricultural and environmental consequences if an herbicide were released only to find that it caused serious depression of activity or even death of nitrifying bacteria in soil. This has not happened because questions about possible effects on soil microorganisms are asked repetitively by manufacturers. Effects expressed as depression or stimulation of activity are both found. It is generally accepted that registered

TABLE 15.8. Soil Persistence of Phytotoxic Activity and Use of Some Herbicides.

Herbicide name			Rate	Soil persistence			
Common	Trade	Major crop(s)	pound or ounce ai/A	1 wk	>1 mo	2 mo	<3 mo
Alachlor	Lasso	Soybeans, corn, dry beans	2–3			X	
Ametryn	Evik	Bananas, pineapple, sugarcane	4–8				X
Amitrole	Amitrol	Noncropland	2–10		X		
Ammonium sulphamate	AMS soil sterilant	Woody plant control	50–400			X	
Atrazine	Aatrex	Corn	1–3				X
Benefin	Balan	Lettuce, peanuts, tobacco, turf	1–1.5				X
Borates	Several	Sterilant	0.5–100 lb/sq ft				X
Bromacil	Hyvar	Noncropland, citrus	1.5–25				X
Bromoxynil	Brominal	Small grains, alfalfa, corn	0.5–1	X			
Butylate	Sutan	Corn	3–4			X	
Chlorates	Several	Noncropland	1–8#/sq rd				X
Chlorimuron	Classic	Soybeans, noncrop	0.125–1.3 oz/A			X	
Chlorsulfuron	Glean	Wheat	1/6–1/2 oz			X	
Cyanazine	Bladex	Corn	1.2–2			X	
Cycloate	Ro-Neet	Sugarbeets	3–6			X	
DCPA	Dacthal	Turf	4–10				X
Dithiopyr	Dimension	Rice, turf	0.05–0.5		X		
Dicamba	Banvel	Small grains	0.5–3				X
Dichlobenil	Casoron	Aquatics, ornamentals	0.75–4				X
Diphenamid	Enide	Tomatoes	4				X
Diuron	Karmex	Cotton, alfalfa, orchards	0.6–6.4				X
Endothall	Endothal	Turf, aquatics, sugarbeet	1–2		X		

(*Continues*)

TABLE 15.8. (*Continued*)

Herbicide name			Rate	Soil persistence			
Common	Trade	Major crop(s)	pound or ounce ai/A	1 wk	>1 mo	2 mo	<3 mo
EPTC	Eptam	Potatoes, beans, alfalfa	2–6	X			
Glyphosate	Round-Up	Contact-nonselective	1–4	X			
Imazethapyr	Pursuit	Alfalfa, soybeans, peanuts	0.05–0.09				X
MCPA	Several	Wheat, rice	0.25–1.5		X		
Metribuzin	Sencor/Lexone	Soybean, potato, alfalfa	0.5–1.5			X	
MSMA	Several	Noncropland, cotton	2–4	X			
Paraquat	Paraquat	Desiccant, min. tillage, peanuts	5–1	X			
Pendimethalin	Prowl	Corn, sorghum, soybean, cotton, potatoes, tobacco, peanuts	0.5–2			X	
Picloram	Tordon	Brush, rangeland	0.25–1.5				X
Primisulfuron	Beacon	Corn	0.02–0.05		X		
Prometryn	Caparol	Cotton	0.5–2.5			X	
Propachlor	Ramrod	Corn	3–6			X	
Propanil	Rogue	Rice	3–6	X			
Pyrazon	Pyramin	Sugarbeets	2–4			X	
Simazine	Princep	Corn, orchards	2–4				X
Sodium chlorate	Several	Sterilant	0.5–2.25 lbs 100 sq ft				X
2,4-D	Several	Corn, turf, small grain	0.25–2	X			
Terbacil	Sinbar	Peppermint	0.8–3.2				X
Terbutryn	Igran	Wheat, sorghum	1.2–2.4			X	
Triallate	Avadex-BW	Small grains	1–1.5		X		
Trifluralin	Treflan	Cotton, soybeans, alfalfa	0.5–1				X
Vernolate	Vernam	Soybean, peanut, tobacco	2–4		X		
Weed oils		General use		X			

NOTE: Persistence of any herbicide varies with rate, climatic, and soil conditions.

herbicides do not cause permanent damage to the soil microflora when used according to label directions.

Weed scientists, agriculturalists, and manufacturers must also know whether herbicides will accumulate in soil at a rate faster than their rate of dissipation. Under normal agricultural use patterns the answer is "No!" (Figure 15.3; Hamaker, 1976). The assumptions used to make this conclusion are that 1 lb of herbicide is applied annually at about the same time and the time it takes for half of it to degrade (its half-life) is 1 year. After 1 year, ½ lb would remain and another pound would be applied. Continuing this sequence produces the sawtooth pattern in Figure 15.3. Residues will never exceed twice the annual rate of application and therefore, except in very unusual circumstances (very cold, very dry, very long half-life) herbicides do not accumulate in soil with repeated annual use. All herbicides in use today have soil half-lives much shorter than 1 year and most herbicides are not used repetitively on the same field over several years. Therefore, the example is an extreme one, but illustrates the point well.

In most cases initial rate of degradation is independent of herbicide concentration in soil. If high rates degraded more slowly or if an herbicide were not degraded, residues would accumulate. Residues could accumulate if there were several applications in one growing season. While this has been unusual, it is now common for some herbicides to be applied more than once to crops when they have been genetically modified to be resistant to an herbicide (see Chapter 10).

When an herbicide is applied to soil, adsorption determines availability to plants and leachability. Absorption and translocation by plants lead to activity. Liability with respect to degradation in soil and susceptibility to physical processes in soil that do not degrade herbicides but move them to different sites must be understood to assure proper use and environmental care. Herbicide

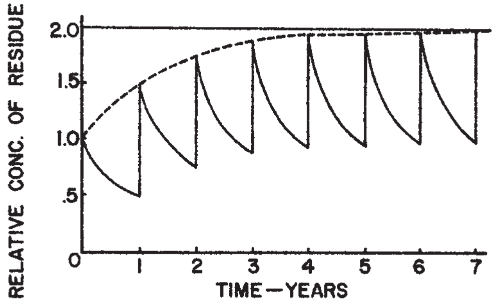

FIGURE 15.3. Residue pattern for a single, annual application and a half-life of 1 year (Hamaker, 1976).

persistence in soil can be a problem but it is essential for performance of some herbicides and for control of some weeds. Phytotoxicity that disappears too rapidly is not always good because weeds do not all emerge at once. Continued research will direct future use and take advantage of persistence when necessary and manage it where possible.

THINGS TO THINK ABOUT

1. How does the physical structure of soil affect herbicides?
2. How do a soil's chemical properties affect herbicides?
3. What is the role of adsorption in herbicide activity?
4. How do adsorption and leaching interact?
5. How do adsorption and volatility interact?
6. How do soil microorganisms affect herbicides in soil?
7. What are some nonenzymatic reactions that affect herbicides in soil?
8. What role does photodegradation of herbicides play?
9. What factors determine how long an herbicide persists in soil?
10. Do herbicides accumulate in the environment?

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CHAPTER 16

Herbicide Formulation

FUNDAMENTAL CONCEPTS

- All herbicides are formulated.
- A formulation is a physical mixture of several or one herbicide and inert ingredients that provides effective and economical weed control.
- The goals of formulation are to improve biological efficacy and to put the herbicide in a physical form convenient for use.
- There are eight basic types of herbicide formulations.

LEARNING OBJECTIVES

- To know the goals of formulation.
- To understand why users can assume herbicide mixtures are homogeneous.
- To know the physical characteristics of different herbicide formulations.

I. INTRODUCTION

If an herbicide has excellent biological activity and can be produced safely at reasonable cost, it may never reach the market if it cannot be formulated to retain or enhance its biological activity. All herbicides are formulated, which means they are combined with a liquid or solid carrier so they can be applied uniformly, transported, and still perform effectively. A variety of formulations have been designed for particular methods of application, to gain increased selectivity, to facilitate use, or increase effectiveness. A formulation is a physical mixture of several or one herbicide(s) and inert ingredients that provides effective, economical weed control. It is important to note that a formulation is a physical, not a chemical, mixture. That is, chemical reactions are undesirable and not an intended result of the mixing. Each formulation has one or several biologically active chemicals. The second issue of Volume 10 (1996) of the journal *Weed Technology* lists 134 separate herbicides formulated into over 204 products with different trade names. The same issue of the journal also lists 112 formulations with two or more active ingredients. Formulations include inert ingredients that can be chemically or biologically active but have no herbicidal activity. Effectiveness is a clear, objective judgment that means the product performs as labeled or it does not. Whether or not a formulation is economical is often a subjective judgment.

Formulation chemists have two primary goals. The first is to improve biological effectiveness by altering vapor or liquid mobility in soil, changing resistance to breakdown, or improving ability to penetrate biological surfaces. The second, equally important, goal is to place the herbicide in a physical form convenient for users and appropriate for intended uses. A formulation should also be convenient to use, as inexpensive as possible, and have good shelf life. Exactly how formulation chemists do all of this involves art and science. Many aspects of formulation are trade secrets and there are no complete texts on the art of herbicide formulation.

> Formulation can be crucial to success. The phytotoxicity of trichloroacetic acid was first discovered by a DuPont scientist, and the ammonium salt was patented. The Dow Chemical Company patented the sodium salt, which is a different chemical and a different formulation. The sodium salt was the successful herbicide.

The pesticide chemical industry is dominated by a few large companies engaged in a wide range of activities in addition to pesticide production. In 1970 there were 46 separate companies in the United States engaged in synthesizing, screening, and developing their own herbicides. In 2005 only eight were so engaged (Appleby, 2005); only four are US-based companies, although all operate internationally. Each company may buy or synthesize (create) several hundred to several thousand new chemical structures annually. Each major group in a company examines compounds obtained or synthesized by another group to see if they have activity specific to the group's interests. Thus, the agricultural group obtains chemical compounds from other groups (e.g., pharmacuetical, dye, plastics, etc.). Agricultural groups also employ organic chemists to synthesize new compounds based on known chemical groups or observed structure activity relationships.

Biologists, in the pesticide development group, receive a few to several hundred grams of a compound and preformulate the material so it can be applied to plants to determine biological activity. Chemists receive small samples and determine several physical and chemical properties such as: melting point, boiling point, rate of hydrolysis, vapor pressure, specific gravity, solubility, and susceptibility to ultraviolet degradation. Inherent biological activity is determined by biologists working closely with chemists.

During development, inert ingredients are selected to be formulated with a potential herbicide. The formulation chemist determines the physical properties of the formulation and is concerned about compatibility of ingredients with the potential herbicide and potential container material.

When an herbicide is marketed, a farmer or custom applicator will move it from a point of distribution to a point of use or further sale where it maybe stored under a variety of conditions. The formulation chemist must be concerned about stability of an herbicide formulation that may be stored in a shed where things freeze in the winter and where the temperature might be 120°F at noon in the summertime. A formulation that spontaneously combusts or explodes at temperatures above 100°F is obviously not acceptable. Formulations that freeze but do not renew activity on thawing are not acceptable. Formulators must be concerned about storage at various temperatures for different times and the effects of storage conditions on stability of active ingredients, on performance, and on wettability and dispersion. Chemists can modify formulations to affect solubility, volatility, and phytotoxicity.

When a user selects an herbicide and mixes it for spraying, an assumption is made that is rarely thought about. Most herbicides are added to a volume of carrier, usually water, and mixed in a spray tank. It is assumed that the mixture is homogeneous and that any volume of water taken from a spray tank contains the same amount of herbicide that any other volume of water contains. With variable water hardness (presence of divalent cations, such as calcium, magnesium, iron), suspended particulates, and microbial activity, the formulation chemist cannot assume homogeneity. Homogeneity must be tested for and assured.

When a formulation is added to water in a spray tank foaming can occur. Some foaming is inevitable if a surfactant is included, but excessive foaming is undesirable. It leads to imprecise determination of volume, and environmental contamination if foam overflows the tank. Control of foaming is a formulation problem.

Formulation chemists must be concerned about spray solution viscosity because it affects flow patterns, particle size, and weed control. The primary goal of formulation is to maintain or improve biological efficacy. A homogeneous formulation that is stable at all possible temperatures to which it will be exposed, does not foam, and maintains appropriate viscosity, but that, in the process of formulation, loses its phytotoxicity is a failure.

If a formulation performs satisfactorily in spray equipment and has passed all of the preceding tests, then chemists and biologists are concerned with how it interacts with the weed. The following questions are asked:

1. What percent of what is applied is retained on the weed?
2. What is the residual nature of the herbicide on the weed?
3. Does the herbicide penetrate the plant and translocate?
4. Does the herbicide form crystals on the plant surface?
5. What is the formulation's biological efficacy?
6. What is the site and mode of action?
7. What is the herbicide's persistence in the environment.
8. What are the possible effects of the herbicide on nontarget organisms through drift, soil residue, residue in water, and presence in other parts of a food web?

Formulation chemists are included in manufacturing decisions. Formulations must achieve the highest practical degree of efficacy at the lowest cost. Formulation chemists discuss formulations with chemical engineers to see if a formulation that works can be manufactured economically. The formulation chemist is concerned about packaging. A package that is sensitive to moisture is obviously inappropriate. One does not want a package that will be degraded by its contents. Thus, a formulation must maintain biological efficacy and be compatible with containers that will inevitably be stored under diverse conditions.

II. TYPES OF HERBICIDE FORMULATIONS

There are two general types of herbicide formulations: liquid and dry. However, nothing as complex as herbicide formulation should be divided into two simple categories. Liquid formulations include solution concentrates, emulsifiable concentrates, and flowables. Dry formulations include wettable powders, dry flowables, and granules.

A. Liquid Formulations

Solution Concentrate

A solution concentrate is an herbicide dissolved in a solvent system designed to provide a concentrate soluble in a carrier, usually water. If an herbicide is immiscible with water, a one-phase solution containing the herbicide, one or more emulsifiers, and one or more solvents can be made to force or bridge an herbicide into solution or very fine suspension. The basic requirements for making a solution concentrate are dependent on active ingredient solubility. The herbicide must be soluble in a small enough quantity of solvent to make packaging and shipping economical. The concentrate must be completely and rapidly soluble in water at all temperatures and concentrate-carrier ratios likely to be encountered when it is used. Usually, solution concentrates require little formulation and have a high concentration of active ingredient. Some acidic salts are formulated as solution concentrates but few herbicides are soluble enough and also capable of being stored with very high or low temperatures, as a water solution. The formulation is not widely used.

Emulsifiable Concentrate

An emulsifiable concentrate consists of the herbicide dissolved in an organic solvent with sufficient emulsifier added to create an oil-in-water emulsion when the concentrate is added to water. Salts of acidic herbicides that are soluble in water and could be formulated as solution concentrates are commonly formulated as emulsifiable concentrates because the herbicide may react with metallic ions in water, precipitating the active ingredient and clogging spray equipment. These formulations are used when the active ingredient may not enter plant foliage readily due to high water surface tension or evaporation that leaves herbicides on foliage and results in no activity.

Other herbicides have low water solubility but can be dissolved in an organic solvent (e.g., xylene) and mixed with water to form an emulsion. An emulsion is a mixture in which one liquid is suspended in another (e.g., fat globules in milk). In herbicide emulsions, water (the carrier) is the continuous phase and oil globules (solvent plus technical herbicide) are dispersed in it. This is called an oil-in-water (O/W) emulsion. Oil soluble esters of acid herbicides and other herbicides such as the carbamothioates, dinitroanilines, and some chloroacetamides, are formulated in this way. Because phases may separate, an emulsifying agent is added to keep the dispersed phase (herbicide) in suspension. This combines the two liquids without direct contact between them and adverse reactions between the chemicals are not likely. Most agricultural emulsifiable concentrates consist of 60 to 65% (by weight) of herbicide dissolved in 30 to 35% organic solvent with 3 to 7% of an appropriate emulsifier added to create an oil/water emulsion when the concentrate is added to water. They may contain a small amount of emulsion stabilizer and a surfactant selected to permit appropriate interaction with plant surfaces.

Most manufacturers use the highest possible concentration but 4 lbs/gal is common. Almost everyone knows that if there are 4 lbs in a gallon, there is

1 lb in a quart and ½ lb in a pint, and so on, and pint or quart measures are easy to find in the United States.

Emulsifiable concentrates form an emulsion when added to water that is opaque or milky. Thus, if one sees a milky or opaque herbicide mixture, it is reasonable to conclude it was made from an emulsifiable concentrate. These concentrates usually penetrate waxy foliage better than other formulations. The solvent, in some cases, is also phytotoxic and aids herbicide activity. They can be applied in hard water without adverse reactions and are less apt to be washed off foliage by rain or irrigation. Herbicides formulated in this way evaporate slowly from plant surfaces. The formulations are easy and inexpensive to make and easy to measure and handle. They are the first method attempted for many herbicides.

Advantages of emulsifiable concentrates include low price, ease of handling and transport, agitation is not required, and nozzle plugging is rare. The formulants (solvents and other ingredients) may be toxic and because they are concentrated, over application is a potential problem. A formulation challenge is to minimize hazards to machines and people from required toxic formulants.

Invert Emulsions

In an invert emulsion (W/O), oil is the continuous phase and water the dispersed phase. A common example is mayonnaise. Inverts' primary advantage is drift reduction because they are more viscous and produce large drops. They are used in formulation of phenoxyacid herbicides for rangeland and industrial weed control. Inverts are nearly always applied in a large volume of diesel fuel or another low-grade petroleum product to aid plant absorption. Special emulsifiers are required and the formulation is usually expensive.

Flowable Concentrate

Flowable concentrates can be thought of as liquid extensions of wettable powders. They are concentrated aqueous dispersions of herbicides that are insoluble or nearly so in water. Not many of these formulations are available. They contain little or no organic solvent but do include clays similar to those used in wettable powders, some oil, water, an emulsifying agent, and a suspending agent. These approach other liquid formulations in ease of dispersion in water and ease of measurement and do not require vigorous agitation. They are more difficult to make and have been used in lieu of wettable powder formulations. The entire system can gel and become unusable or the system can become solid with the oil portion rising to the surface.

Encapsulated

Encapsulated formulations enclose dry or liquid herbicide molecules in microscopic, porous polymer (plastic) capsules that are sprayed in water suspension. After application the capsule releases the herbicide slowly. Rate of release can be controlled so timed release can be achieved. They offer the advantage of timed release through a longer portion of the crop season. With most formulations, maximum availability occurs at application, which may coincide with maximum crop susceptibility and the lowest weed population. These formulations attempt to change that. They are water applied, mix easily, and won't freeze.

B. Dry Formulations

Dusts and Dry Powders

Dusts are finely powdered, free-flowing, dry materials used to provide extensive surface coverage. They are relatively easy to formulate, but no herbicides are formulated as dusts because of the drift potential. Some herbicides are so soluble in water that they require little formulation. Spontaneity of solution can be a problem but few herbicides have sufficient water solubility and therefore for reason of drift avoidance and low water solubility, none are formulated as dry powders.

Wettable Powders

Wettable powders are finally divided (dust-like) solids that are easily suspended in water. When herbicides are insoluble in water or oil solvents, the formulation chemist may turn to wettable powders. They are formulated by impregnating the active ingredient in or on an inert material such as a clay and adding a wetting and dispersing agent. The wetting agent wets the active ingredient when it is mixed with water. Dispersing agents disperse the finely ground particles when mixed with water. A wettable powder with 50% active ingredient may contain 42% clay, 2% wetting agent, 2% dispersing agent, 4% inert ingredients, and 50% active herbicide. Because wettable powders form suspensions, not solutions, they will settle without continued agitation in the spray tank. These formulations typically have less foliar activity than liquid formulations. Because they are suspended, finely divided solids, their abrasive action can wear pumps and spray nozzle tips and frequent calibration is required. To aid dispersion and assure homogeneity, wettable powders should be mixed in a thick slurry before mixing with water in the spray tank. Most of the triazines, phenylureas, uracils, and members of several other herbicide groups have been formulated as wettable powders. A major problem with this formulation is the difficulty of measuring weight of a dry powder in the field.

Wettable powders can present an inhalation hazard to those measuring them or mixing them in water. Vigorous agitation in the spray tank is required. They are the most abrasive of formulations to nozzle tips and pumps and frequent nozzle plugging can be problems.

Granules

Some herbicides can be formulated as granules: solid materials with 2 to 10% active ingredient. The cost per unit of herbicide is high. Granules are not applied in water or oil carriers and there is less drift hazard. They are not sprayed but applied as solid granules that tend to fall off plant foliage with little or no damage to plants via foliar uptake. Granular formulations are restricted to herbicides with soil activity. Equipment required for application can be inexpensive and application can be combined with other field operations. However, uniform application is more difficult and granules may be moved by wind or water after application.

Granular technology combines 5 to 10% a.i., with 1 to 2% surfactant and the balance is carrier. Carriers must be available in a uniform size range, free of dust and fine particles, and their structure must not be destroyed with repeated handling. The granule must have sufficient adsorptive capacity to take up and hold the active ingredient. Granules are bulky to handle, costly to ship, and are expensive per unit of active ingredient.

A mycoherbicide (see Chapter 11) has been formulated as a unique kind of granule (Connick et al., 1991; Daigle et al., 2002). The product is not commercially available but is called “Pesta.” Appropriate fungal propagules were entrapped in a matrix of wheat gluten. A dough prepared from wheat flour, filler, fungus, and water was rolled into a thin sheet (the process for preparation of pasta) air-dried, and ground into granules. The fungus was the active agent that grew and sporulated on the wheat granules after application to soil. Acceptable control of four broadleaved species has been obtained (Connick et al., 1991). A strain of *Pseudomona fluorescens*, a pathogen of green foxtail, has been successfully formulated with oat flour. It has suppressed up to 90% emergence of green foxtail in field studies (Daigle et al., 2002).

Dry Flowable and Water Dispersible Granules

Dry flowable and water dispersible granule formulations combine granule and wettable powder technology. A wettable powder resembles flour and a granule is a large particle. A dry flowable is dustless, small, dry particles that flow and are measured by volume rather than weight prior to mixing in water and spray application. They offer the convenience of measurement of liquid formulations, decrease the disadvantages of liquid formulations, and retain the advantages of solid formulations. Many herbicides are now formulated as dry flowables.

Water-Soluble Packets and Effervescent Tablets

Water-soluble packets reduce mixing and handling hazards by eliminating direct contact with the formulation. The package containing the formulated herbicide dissolves when placed in water. Some agitation is required to mix the formulation in the spray tank. These packets are usually small and are very appropriate for small land-holders in the developing world.

Effervescent tablets resemble Alka-Seltzer™ tablets when mixed in water. The usually palm size tablet can be used whole or broken into pieces. Some agitation is required to mix the formulation in the spray tank.

Other

Parasitic weeds are among the most difficult challenges facing weed scientists (see Chapter 20). Among the things that make management difficult are the fact that the parasite attaches to and becomes part of the crop plant, the seeds are very small and cannot be selectively controlled, and the parasite usually does not emerge until after the crop plant has become established. Witchweeds (*Striga* spp.) have not been successfully controlled in affected crops until after some crop damage has occurred. Kanampiu et al. (2003) have demonstrated season-long control of witchweed in corn (maize) in Africa by coating the crop seed with either the imidazolinone herbicide imazapyr or the benzoate herbicide pyrithiobac. The herbicides from different chemical groups both inhibit amino acid biosynthesis through inhibition of the acetolactate synthesis (ALS) enzyme required for biosynthesis of branched-chain amino acids. Seed coating resulted in a three- to fourfold increase in maize yield when witchweed density was high (12 plants per square meter). This method is both an herbicide formulation and application challenge in that one must be able to coat the seed with the herbicide in a durable manner or develop a way to have the seed imbibe herbicide (Kanampiu et al., 2003). The African work has shown that herbicide concentration in the immediate vicinity of the seed is quite high but it dissipates before the next planting season and does not injure legumes planted at least 15 cm from the maize row as second or companion crops. Without seed treatment there is total crop loss from witchweed.

III. SURFACTANTS AND ADJUVANTS

Surfactants, surface-active agents, do many things in formulations, including increasing wettability and spreadability, enhancing phytotoxicity, and increasing penetration. Their effects are due to their ability to increase wetting of the target surface and enhance penetration. It has been shown that one of the things surfactants do is reduce the energy required to absorb herbicides across cuticle and exterior leaf membrane barriers. Surfactants may be part of the purchased formulation (e.g., glyphosate) or added to the spray tank prior to use if recommended on the label (e.g., Gramoxone).

An adjuvant is something added that may or may not be phytotoxic. One example is addition of a surfactant to promote foliar activity, spreading, sticking, or absorption. There are safeners or protectants available for use with specific carbamothioate or chloroacetamide herbicides, which extend their range of selectivity. Spray modifiers are available in several forms to reduce drift or promote spreading and sticking. If foaming is a problem, there are antifoam agents. Nitrogen has been found to enhance activity of some herbicides when added to the spray tank. Ammonium sulfate is used as an adjuvant and increases herbicidal activity in some cases. The herbicide label should always be consulted as the one reliable guide on use of surfactants or adjuvants with any herbicide.

THINGS TO THINK ABOUT

1. Why are all herbicides formulated?
2. What is an acceptable definition for each type of formulation?
3. What are the advantages and disadvantages of each type of herbicide formulation?
4. What is a surfactant, and what does it do in herbicide formulations?
5. What is an adjuvant, and what does it do in herbicide formulations?

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CHAPTER 17

Herbicides and the Environment

FUNDAMENTAL CONCEPTS

- Most herbicides are synthetic organic chemical molecules that do not occur naturally in the environment but all are not inherently dangerous when used properly.
- Herbicides control weeds and manage vegetation in situations where no other method is as efficient.
- Herbicide performance is measured by activity, selectivity, and soil residual behavior.
- Herbicide resistance is an important, manageable aspect of herbicide use.
- There are positive and negative interactions that occur whenever weeds are controlled.
- Science can measure risk but safety is a normative political judgement.

LEARNING OBJECTIVES

- To understand how activity, selectivity, and residue characteristics determine an herbicide's environmental interactions.
- To understand how intended weed management can have positive and negative environmental effects.
- To know that herbicides and plant pathogens interact and how this affects herbicide use.
- To understand the energy relationships of herbicide use.
- To appreciate the complexity of weed management's interactions with humans and the environment.
- To understand how the LD_{50} and perception of risk affect herbicide use.
- To know rules for safe use of herbicides.

Herbicides, the dominant weed management technique, are synthetic organic chemicals that do not occur naturally in the environment. That does not make them inherently evil or dangerous. It does, however, define a need for caution and should encourage attention to possible detrimental effects that can be prevented by intelligent use. Herbicides are the most commonly used pesticide[1] in the United States in terms of the dollars spent to buy them and the number of pounds used. In 2001, 85 to 90 million pounds of glyphosate were used and it replaced atrazine as the most widely used pesticide in agriculture. In the home/garden and industrial/commercial/government sectors, 2,4-D was the most widely used pesticide. Annual US pesticide expenditures were a bit over $11 billion in 2001, accounting for 34% of the world market (http://www.epa.gov/oppbead1/pestsales/index.htm).

This chapter presents information on harmful and beneficial aspects of herbicides and their environmental interactions. It is not an exhaustive discussion of weed management-environment, herbicide-environment, or herbicide-human interactions. That is not the purpose of this book. Sources of additional information have been cited at the end of the chapter. It is incorrect to assume that all weed management-environmental interactions or effects of herbicides are negative or harmful. Some are, some are not. Examples of both will be presented to encourage understanding of and clear thought about possible environmental interactions when herbicides are used to manage weeds.

Perhaps it will be wise to pause here to state the author's bias and thus make it clear rather than suspected. My bias is close to that of Berenbaum's (2000) and the many coauthors who wrote the National Academy of Sciences report on the future role of pesticides in US agriculture. Their goal, expressed as a coda, follows:

> Our goal in agriculture should be the production of high-quality food and fiber at low cost and with minimal deleterious effects on humans or the environment. To make agriculture more productive and profitable in the face of rising costs and standards of human and environmental health, we will have to use the best combination of available technologies. These technologies should include chemical, as well as biological and recombinant, methods of pest control integrated into ecologically balanced programs. The effort to reach the goal must be based on sound fundamental and applied research, and decisions must be based on science.

I. HERBICIDE PERFORMANCE

Performance—the result of weed control—is the reason herbicides are used. They work. Therefore, a positive aspect of herbicide-environment interaction is vegetation management and weed control. Herbicides control undesirable plants—weeds—in many places, and that is an advantage for all of with weed

[1]*Pesticide* is the general term for all pest control chemicals including herbicides, insecticides, fungicides, and so forth.

problems, especially farmers, who benefit from reduced food costs because of reduced production costs.

Herbicides that are used in agriculture solve one aspect of the problem of weeds. Weeds also cause aesthetic pollution when they interfere with enjoyment of our world. Here are some examples:

1. Bicycle riders think the world would be a better place without puncturevine and sandbur. Both produce seeds with sharp, durable spines that easily puncture tires.
2. Some people are very allergic to poison ivy and poison oak. They suffer bouts of itching and discomfort and don't want to tolerate either in their yard or garden. Herbicides help clear our immediate environment of these unwanted plants.
3. Plants that cause allergies can be managed by herbicides. Thousands of people suffer from hay fever caused by weed pollen.
4. Many weeds and other common plants are poisonous when consumed. Some poisonous weeds are larkspur, monkshood, spotted water hemlock, nightshades, buttercups, poison hemlock, and jimsonweed. Other plants that are poisonous when ingested are lily-of-the-valley, oleander, wild cherries, rhubarb, foxglove, iris, and, sadly, although you can kiss it or be kissed under it, mistletoe.
5. Not too many homeowners love crabgrass or dandelions in their lawns. Herbicides are the only technique available to control these pests quickly, easily, and inexpensively. Herbicides should be combined with proper fertilization, mowing, and water management.
6. Few fishermen fish where it is hard to see into the water because of aquatic vegetation. Proper weed management of aquatic sites may include herbicides because of their ability to selectively control aquatic plants without polluting water.

No one advocates herbicides in all cases where some plant bothers someone who decides it is a weed and should be controlled. The preceding list is an illustration of places where herbicides, perhaps uniquely, provide a way to control weeds. Weeds often exist in places where no other control technology is appropriate.

Herbicide performance is measured in terms of activity, selectivity, and residual characteristics. Activity is reflected in the rate used to control weeds. How much is needed is another way of asking how active the herbicide is. Selectivity (see Chapter 12) determines the plants that are affected and those that are not. It determines the crops or cropping systems in which an herbicide can be used. Soil residual characteristics (see Chapter 15) determine how much of the herbicide resides in soil to control weeds over time and possibly affect the next year's crop.

Each of these traits is affected by environmental factors including wind, rain, air and soil temperature, light, humidity, soil texture (adsorptive capacity), soil pH, and other plants. These are the givens, albeit complicated ones, of herbicide use.

II. ECOLOGICAL CHANGES

A. Effects of Herbicide Use

Weed control with herbicides concerns weed scientists, ecologists, and other scientists because of frequently unintended but inevitable ecological alteration. A major reason annual grasses have become dominant weeds in wheat and barley is that widespread use of 2,4-D successfully controlled annual broadleaved weeds. Failure or lack of preventive programs of field and seed sanitation contributed to development of the annual grass problem. Without 2,4-D's success it is unlikely that annual grasses would ever have developed into the dominant weed problems in small grains. 2,4-D use yielded all the benefits of good weed control: improved yield, ease of harvest, lower production cost, and so on. It also yielded an unintentional, but predictable, ecological alteration: a major vegetation shift and the opportunity for different weeds to succeed. It seems odd that a successful weed control technique could create a problem, but it is true. In fact, any technology creates and solves problems at the same time. Predicting what problems will be created is a much more difficult task than observing what problem has been solved.

In the US pacific northwest, continuous wheat is a common cropping system. Phenoxy acid herbicides have been used on some fields for 20 years leading to changes in the weedy vegetation (Table 17.1; McCurdy and Molberg, 1974). Each of the herbicides in Table 17.1 is active against broadleaved species, but they are not equally active against all species. Because the work in Table 17.1 was completed in the early 1970s, it is possible the poor control of redroot pigweed may actually have been the appearance of resistance to the herbicides (see section III of Chapter 12).

A similar situation, although not well documented, is the invasion of corn fields by yellow nutsedge after several years of successful use of atrazine for weed control in corn. Yellow nutsedge is not affected by atrazine and it moved into the vacant niches opened by atrazine's successful control of other weeds. Atrazine's success created opportunities for invasion by crabgrass, witchgrass, fall panicum, shattercane, and wild proso millet, none of which are controlled by normal use rates of atrazine.

The phenomenon of vegetation shifts is not limited to annually cropped fields (Table 17.2). Herbicides are used in orchards to eliminate broadleaved

TABLE 17.1. Percent Weed Reduction in Wheat Fields Treated Annually for 20 Years with a Phenoxyacid Herbicide (McCurdy and Molberg, 1974).

	Herbicide		
Weed species	2,4-D amine	2,4-D ester	MCPA
Stinkweed	97	94	98
Russian thistle	88	58	35
Common lambsquarters	90	85	86
Wild buckwheat	32	54	51
Wild tomato	52	53	23
Redroot pigweed	55	15	30
Total all weeds	86	83	69

TABLE 17.2. Plant Genera Encouraged After Successive Annual Applications (Brown, 1978, after Schubert, 1972).

Genera encouraged	After successive annual application of
Rumex	2,4,5-T, simazine, diuron, or terbacil
Plantago	2,4,5-T amine, diuron, or monuron
Polygonum	2,4,5-TP, simazine, or diuron
Convolvulus	Simazine, diuron, or terbacil
Rubus	Simazine, diuron, terbacil, or dichlobenil
Cerastium	Dalapon or amitrole

weeds and encourage a grass ground cover. This makes other orchard maintenance activities easier and facilitates harvest. After four years and six separate herbicide applications of specific herbicides in an apple orchard there were few patches of bare ground, but the soil was not barren (Schubert, 1972). Continued application of the same herbicide or herbicides that affect the same weeds encourages unaffected genera because those susceptible to the herbicides are controlled.

The widely accepted lesson of these data is that herbicide rotation is a good idea. Continued use of a single herbicide for many years on one field *will* change the nature of the weedy flora and may complicate weed management.

On Black Mesa in western Colorado the butyl ester of 2,4-D was used to control pocket gophers (*Thomomys talpoides*; Tietjen et al., 1967). In large

TABLE 17.3. Pre- and Postspray Forb Composition in Two Locations (Tietjen et al., 1967).

	Composition of forbs		
Location	Prespray	Postspray(%)	After 5 years
South Crystal Gulch	77	9	44
Myers Gulch	63	9	10

doses, 2,4-D is toxic to many mammals, but, when used to control weeds, the dose is insufficient to kill pocket gophers, which were not killed, although their population was reduced. Pocket gophers live by consuming small, broadleaved forbs that were abundant on Black Mesa. The 2,4-D reduced the forb population from 77 (South Crystal Gulch) or 63% (Myers Gulch) to 9% and nearly eliminated the pocket gopher's food supply (Table 17.3). Use of 2,4-D closed the pocket gopher's grocery store, so they had to move to a new neighborhood or face starvation. Eventually the forb population recovered, but after five years it had still not achieved pre-2,4-D levels. A detailed analysis of vegetative composition on Grand Mesa, Colorado, three years after 2,4-D was applied showed that slender wheatgrass increased with a corresponding decrease in broadleaved species (Turner, 1969).

Santillo et al. (1989a) thought glyphosate, a contact, broad-spectrum herbicide, would affect small forest-dwelling mammals by altering vegetation structure and cover and by reducing plant and insect food resources. Glyphosate applied at 4 lb a.i./acre controlled 75% of nonconiferous, brushy plants. Insectivore and herbivore species were less abundant for the three years of observation after glyphosate application. Omnivores were equally abundant in treated and control areas. The difference in small mammal abundance paralleled herbicide-induced reductions in invertebrate species and plant cover. The total number of birds was lower on clear-cut areas treated with glyphosate (Santillo et al., 1989b).

Careful study will very likely find a negative ecological effect every time an herbicide is used, but that is not an adequate reason to ban all herbicides. Eliminating herbicides because they have ecological disadvantages means their ecological advantages will also be lost. The environmental effects of unrestricted weed spread may be far more important than the negative effects of herbicide use. The disadvantages of herbicide use must be balanced against prevention of weed spread, net gains in production of useful crops, and reductions in labor required to produce crops. It is also true that herbicide-caused depressions in community diversity may be small and transitory. Three herbicides that are effective against broadleaved species were applied to control spotted knapweed in Montana (Rice et al., 1992). Weed control was 84 to 90% two years after application. There was a small decline in community diversity one year after spraying, but diversity increased relative to areas with spotted knapweed two years after spraying. The data suggest all herbicide treated areas had greater diversity three years after spraying. Aggressive, perennial weeds such as spotted knapweed tend to form nearly monocultural communities. The substituted urea herbicide, tebuthiuron enhanced rangeland diversity, increased forage production for livestock grazing, improved wildlife habitat, and protected against watershed erosion in studies in new Mexico and Wyoming (Olson et al., 1994). Controlling weedy plants with herbicides that have no other harmful environmental effects (e.g., leaching, drift, hazard to non-target species) is wise vegetation management.

B. Herbicide Resistance

Herbicide *resistance*, discussed in detail in Chapter 12, is the decreased response of a weed population to an herbicide (LeBaron and Gressel, 1982). It is "survival of a segment of the population of a plant species following an herbicide dose lethal to the normal population" (Penner, 1994). Resistance is contrasted with tolerance or the natural and normal variability of response to herbicides that exists within a species and can easily and quickly evolve (LeBaron and Gressel, 1982). *Tolerance* is characterized by "survival of the normal population of a plant species following an herbicide dosage lethal to other species" (Penner, 1994). The terms are not always clearly distinguished and often are used as synonyms. The ecological aspect is the shift of the population to the resistant biotype. The weed species doesn't change; the ability to control it does.

For many years, weed scientists knew that insects developed resistance to insecticides, and more of the same insecticide did not solve the problem, nor would new insecticides or combinations help much. Weed scientists assumed that weeds could become resistant to herbicides but that it was not likely to be a major problem for several reasons. The reasons for this belief were all logical but wrong because herbicide resistance developed and is a serious problem for weed scientists.

It is equally incorrect to assume that the phenomenon of resistance is the death knell for herbicides. Resistant weeds are not super weeds and are often less fit ecologically than their susceptible relatives. It is important to recognize that resistance is possible and to determine the reasons for it. Identification of the cause and mechanism of action of resistance was one impetus for the intentional use of biotechnology to transfer resistance to crops.

C. Enhanced Soil Degradation

Because of the crop grown and the weed problem encountered, some soils have been treated with the same herbicide several years in succession. This has led to enhanced degradation that was first reported for EPTC, a carbamothioate herbicide, in New Zealand (Rahman et al., 1979). Since then, several cases of enhanced or accelerated degradation in soils repeatedly treated with carbamothioate or phenoxy acid herbicides have been reported. Resistance means the herbicide works less well with time. This is the opposite problem: Microorganisms responsible for herbicide degradation become more capable of degrading the herbicide and weed control decreases. The precise mechanism is one of four (Gressel, 1990).

1. The soil could be enriched in a population of a rare or minor microorganism that increases because of the herbicide and rapidly degrades it.
2. Repeated application of the herbicide could select microorganisms from existing populations that degrade the herbicide more rapidly.
3. It is well known that substrates are capable of inducing enzymes in microorganisms. The presence of the substrate (the herbicide) could induce enzymes that rapidly degrade the herbicide *or* induce mutations in microorganisms so they are more capable of degrading the herbicide.
4. Finally, it is possible that when the herbicide is present with other soil chemicals, rapid degradation is promoted. This, co-induction, is related to the presence of another compound or compounds that may not be degraded.

The phenomenon of enhanced degradation has not eliminated use of susceptible herbicides. It has encouraged development of alternative control strategies and new chemicals designed to inhibit rapid degradation. Both techniques have been successful and enhanced degradation is real but rare.

D. Influence of Herbicides on Soil

Most of any herbicide application reaches the soil, and soil-herbicide interactions are inevitable (see Chapter 15). An important question is "Do herbicides damage soil or any of its living components?" It would be tragic if an herbicide were approved for use that destroyed an important decomposer organism or affected the nitrogen cycle. This has not happened, and it is not likely to happen because of careful and continuing evaluation of herbicides, and all other pesticides, by the manufacturer and the US Environmental Protection Agency, before approval for use (see Chapter 18). The approval process cannot detect all possible environmental interactions because often scientists and regulators don't even know what questions to ask until after an observation has been made. However, one should not assume that pesticide use in the United States is one large experiment where no problems are anticipated or addressed until after an observation has been made. Nature is more complex and the present level of understanding does not permit anyone to anticipate or ask every question that nature may reveal as technology develops.

With normal use rates, the quantity of herbicide applied to soil is too small in relation to total soil volume to have any detectable influence on a soil's physical or chemical state. Research has shown that tilling soil has limited benefits other than weed control, except the negative effects of breaking weed seed dormancy and enhancing soil erosion. Without herbicides, investigation of the effects of tillage would have been impossible because of excessive weed growth.

Part of the research on any candidate herbicide is a determination of its effects on soil microorganisms. Nearly all investigations show a positive or negative effect. Reactions such as nitrification are often suppressed, but, at field use rates, suppression is not permanent. Because of large populations, short reproductive cycles, and great adaptability to environmental insult microorganism populations are very resilient.

Metham, a dithiocarbamate, is a soil fumigant applied to seed beds to control weeds and plant pathogens. It is a general biocide and can decimate a soil's microorganism population. But one of the most difficult things to do in the laboratory is to keep soil sterile. Microorganisms are ubiquitous and sterility, while easy to obtain, is almost impossible to maintain with exposure to air and water.

E. Herbicide-Disease Interactions

One of the simple rules of ecology (see Chapter 6) has become almost a cliché: In the natural world, you cannot do just *one* thing. Everything is connected to everything else, and it is impossible to tinker with one environmental parameter without affecting others. All possible effects of an environmental intervention cannot be determined in advance and one must act. Food must be grown and weeds must be managed. All environmental effects of food production and weed management are not known but we cannot stop either while all possible effects are determined. Food must be produced because we must eat.

Some herbicides promote plant diseases and others reduce disease incidence. Herbicides predisposed 20 hosts (crops and weeds) to higher disease levels in cases involving 20 pathogens (Altman and Campbell, 1977). One of the earliest reports was after herbicide use in peanuts. Where herbicides had been used, peanuts were larger and more vigorous, and the effect was seen in the absence of weeds. This work involved the no longer used dinitro and other phenolic herbicides, and it was proposed, and later proven, that these herbicides inhibited growth and vigor of parasitic and pathogenic fungi that affected peanuts. Sugarbeets grown in nematode-infested soil and treated with tillam (a carbamothioate) had a higher level of nematode infestation six years later than those grown in soil not treated with tillam (Altman et al., 1990). It has also been reported that the carbamothioate herbicide cycloate enhanced cyst development on sugarbeet roots (Altman et al., 1990). Soil residues of chlorsulfuron increased Take-all (*Gaeumannomyces graminis* Var. *tritici*) and *Rhizoctonia*, root diseases of barley and wheat, and yield was reduced (Rovira and McDonald, 1986). The soil applied herbicide trifluralin alters the Fusarium disease syndrome in beans.

It was not intuitively obvious that these interactions should occur. They are examples of the fact that, in nature, one cannot do just one thing. Herbicide-disease interactions are another element in the equation that must be considered in weed management systems. The data are not available to predict if there will be an interaction and, if so, what kind it will be for all herbicide, crop, and disease combinations. The possibility exists and must be considered. A few examples are cited in Table 17.4. Norris et al. (2003) provide a detailed discussion of pest interactions.

TABLE 17.4. Examples of Herbicide-Disease Interactions (Katan and Eshel, 1973).

Organism	Disease and crop	Herbicide
Diseases Promoted		
Rhizoctonia solani	Damping off—cotton	Trifluralin
Helminthosporium sativum	Seedling disease—barley	Maleic hydrazide
Fusarium oxysporum	Wilt disease—tomato	Maleic hydrazide, Dalapon
Alternaria solani	Early blight—tomato	2,4-D
Diseases Suppressed		
Cercosporella herpotrichoides	Foot rot—wheat	Diuron
Fusarium oxysporum	Wilt disease—tomato	Propham,TCA
Alternaria solani	Early blight—tomato	Maleic hydrazide, Dalapon

III. ENVIRONMENTAL CONTAMINATION

A. Effects on Water

A US Geological Survey study (http://water.wr.usgs.gov/pnsp/gw/gw_4.html; accessed March 3, 1999, USGS fact sheet FS-244-95) found pesticides or their transformation products in groundwaters of more than 43 states. Atrazine, simazine, alachlor, and metolachlor were among the most frequently detected herbicides (Heilprin, 2006). The proportion of sampled wells with detectable pesticide levels ranged from 4% for nationwide, rural domestic wells to 62% for postplanting sampling of wells in corn and soybean areas of the northern midcontinent. Concentrations were 1 microgram or less in more than 95% of the samples.

Studies have also been done of surface waters. The herbicides detected most frequently in eight geographically dispersed (three in northeastern states, two in southeastern states, and three in western states) US urban streams were the triazines prometon, simazine, atrazine; the substituted urea tebuthiuron; and the chloroacetamide metolachlor (Hoffman et al., 2000). The study looked for 52 herbicides and detected 28 in one or more urban streams. Of 215 samples, only 17 detected no herbicides. The most frequently detected herbicides in streams in agricultural areas were in the same chemical groups as those found in ground water: atrazine, metolachlor, plus the triazine, cyanazine. In 19 of every 20 streams in agricultural, urban, or mixed land use watersheds, pesticide contamination was found at nearly all times of the year. It is important to note that the concentrations nearly always complied with the EPA's drinking water standards, although the sample size did not reflect a person's drinking water consumption. Heilprin (2006) notes that "the large majority of pesticide detections in streams and groundwater were trace amounts, far below scientifically based minimum levels set for protecting human health and the environment."

Pesticides have been detected in surface waters in all US regions. A series of reviewed studies included 98 pesticides and 20 pesticide transformation products and found that 76 were detected in one or more surface water sites in at least one study (http://water.wr.usgs.gov/pnsp/fs-039-97/sw4.html, USGS fact sheet FS-039-97; accessed March 22, 1999). The herbicides atrazine, cyanazine, simazine, metolachlor, and alachlor were detected more frequently than other pesticides.

The National Water Quality Assessment Program has shown that pesticide contamination of streams and groundwater occurs in geographic and seasonal patterns that follow cropping patterns and associated pesticide use. The most frequently and heavily used pesticides (i.e., herbicides) account for most detections. Herbicides commonly occur as mixtures with other pesticides and transformation products. Perhaps the most important finding is that one or more pesticides were found in almost every stream sample collected. More than 95% of stream samples and nearly 50% of well samples contained at least one pesticide (Gilliom et al., 1999).

B. Human Effects

General

Assessment of the effects of herbicides on people and the environment is confounded by at least four factors:

1. The changing character of the environment and our attitude toward it.
2. The changing character of the population.
3. The changing character of the problem.
4. The changing character of public health responsibility.

Everyone wants a protected and protecting environment, but we must also have a productive environment. At least part of the debate about the relationship between herbicides, human health, and the environment centers on differing views of the appropriate balance among these things and how to achieve it. The discussion always includes one or more of three concepts:

1. Toxicity—the inherent capability of something to cause injury.
2. Risk or hazard—the probability that injury will occur.
3. Safety—the practical certainty that injury will not occur.

Science can measure toxicity and estimate risk, but science cannot measure or determine safety (see section V). Safety is a normative political judgment and is frequently mandated by legislative acts. Safety is usually not a scientific question; it is a political question. It is true as Conway and Pretty (1991, p. 576) assert that one of the biggest problems of herbicide use is misuse. It is reasonable to claim that the pesticide industry seeks safer herbicides. Until safer herbicides are developed, the careful and accurate application of existing herbicides is the best way to assure reduced environmental pollution and minimize harm to humans. Although herbicide misapplication and misuse are a primary cause of environmental damage, they are not the only problems. Herbicides are toxic to other forms of life, and they move in the environment. These things can cause major environmental effects and affect ecological relationships. A condition of herbicide use is putting it in the environment. It is wrong to assume that an herbicide will affect weeds and nothing else. That is sloppy ecological thinking and poor science. Weed management is basically an ecological problem of relationships between weeds, other plants, nontarget organisms, and the environment. These can be studied and, when detrimental effects are discovered, changes can be made in use patterns or use can be discontinued.

In the past, those who worked with herbicides knew about ecological relationships but did not ask the right questions about the effect of herbicides on ecological systems. Today the right questions are being asked and environmental effects are examined, in depth, with great care. Because good questions are asked and answered we should not assume all problems have been solved and no future environmental effects or ecological disruptions will occur because of herbicide use. These are some good questions that must be asked about all herbicides:

1. What are possible effects on public health?
2. Will domestic animals be affected?
3. Will products for human consumption be contaminated (e.g., meat, milk, fruits, or vegetables)?
4. Will beneficial natural predators or parasites be affected?
5. What is the likelihood of resistance developing?
6. Will honeybees or wild bees be affected and will pollination be reduced?
7. Will there be crop damage?
8. Will ground- or surface water be contaminated?
9. Will there be negative affects on fish, wild birds, mammals, microorganisms, or invertebrates?

Even with the sophisticated scientific capabilities of the world's developed countries there is a limited capability to predict environmental hazards. When a limited capability to predict all results is coupled with the dominant attitude that, while effects may be real, they will be minimal, the result may be an inattention to small but real effects. For example, the report of Heilprin (2006) notes that "the large majority of pesticide detections in streams and groundwater were trace amounts, far below scientifically based minimum levels set for protecting human health and the environment." That is—yes, they are there, but they are below the scientifically set limits for human and environmental safety. Therefore, they are not a problem. Stop worrying. Such data are consistent with the coda from the National Academy of Sciences report cited at the beginning of this chapter (Berenbaum, 2000). The conclusion is based on sound fundamental and applied research. It is a scientifically based decision, and, therefore, the argument goes, one should assume it is correct. One should have faith in the widespread applicability of the decision.

But many people don't have faith in scientifically based decisions on pesticide safety. Why is there widespread mistrust of scientifically set limits for human and environmental safety?

One reason is the arguments in favor of herbicides and other aspects of modern agricultural technology are based on what Shader-Frechette (1991) calls the “realism argument.” She cites Kraybill (1975, pp. 10, 16) and Furtick (1976, p. 12), who both make the claim that life is dangerous, and while chemical pest control is risky, “it is realistic to accept the minimal degree of risk it presents, since absolute safety is unattainable in any sector of life.” Bender (1994, p. 92) agrees with Shader-Frechette. He notes the following arguments commonly employed in defense of pesticide use:

1. Abrupt cessation of chemical use would cause calamity.
2. The key to pesticide safety is following label directions.
3. Farmers have a moral obligation to feed the world.
4. The world is filled with risks.

Bender finds problems with each of these claims, which he defines as sophistry, and denies their validity. Implicit in these claims is the claim that concerns about agricultural chemicals are all out of proportion to the actual risks (Shader-Frechette’s realism argument). He claims the proponents of pesticides propose that what is needed is more knowledge and then all problems will be solved or simply disappear. More knowledge will show that many of the fears about pesticides are simply irrational (Bender, 1994, p. 111).

Doering (1992, p. 239) supports Bender’s (1994) argument. He claims that even if a member of the general public had the same scientific knowledge as the scientist, he or she still might have different risk preferences. Their values about production benefits versus environmental or health concerns may be quite different. Second, members of the general public may never possess adequate knowledge in the view of scientists. Third, public perceptions of risks may not ever correspond with scientific facts. That is, the public may rely on other sources of information (National Public Radio, TV news, magazines, newspapers, etc.) that they regard as more trustworthy. Finally, Doering (1992) notes that scientific facts have notably missed some of the big trade-offs by focusing on just the facts. For example, is more yield always better than improved quality? Should more yield or more profit for someone always trump environmental improvement? What can justify harm to public health? If a pesticide is in my water is it okay if it is present below the scientifically set limits for human and environmental safety. What if, as Mackay (1988) asks, it is a chemical that has disruptive potential? What if it is a molecule that in very low concentrations has the potential to direct future events? Should we be worried and whose values determine what should be done? These are all hard questions with no easy answers.

The realism argument correctly asserts that risks and benefits must be balanced by scientifically based decisions. What is incorrect is the claim that “the moral acceptability of a hazard, like pesticide use, is a matter only of risk magnitude or degree of physical danger" (Shader-Frechette, 1991). This view ignores or dismisses risk distribution: Is the distribution of risk equitable among all that are or might be affected? It also ignores whether risk is accepted voluntarily or imposed involuntarily. The realism argument is accepted by the agricultural community and those who favor pesticide use and scientifically based risk assessment. They accept the benefits to agriculture but have not picked up the mantle of proof to demonstrate, beyond some level of reasonable doubt, that public well-being is served. There is no doubt that there have been enormous benefits to pesticide manufacturers and some users. Corporate stockholders have benefitted as manufacturers have fulfilled a primary obligation to maximize shareholder return, as they are legally mandated to do. But corporate managers tend to filter out externalities such as consideration of public well-being such as general public health, worker safety, equitable income distribution, and the well-being of natural communities, animals, plants, other sentient, and perhaps, non-sentient, creatures, soil, and the atmosphere (Nace, 2006). Shouldn't public policy be directed toward reducing unnecessary pesticide residues in the human diet (Culliney et al., 1992)? In the United States in 1993, at least 35% of food purchased by consumers contained measurable levels of pesticide residues (FDA, 1993), but only 1.1% were found to have pesticide residues above the FDA tolerance level (Pimentel, 1997). There is evidence that concern about contamination of human food should be even greater in other countries. For example, as much as 80% of food available in Indian markets had pesticide residues (Singh, 1993, as cited in Pimentel, 1997), and the residues were primarily from chlorinated hydrocarbon insecticides. In view of these data, one wants to argue that public policy (Culliney et al., 1992) is inadequate.

It is often helpful when thinking about complex issues to consider related, perhaps more familiar, matters as examples. Two will be discussed briefly.

The Case of Fluorides

Fluorine is poisonous and is an element in some herbicides. Its most famous and, in some circles, still controversial, use is as an intentional additive to drinking water to prevent tooth decay. It is added to drinking water at about 1 ppm and debate has rarely focused on its efficacy. The debate is about its toxicity to people who must drink water to survive and should not be poisoned because they cannot avoid drinking water.

The determining factor in fluoride toxicity is the same as it is for the toxicity of any chemical: dose or concentration. A 150-pound man will become ill if he ingests 0.25 mg of fluorine in one day. The same man will become very sick if he ingests 1 gram, and he will die if he ingests 4 to 8 grams. At the prevailing level of fluorine in US drinking water, a 150-pound man would have to drink more than 42 gallons of water containing 1 ppm of fluorine to consume 0.25 mg. To ingest 1 gram, he would have to drink more than three bathtubsful. The man would die from water intoxication long before he would be affected by fluorine toxicity.

2,4,5-T

2,4,5-T controls a wide range of broadleaved and woody plants. It has been used selectively in crops, on home lawns, in forests, and in rice. When the United States was engaged in the Vietnam War, a 2,4,5-T ester was used in combination with a 2,4-D ester as Agent Orange to eliminate unwanted vegetation. When 2,4,5-T is manufactured, temperature control is required to minimize formation of an undesirable, nonphytotoxic contaminant: 2,3,7,8-tetrachloroparadioxin. It is one member of a family of compounds known as dioxins and is a potent teratogen. A teratogen causes terata, or birth defects, when pregnant women are exposed to it. This dioxin also causes chloracne, a skin condition characterized by blisters and irritation. There was never any debate about whether the dioxin contaminant in 2,4,5-T was a teratogen or caused chloracne. Part of the concern and debate ensued because of the unknown level of exposure of Vietnam-era servicemen and American women to the contaminant.

The *Pesticides Monitoring Journal* reports surveys of pesticide levels found in the American food supply. In one report they surveyed 24,000 food samples and found that 3 contained measurable quantities of 2,4,5-T; 2 in milk and 1 in meat. Reported on a whole-milk and fresh meat basis, the average 2,4,5-T content was 0.006 ppm. For all 24,000 samples, the 2,4,5-T content was 7.5×10^{-7} ppm, or roughly equal to 1 mg in 133,000 metric tons. Based on other studies, the presumed maximum nonteratogenic dose of 2,4,5-T with the dioxin contaminant for a 130-pound pregnant woman is 1.26 grams daily. At the observed level of 2,4,5-T in the nation's food supply, a 130-pound pregnant woman could have consumed 170 million tons of food per day for 9 days without fear of teratogenic effects on a fetus.

Many people want absolute assurance of safety, and any risk of bearing a deformed child is too high if the risks can be eliminated. Certainly the risk of exposure to an herbicide can be minimized if not eliminated, and even if it is infinitesimally small, many think it is too large and should be eliminated.

A Harvard scientist[2] disputed the 2,4,5-T toxicity theory and calculated the risks associated with spraying 2,4,5-T. If a person applied 2,4,5-T with a backpack sprayer 5 days a week, 4 months a year for 30 years the chances of developing a tumor would be 0.4 per million. Other risks of developing a

[2]Wilson, R. Cited in the *Pesticide Pipeline*. Colorado State Univ. XIV (7) July 1981.

TABLE 17.5. Risks of Developing a Tumor.

Activity	Chance of developing a tumor (per million)
Smoking cigarettes	1,200
Being in a room with a smoker	10
Eating 1/4 pound of charcoal-broiled steak per week	0.4
Drinking 1 can of diet soda with saccharin per day	10
Drinking milk with aflatoxin or eating 4 tablespoons of peanut butter per day	10
Drinking 1 can of beer per day	10
Sunbathing	5,000

tumor are larger (Table 17.5). Zimdahl (2006; see Chapter 3) includes a more complete discussion of the issues surrounding 2,4,5-T.

Summary

The data required to resolve the human and environmental questions raised herein are difficult to obtain, and the data and the solutions they suggest are controversial. Yet, decisions *must* be made. Weeds and other agricultural pests must be controlled. Informed debate is best, but debaters should understand that such decisions, when made, will be based in part on factual information and in part on perceptions or other relevant things that may have no basis in scientific fact.

Table 17.6 shows data on the risk of death associated with certain human activities which many people do voluntarily. These data are presented not to provide a conclusion or judgment about herbicides and the environment or herbicides and human welfare. Such statements can be found in several of the references cited in the literature available section at the end of this chapter. In most cases, thought is required. It cannot be overemphasized that the end of these debates is usually a value judgment, not a clear decision based solely on scientific fact. It may be true that chances of getting cancer are increased by 1 in 1,000,000 by consuming Miami drinking water for one year. Residents and visitors in Miami must decide what, if anything, they propose to do about the scientific evidence. How does one judge the importance of the facts to life? This is a question that must be dealt with by those who consider the problems and advantages of herbicides in the environment.

There is another point of view that should be considered when thinking about herbicides and the environment. The United States is a rich country that can afford to ask and answer difficult environmental questions. We can afford

TABLE 17.6. Acts That Increase the Risk of Death by 0.000001 (1 Chance in 1 Million).

Act	Hazard
Smoking 1.4 cigarettes per day	Cancer, heart disease
Drinking ½ liter of wine per day	Cirrhosis of liver
Spending 1 hour per day in a coal mine	Black lung disease
Spending 3 hours per day in a coal mine	Accident
Living 2 days in New York or Boston	Air pollution
Traveling 6 minutes by canoe	Accident
Traveling 300 miles by car	Accident
Traveling 10 miles by bicycle	Accident
Flying 1,000 miles by jet	Accident
Flying 6,000 miles by jet	Cancer from cosmic radiation
Living 2 months in Denver on vacation from New York	Cancer from cosmic radiation
Living 2 months in average stone or brick home	Cancer from natural radioactivity
One chest X-ray in a good hospital	Radiation cancer
Living 2 months with a smoker	Cancer, heart disease
Eating 40 tablespoons of peanut butter	Liver cancer from aflatoxin-B
Consuming Miami drinking water for 1 year	Cancer from chloroform
Drinking 30 12-ounce cans of diet soda (at one time)	Cancer from saccharin
Living 5 years in the open at the site boundary of a nuclear power plant	Radiation cancer
Living 150 years within 20 miles of a nuclear plant	Radiation cancer
Eating 100 charbroiled steaks (all at one time)	Benzpyrene-induced cancer

to make decisions that favor environmental protection over productivity or the opposite. Poor countries may not choose, or be able to afford, to put productivity second. Most of the world's people are poor, hungry, landless, lack formal education, do not have access to adequate or, more likely, any health care, or a hope for a brighter future. If one is hungry, one has only one need: food. Obtaining or producing food is the only goal and environmental questions, if thought of, are obstacles that may stand in the way of food production. One can argue that without consideration of environmental questions, such as whether or not the risk of soil, personal, or environmental contamination from herbicides is acceptable, long-term food production may be at risk. However, if one is hungry, only the short-term goal of obtaining sufficient food is important. Attitudes toward herbicides may be very different when herbicides are perceived, correctly or incorrectly, primarily as a way to produce food rather than primarily as environmental risks.

C. Global Change

It was true in the United States and is still true in most of the world's developing countries that possible or real environmental hazards of pesticides are given low priority. Many of the world's developing countries do not have good environmental policies. An important and hotly debated reason for problems with pesticides in developing countries is the lack of suitable alternatives to pesticides that offer comparable efficacy and labor efficiency.

Pimentel (1997) notes the widespread concern that as much as 40% of all food and fiber produced is lost to pests before it can be consumed by humans, despite the 2.5 million pounds of pesticides applied to the world's crops each year. Most authors agree that losses would be even higher if no pesticides were used. US crop losses might be greater than 60% with an economic loss of US $90 billion (Pimentel, 1997)—an economic catastrophe. Pimentel also reports that although US pesticide use has increased over the past five decades, crop losses have not declined because of changes in cropping practices that included abandoning crop rotations and reduced field sanitation practices in an ever more monocultural agriculture. Pimentel also points to more stringent cosmetic standards for produce that have been implemented by government regulations and encouraged by consumer demand.

Thus, we are faced with increased pesticide use and continued high losses to pests during and after production in a world with a growing population that demands more high-quality food. The next 50 years is forecast to be the final period of rapid agricultural expansion, which will be driven by increasing demand for food by more people who through economic development are able to afford more and better food (Tilman et al., 2001). The demand on agriculture for more production will only exacerbate its already significant environmental effects. More people demand more food, and as they pursue the quite understandable goal of becoming richer, they will demand food of higher quality as well as more meat. Agriculture's environmental effects will increase. It is forecast that as much as a billion acres of land now in natural ecosystems will be converted to agricultural use by 2050. This is a loss of natural ecosystems and the ecosystem services they provide, larger than the continental United States. This will be accompanied by a "2.4- to 2.7-fold increase in nitrogen- and phosphorus-driven eutrophication of terrestrial freshwater, and near-shore ecosystems and comparable increases in pesticide use" (Tilman et al., 2001). If past trends continue, global pesticide production, which has increased for the past 40 years, will be 1.7 times greater in 2020 and 2.7 times greater than the present consumption in 2050 (Tilman et al., 2001). It is likely that herbicides will continue to dominate pesticide use. This means that humans, the environment, and other creatures will be exposed to higher levels of pesticides, with presently unknown consequences. It also means that the effects of agricultural technology may rival in their social and environmental effects those of climate change (i.e., global warming) the planet is now experiencing.

Agriculture is the largest and most ubiquitous environmental interaction of humans. It is already the greatest threat to the extinction of birds (Green et al., 2004). Available data clearly indicate the need for what Tilman et al. (2001) call a "greener revolution": an environmentally sustainable revolution. In practical terms, this means using existing knowledge to reduce agriculture's inevitable environmental effects and increase productivity. Agriculture's effects on wildlife can be mitigated in one of two ways. The first is to practice wildlife-friendly farming, which is a good thing but it almost inevitably reduces yields. The second is to use the best agricultural practices on the best land to increase yield and prevent conversion of more land to agriculture that the first solution demands (Green et al., 2004). Both solutions require greater use of integrated weed (and other pest) management programs, application specificity (e.g., herbicides will be applied only to areas where weeds grow and not to entire fields), site- and time-appropriate amounts of herbicides will be used, irrigation will be site- and time-appropriate, cover crops will be used to reduce soil erosion especially on fallow land, inter-row areas, and in buffer strips between fields, appropriate use of more productive cultivars to increase yield and reduce fertilizer, water, and pesticide runoff to non-agricultural areas (Tilman et al., 2001). Yield of agricultural crops will continue to be an important measure of any program's, indeed of agriculture's, success. It cannot be the only measure if we are to have a greener revolution, indeed what Conway (1997) calls a "Doubly Green Revolution" to feed all in the 21st century. If crop yields do not increase, more land will be required to feed all the people. Just to maintain current food consumption levels will require a near doubling of cropped land by 2050 to feed the projected 8+ billion people who will be alive. The success of a doubly green revolution must be based on all the costs and benefits of agricultural production, not just yield. These include "agriculture-dependent gains and losses in values of such ecosystem goods and services as potable water, biodiversity, carbon storage, pest control, pollination, fisheries, and recreation" (Tilman et al., 2001). The balance between high-yield farming and minimal environmental effect is delicate and it is not the purpose of this book to explore it in detail. Interested readers are directed to one or more of the references provided in the literature available section at the end of this chapter.

IV. ENERGY RELATIONSHIPS

In 1974 Nalewaja projected that if all the corn grown in the United States were weeded by hand in six weeks, it would take over 17 million people working

40 hours per week. That was more than four times the number of workers then employed on US farms. The job had to be done in six weeks because of the early critical period for weed control in corn. If weeding was not done during the critical period, yield would decrease. There was not enough labor available to weed the US corn crop in 1974, and that is still true. It is doubtful that even if people were available that they would be in the right place at the right time and be willing to weed corn or any other crop. Hand-weeding or -hoeing is not among life's desired occupations.

Yet corn, and other crops, have to be weeded. Not all acres and all crops need the same amount of weeding, but all need some. In agriculture's early days, animals were substituted for hand-labor, and as hand-labor became scarce and more expensive and acreages grew, large animals were inadequate for the task. Tractors replaced animal power. If the tractors on US farms were not used, it has been estimated that it would take more than 60 million horses and mules to replace them. There aren't that many work animals available in the United States, and the land required to grow feed for them would reduce available crop land. The shift from hand-labor to animals reduced the need for human labor. The change to tractors added more petroleum energy to agriculture's input requirements. The trend has continued, and agriculture has become more mechanized and chemicalized. Nitrogen fertilizer and pesticides are highly dependent on petroleum energy for manufacturing and distribution. The purpose of this section is to discuss, with reference only to the use of herbicides for weed control, US agriculture's dependence on petroleum energy. Is energy use for herbicide manufacture and application efficient? How does herbicide use efficiency compare to other methods of weed control? The quick answer is that herbicides do not demonstrate an overdependence on energy, and their efficiency compares well with other methods of weed control.

A study of the economic relationships for weed control techniques in six experiments on corn showed that when weeds were controlled by hand-labor there was a net economic loss (Nalewaja, 1974). When appropriate herbicides were used, there was a net profit (see Table 12.3 in Chapter 12). Table 12.4 shows similar data for cotton. Of course, all costs are higher than they were in 1974, but the relationship among the techniques is still valid even though absolute costs have changed.

The data in Table 12.5 show the 1974 energy relationships for weed control in corn (Nalewaja, 1974). Land was plowed, disked, and prepared in the conventional manner, and the comparison is only for weed control. The data show an energy advantage for hand-labor, but it is not significantly better than herbicide use. Both are more advantageous than cultivation with a tractor and cultivator. Corn yield with herbicide use or hand-labor was nearly identical. Table 17.7 shows energy costs for several weed control practices. Some equipment requires more energy than others, and energy costs for herbicides increase directly with rate, although application cost is constant. Hand-labor is not the

TABLE 17.7. **Energy Inputs per Performance for Various Weed Control Practices (Nalewaja, 1974).**

	Energy input				
Method	Gas	Indirect machine	Hand labor (kcals/ha)	Herbicide	Total
Hand labor			53,800		53,800
Field cultivator	120,800	60,400	170		181,370
Tandem disk	93,100	46,500	220		139,820
Rod weeder	26,000	13,000	170		39,170
Rotary hoe	19,700	9,800	120		29,620
Row cultivator	36,700	18,300	310		55,310
Rotary tiller	262,300	131,100	930		394,330
Herbicide					
0.5 kg/ha	8,100	4,000	70	13,600	25,770
1.0 kg/ha	8,100	4,000	70	27,200	39,370
2.0 kg/ha	8,100	4,000	70	54,400	66,570
4.5 kg/ha	8,100	4,000	70	108,700	120,870

cheapest way to weed crops in terms of energy expended. The sulfonylurea and imidazolinone herbicides use fractions of an ounce per acre, and energy costs compare favorably with any other method of weed control. The energy costs for mechanical tillage and cultivation do not compare favorably with herbicides.

Most US cropping systems replace human and animal energy with petroleum energy in the form of fuel for tractors and other machines, manufacture of nitrogen and other fertilizer, and water pumping for irrigation, transportation, and pest control. US agriculture is energy based, but it is not the major energy consuming sector of the US economy. Farm production consumes only 3% of total US energy. Petroleum energy has been substituted for hand labor and animal power and chemical energy substitutes for mechanical energy. But herbicides and the cost of application are not a significant portion of the energy cost of producing crops (Table 17.8; Pimentel and Pimentel, 1979). The energy used for herbicides ranges from 0.1% of total energy expended to produce oranges to 27.3% for soybeans. The mean for the 19 crops is 6.8% and is a reasonable estimate of energy use for weed control in US crops.

Is the level of energy expenditure excessive? There is no clear answer. Many argue that the business of agriculture is to produce food at a reasonable cost

TABLE 17.8. Energy Inputs for Herbicides in Several Crops (Pimentel and Pimentel, 1979).

	Herbicide as percent of total energy		
Crop	Location	Rate (kg/ha)	For herbicides (%)
Corn (grain)	US	2	3.1
Corn (silage)	NY	2.5	4.0
Wheat	US	0.5	1.8
Oats	US	0.2	0.9
Rice	Philippines	0.6	2.4
Rice	CA	11.2	7.7
Rice	Japan	7	9.7
Sorghum	US	4.5	8.4
Soybean	US	5	27.3
Dry bean	US	4	14.6
Peanuts	GA	16	14.6
Potato	NY	18	11.2
Apple	US	2	1.1
Orange	US	0.2	0.1
Spinach	US	2	1.6
Tomato	CA	2	1.2
Brussels sprouts	US	10	12.4
Alfalfa	OH	0.2	0.8
Hay	US	1	5.8
		Average	6.8

to the consumer and profit to the grower. Agriculture's business is not to produce energy, but it must use it efficiently and responsibly. Herbicides are an efficient use of energy, in view of the energy costs and efficiency of alternative methods of weed control, which must be done.

The weed control and management techniques used by US agriculture could be more efficient and conserve more energy. Weed scientists are effectively integrating weed control techniques that use less energy. Herbicide rates are decreasing, and energy use for weed control will decrease. It cannot go to zero because agriculture and weed management require energy. Agriculturalists and the general society will participate in the debate over what form the energy will take and how much is needed. There is no question that agriculture can become more efficient and use less of the total US energy supply. How this will be achieved is not clear. Some production systems use far less energy (see Table 12.7). A rapid move to these systems would compel a sacrifice of food production for energy conservation; presently not a good trade.

V. HERBICIDE SAFETY

How safe are herbicides? It is a simple question, but a definitive answer is hard to find because each answer may have a bias that should be understood. A reasonable response to the question is, compared to what? Compared to some things, herbicides are dangerous but compared to others they are safe. Most people believe herbicides, and all other pesticides, are very dangerous. They are regarded as poisons; things that are not safe to use or be around. They are poisons. If they weren't poisonous to something they wouldn't be useful as herbicides. The suffix *icide* comes from the Latin *caedere*, meaning "to kill."

Answers to safety questions are complex. The questioner usually expects a factual response, not an opinion, but answers are nearly always composed of fact *and* opinion. Some respondents are vested, automatically, with authority and veracity by a questioner but that does not deny the fact that most answers are part opinion.

There are facts about herbicide safety; not all answers are entirely opinions. The dermal and oral LD_{50} (lethal dose at which 50% of the test population dies) for all herbicides is known. Necessary safety precautions during use and storage are well known. The agrichemical industry knows and avoids uses that create problems. The US Environmental Protection Agency and state agencies regulate herbicide use and users to reduce, if not eliminate, the inherent dangers of herbicide use.

A. Perception of Risk

Science can measure risk and determine the probability of occurrence of a defined risk. Science cannot measure safety. Safety is a normative personal or political judgment. Judgment of safety is not, and cannot become, a scientific decision. Science plays a role in creating the data on which many judgments and decisions are based, but scientists, through the scientific process, cannot determine what should be done about their data. Something may be described as unsafe because it is found through experiment and observation (the methods of science) to increase the risk of undesirable consequences. For example, motorcycle riding without a helmet can be fatal when an accident occurs. Scientists can measure the risk (the likelihood) of a fatal accident from riding a motorcycle without a helmet. Parents may decide not to buy a child a motorcycle, insurance companies may charge high premiums, and legislative bodies may pass laws requiring helmets because of the scientific evidence. Scientists may agree with these actions, but science does not create them.

People perceive risk in different ways depending on where they live, how rich or poor they are, what their options are, their level of education, their friends, the scientific evidence they are aware of, what they read, and so on. Perception of risk may differ from the facts as determined by scientific study. Table 17.9 is from a frequently cited study that shows how three different groups judged the risk of several common things. It is obvious that not all share the same perception of risk. In addition to reporting how people in various groups perceive risk, Table 17.9 also shows the actual number of deaths from the hazard. Neither actual deaths nor perceptions of risk are an adequate way to decide what to do. It is not the purpose of this section to debate the question of herbicide safety but rather to frame a perspective from which the debate can proceed. The annual US death rate from motor vehicle accidents was 41,611 people in 1999 (Nat. Trans Safety Board, 1999). People properly conclude that automobiles are dangerous. Yet people drive too fast, don't use seatbelts, and drive after consuming alcohol. Because they think they are in control, many people don't think automobiles are as dangerous as they are. The danger is there, but as long as people believe they are in control, they believe the risk is acceptable—but acceptable to whom? (Starr and Whipple, 1980). The answer may be determined legislatively, or it may be determined by one's perception of the risk. Many are much more likely to accept even a very risky activity (i.e., mountain climbing, hang gliding, or automobile driving) if they are able to assume the risk voluntarily, the likely effects are perceived to be delayed, the risk is a known common hazard, there are no alternatives available, and the consequences are thought to be reversible. When the opposite situations prevail, risks are accepted less readily. With pesticides the US death rate is about 30 per year, but pesticides are regarded as more risky and dangerous than the data show they really are. This is because they are seen as uncontrolled, involuntary risks with irreversible, severe, rapid consequences. They are perceived as things likely to be misused and regarded as dreaded uncommon hazards.

More Americans die from bee stings (30 to 120 each year; http://dentalresource.org/topic43stikng.htm), drug poisoning (7,000/year), and falls (13,000/year; National Safety Council, Accident Facts, 1994–1997) than from pesticides. There are 2,000 to 3,000 cases of pesticide poisoning each year in the United States from voluntary and involuntary exposure but only a few

TABLE 17.9. Actual Risk and the Perception of Risk by Three Groups (Adapted from Slovik, 1982).

Rank order of actual risk	Activity	Perceived risk			
		US deaths/ year	League of women voters	College students	Business and professional club members
1	Smoking	150,000	4	3	4
2	Alcohol	100,000	6	7	5
3	Automobiles	50,000	2	5	3
4	Handguns	17,000	3	2	1
5	Electric power	14,000	18	19	19
6	Motorcycles	3,000	5	6	2
7	Swimming	3,000	19	30	17
8	Surgery	2,800	10	11	9
9	X-rays	2,300	22	17	24
10	Railroads	1,950	24	23	20
11	Private aviation	1,300	7	15	11
12	Construction	1,000	12	14	13
13	Bicycles	1,000	16	24	14
14	Hunting	800	13	18	10
15	Home appliances	200	29	27	27
16	Firefighting	195	11	10	6
17	Police work	160	8	8	7
18	Contraceptives	150	20	9	22
19	Commercial aviation	130	17	16	18
20	Nuclear power	100	1	1	8
21	Mountain climbing	30	15	22	12
22	Power mower	24	27	28	25
23	High school & college football	23	23	26	21
24	Skiing	18	21	25	16
25	Vaccinations	10	30	29	29
26	Food coloring	*	26	20	30
27	Food preservatives	*	25	12	28
28	Pesticides	*	9	4	15
29	Prescription antibiotics	*	28	21	26
30	Spray cans	*	14	13	23

*Not available.

deaths. There are several thousand cases of pesticide poisoning and many more deaths in the world's developing countries each year.

There should be no debate about whether herbicides can be hazardous to humans. They are toxic to people and will poison and may kill, if not used properly. The last phrase is the key: "if not used properly." Many prescription pharmaceuticals, household cleaning agents, aspirin, automotive fuel, and other common products are dangerous if they are not used properly. Their inherent toxicity doesn't change with use, but the possibility of danger increases with improper use. Stupidity doesn't increase the inherent toxicity of anything, but it increases risk.

B. Rules for Safe Use of Herbicides

There are rules for safe use of herbicides that also don't change inherent toxicity but make accidents and the expression of toxicity less likely. The rules are simple, obvious, and often overlooked. Here are some:

Before use

1. Keep away from children.
2. Purchase the right herbicide for the task.
3. Read the label.
4. Follow all label directions.
5. Label equipment so cross-contamination is avoided.

Storage

1. Keep in a locked storage place.
2. Never store any herbicide in anything other than its original container.
3. Store outside the residence and away from food, feed, seed, or fertilizer.
4. Protect liquids from freezing.

Handling

1. Prevent access by children.
2. Mix in a well-ventilated area, preferably outside.
3. Do not inhale spray or dust. Wear a protective breathing mask when needed.
4. Never smoke, eat, or chew while spraying or handling.
5. Wash with soap and water, and change clothing immediately if the herbicide is spilled on skin or clothing.
6. Wear loose-fitting clothing.

7. Wear rubber gloves and rubber boots.
8. If herbicide is swallowed, call a physician or the nearest hospital poison control center at once.
9. If herbicide is splashed in eyes, flush with clean water immediately and call a physician.
10. If symptoms of illness occur during or shortly after handling or use, call a physician or your nearest hospital poison control center.

Application

1. Look out for children.
2. Be aware of the hazards of drift and volatility.
3. Be aware of other people in the area.
4. Do not contaminate wells, cisterns, other water sources, nontarget crops, or animals.
5. Apply at proper time and rate.
6. Do not contaminate food and water containers, including those for livestock.

After use

1. Always dispose of empty containers so they pose no hazard. Puncture containers to prevent reuse.
2. Wash and change to clean clothing.
3. Be sure the person who washes contaminated clothing is aware of the contamination.
4. Clean equipment soon after use.

The precaution concerning children is repeated for good reason. Children often do unexpected things, and adults must always be prepared. The other precautions for herbicide use are not difficult to understand. Most are just common sense. If poisoning occurs, treat it seriously, and take the victim to a physician or hospital promptly. It is always a good idea to take the pesticide container along. Do not move victims who are in shock without treating for shock. It is often true that doing nothing except removing the victim from any possibility of further poisoning is a better thing than doing something if you are not sure what is correct.

C. The LD_{50} of Some Herbicides

The LD_{50} is a good indicator of relative toxicity and safety. It is not the only measure of safety. The LD_{50} may help understand toxicity when it is compared to other things. It is a measure of acute oral, not chronic toxicity. All values

Table 17.10. Pesticide Toxicity Classes Based on LD_{50}.

Toxicity class	Signal words*	LD_{50}	Toxic amount
I	Danger—poison + a skull & crossbones	5 6–49	a taste to 7 drops 8 drops to a teaspoonful
II	Warning—may be fatal	50–499	1 teaspoonful to 1 table spoonful or 1 ounce
III	Caution	500–4,999	1 ounce to 1 pint
IV	Caution	5,000–14,999	1 pint to 1 quart

*Signal words must appear on pesticide label.

Table 17.11. The Ld_{50} of Some Herbicides and a Few Other Chemicals.

	LD_{50} (mg/kg)
Common name	Technical[a]
Herbicide	
Acetochlor	2,148
Acifluorfen	1,540
Alachlor	930–1,350
Ametryn	1,160
Amitrole	>5,000
Atrazine	3,090
Benefin	>5,000
Bensulfuron	>5,000
Bensulide	770
Bentazon	1,100
Bromacil	175
Bromoxynil	440
Butachlor	2,000
Butylate	4,659
Chlorimuron	4,102
Chloroxuron	3,700
Chlorsulfuron	5,545
Clomazone	2,077
Clopyralid	4,300
Copper sulphate	470
Cyanazine	334

(Continues)

TABLE 17.11. (*Continued*)

	LD$_{50}$ (mg/kg)
Common name	Technical[a]
Cycloate	3,200
2,4-D acid	764
2,4-D dimethylamine	>1,000
DCPA	>10,000
Desmedipham	>10,250
Dicamba	1,028
Dichlobenil	4,460
Dichlorprop	800
Diclofop methyl ester	557–580
Difenzoquat	617
Diquat	230
Diuron	3,400
DSMA	1,935
Endothal	38–51
Ethalfluralin	>10,000
Ethofumesate	>6,400
Fenoxaprop	3,310
Fluazifop-P butylester	4,096
Flumetsulam	>5,000
Fluometuron	6,416
Fomesafen	1,250–2,000
Glufosinate	2,170
Glyphosate—isopropylamine salt	>5,000
Haloxyfop	337
Hexazinone	1,690
Imazamethabenz	>5,000
Imazapyr	>5,000
Imazaquin	>5,000
Imazethapyr	>5,000
Isopropalin	>5,000
Isoxaben	>10,000
Linuron	1,254
MCPA acid	1,160
MCPB	680
Mecoprop	650
Metolachlor	2,877
Metribuzin	1,090
Metsulfuron	5,000+
MSMA	1,800
Napropamide	>5,000
Nicosulfuron	5,000+

(*Continues*)

TABLE 17.11. (*Continued*)

	LD_{50} (mg/kg)
Common name	Technical[a]
Norflurazon	9,000
Oryzalin	>5,000
Oxadiazon	>5,000
Oxyfluorfen	>5,000
Paraquat	112–150
Pendimethalin	>5,000
Phenmedipham	>8,000
Picloram K^+ salt	>5,000
Primisulfuron	5,050
Prodiamine	>5,000
Prometon	4345
Prometryn	4,550
Pronamide	>16,000
Propachlor	1,800
Propanil	1,080
Pyrazon	2,200
Quizalofop	1,670
Sethoxydim	2,676–3,124
Siduron	>7,500
Simazine	>5,000
Sodium chlorate	5,000
Sulfometuron	>5,000
Tebuthiuron	644
Terbacil	1,255
Thifensulfuron	>5000
Triallate	1,100
Triasulfuron	>5,000
Tribenuron	>5,000
Triclopyr	713
Trifluralin	>5,000
Triflusulfuron	>5,000
Other Chemicals	
Aspirin	750
Caffeine	200
DDT	87
Diazinon	66
Ethyl alcohol	4,500
Gasoline	150
Kerosene	50
Methyl parathion	9
Nicotine sulphate	83

(*Continues*)

TABLE 17.11. (*Continued*)

	LD_{50} (mg/kg)
Common name	Technical[a]
Paradichlorobenzene	>1,000
Parathion	3
Phorate	1
Pyrethrins	200
Sodium chloride (table salt)	3,320
Water	25 ml/kg

[a]Herbicide values are for the acute oral LD_{50} in adult rats for technical grade herbicide (= 95% pure).

are expressed in milligrams (mg) per kilogram (kg) of body weight. If the LD_{50} is multiplied by 0.003, it is converted to ounces (oz) per 180-pound man. The value would be different for a woman or for someone of different weight.

The US Environmental Protection Agency has classified all pesticides into four groups based on their toxicity (Table 17.10). Table 17.11 shows the LD_{50} of some herbicides and a few common chemicals. It is wrong to assume that because two things have the same LD_{50}, they are equally toxic. This is because routes and likelihood (the chance) of exposure differ.

In one 5-ounce cup (about 150 ml) of roasted and brewed coffee there is about 85 mg of caffeine. Instant coffee has 60 mg, and there is about 3 mg in decaffeinated coffee. To become poisoned from coffee, a 180-pound man would have to drink 7.6 gallons nonstop. That is impossible, and it is very unlikely that anyone will die from acute caffeine intoxication.

The LD_{50} of ethyl alcohol is 4,500 mg/kg and a 180-pound man would have to consume a little more than 0.8 pints to be acutely poisoned. This is not commonly done, but it is possible and people die from alcohol intoxication.

The LD_{50} as a measure of toxicity of anything is valuable, but its use must be tempered with knowledge of exposure, route of administration, rate, time, and physiological factors. It is a useful, but not a perfect indicator of toxicity.

THINGS TO THINK ABOUT

1. How do weeds interfere with human activities?
2. What ecological changes can occur after herbicide use?
3. How can ecological change, created by herbicides, be prevented or managed?
4. What is herbicide resistance?

5. How do herbicides influence soil?
6. Is herbicide use in US agriculture energy intensive?
7. Are herbicides always harmful to people?
8. Why is the debate about the environment, herbicides, and people so complex?
9. What is the LD_{50} and how is it used?
10. How can herbicides be used safely?

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CHAPTER 18

Pesticide Legislation and Registration

FUNDAMENTAL CONCEPTS

- The pesticide registration process is complex, mandatory, and based on state and federal legislation.
- The US Environmental Protection Agency is the federal organization charged with administration of federal pesticide laws and is responsible for pesticide registration.

LEARNING OBJECTIVES

- To understand the purpose and complexity of federal pesticide laws.
- To be aware of the protection the regulatory process provides the US public.
- To become familiar with the basic steps of pesticide registration under US law.
- To understand the role of pesticide registration and regulation.

I. THE PRINCIPLES OF PESTICIDE REGISTRATION

Most of the world's nation states have some sort of pesticide[1] registration procedure. In some less-developed countries, procedural and data requirements are few to nonexistent, primarily because of fiscal constraints but also because of unawareness of the need. It is also true that the laws in some countries are not fully implemented. Countries that regulate pesticides share

[1]US federal and state pesticide regulations apply equally to all classes of pesticides. The general term *pesticide* will be used in most places in this chapter instead of the specific term *herbicide*.

the goal of providing protection from adverse effects of pesticides and gaining the benefits of pesticide use (Snelson, 1978). These objectives are achieved through the registration process and subsequent control of the pesticide label. Registration enables the regulatory agency to exercise control over use, claims about performance, label directions and precautions, packaging, and advertising to ensure proper use and environmental and human protection. In general, the process protects the public's interest and the manufacturer's rights (Snelson, 1978).

It is apparent from the questions raised regularly in the news media that the public does not have adequate knowledge of the intricacies of pesticide registration and the laws that govern the process. This chapter describes some general aspects of US pesticide registration, but it is not intended to be a complete description of the process.

In the world's developed countries, pesticides have been subject to some kind of governmental regulation for 100 years. The public is aware of pesticides and fearful because of mistakes that have occurred. Nearly everyone knows something negative about DDT. Many are aware of the Agent Orange problem from the Vietnam War (the herbicide of concern was 2,4,5-T) or the Alar (daminozide) scare of the late 1980s and early 1990s.[2] These are examples of the reasons for the public's fear. They cause the public to ask, as Wildavsky (1997) did, "Is it true?" His answer, in most cases, where the public became concerned was "No." Although concern was legitimate, fear was unwarranted.

The public does not know about the intricate and continually reviewed procedures necessary for registration of a pesticide prior to use. Registration is a complex process that should not be confused with registering a pet or a car. It is not simply recording ownership and paying a nominal fee. Registration of pesticides means compliance with legal requirements that establish a regulatory process that demands proof of safety but usually not proof of efficacy on the assumption that no manufacturer is likely to attempt to market a pesticide that does not work as advertised. Different nation-states establish registration processes that conform to their needs. The system in the United States is among the most complex and successful. It is not perfect, and there are many complaints about it from those who argue that protection is not sufficient and, in contrast, from manufacturers who find the process slow,

[2]Alar was marketed by UniRoyal Corp. as a growth regulator for apples. It caused cells to grow more densely and favorably affected fruit set, maturity, firmness, color, and, most important, it delayed fruit drop and extended storage life. The accusation was that its breakdown product, unsymmetrical dimethylhydrazine (UDMH), caused unreasonable risks of cancer especially to children who consumed apple juice and applesauce. UDMH had been shown to cause cancer in test animals. See Wildavsky (1997, pp. 201–222).

expensive, and unnecessarily cautious. The United Kingdom used to work with a voluntary approval scheme wherein a consensus was reached among the manufacturer, government, and users about appropriate regulation. That scheme was abandoned in the mid-1980s because of pressure from the European Economic Community (EEC) for uniform standards. The UK scheme and the European Union (EU) process now resemble the procedures followed in the United States, including provisions that regulate advertising, storage, application, and crop use. Many nations follow the standards put forth by the UN/FAO Codex Committee on Pesticide Residues that establish maximum residue limits (MRLs) for pesticides in food. The CODEX also guides countries on safety regulations for use, storage, and analysis of pesticides.

This chapter describes the history of pesticide legislation and registration in the United States and general procedures that must be followed. Other descriptions are available (Harrison and Loux, 1995; Keller, 1982).

II. FEDERAL LAWS

The Food and Drug Act of 1906 was the first US law that dealt with pesticides, and it was administered originally by the US Department of Agriculture (USDA). Its purpose was "to halt the exposure of the general public to filthy, rotten food, adulteration, substitution, and misleading claims." There were several cases of arsenic poisoning in England from imported US apples, and these stimulated passage of the law.

The first US federal law that directly involved pesticides was the Insecticide Act of 1910. It was passed to stop unethical persons from selling ineffective or adulterated products and was specifically aimed at Paris green, lead arsenate, and other insecticides and fungicides. The law, administered by the USDA, introduced a labeling requirement that mandated an ingredient statement and the manufacturer's name. The early 1900s was a period of slow development of pesticides, and there was little public concern about them because they were generally considered useful. The law did not cover evaluation of hazards of the pesticides it regulated. Chemical analysis for crop residue was the most important enforcement procedure. The Insecticide Act protected the public against the possible loss of crops or damage to property from pesticide use, but there was no assurance that pesticides were not health hazards.

The US Federal Food, Drug, and Cosmetic Act (FFDCA) was passed in 1938 to gain more control of adulteration, misbranding, and substitution of food, drugs, and cosmetics, and to ensure the integrity and safety of food moving in interstate commerce. It was originally enforced by the Federal Security Agency that was abolished in 1953 when the Department of Health, Education, and Welfare (HEW) was created. At the present time, the law is administered by the Department of Health and Human Services, and the US Environmental Protection Agency (EPA), created in 1970, has responsibility for setting tolerances for pesticides. The need for such a law was the increase in use of potentially adulterating chemicals in food, drugs, and cosmetics. Manufacturers were required to prove safety and usefulness. The Federal Security Agency and HEW established safe levels of residues. This required a health agency to make agricultural decisions (on usefulness) and was cumbersome.

III. FEDERAL INSECTICIDE, FUNGICIDE, AND RODENTICIDE ACT

Pesticide development during and after World War II created the need for stronger laws. The USDA, supported by the pesticide industry, developed the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), which became law in 1947. The law retained the key portions of the Insecticide Act of 1910 but extended the principle that a pesticide formulation should meet proper standards. No other federal law had authority over the pesticide and its labeling. The FIFRA added two new ideas to pesticide regulation. The first was that all pesticides intended for shipment in interstate commerce must be registered with the US secretary of agriculture before shipment. The second stipulation was that the USDA was given control over all precautionary statements on the pesticide label. The USDA was empowered to review the public presentation of safety procedures so important to proper use. The law also placed the burden of proof of use and safety on the manufacturer. These provisions stopped shipment of untested or improperly labeled products in interstate commerce by requiring that labeling be adequate and that all labels be approved (registered) by the USDA. Withholding registration was an effective way of stopping shipment of untried pesticides. The USDA could withhold registration until data were provided to prove the pesticide would give the degree of pest control claimed or implied on the label. Labels could also be withheld pending submission of adequate evidence of human safety from appropriate studies. The act had several specific and new items:

1. Protection of the user from physical injury or economic loss.
2. Protection of the public from injury. Previous laws had only protected the purchaser of the product from injury.
3. The manufacturer had to prove that the pesticide was effective for its intended use.
4. A pesticide was defined and limited to economic poisons that were defined as “any substance or mixture of substances intended for preventing,

> destroying, repelling, or mitigating any insects, rodents, fungi, weeds, and other forms of plant or animal life or viruses except viruses on or in living man or animals which the Secretary of Agriculture shall declare to be a pest."

The major public protection came from strict control over every feature of labeling. FIFRA had no control over the user of the product. It left users with the responsibility to read and heed the label and avoid misuse and environmental contamination.

Questions of coverage of economic poisons not specifically defined under the FIFRA of 1947 arose. The law was amended in 1959 to include nematocides, plant regulators, defoliants, and desiccants as economic poisons. Residues of these compounds in or on food or feed crops were regulated by the 1959 amendments. This broadened scope did not include adequate protection for fish and wildlife, and the law was further amended to include pesticides sold for control of moles, birds, predatory animals, and other nonrodent pests. It also included certain plants and viruses when they are injurious to plants, domestic animals, or people. Thus, it was possible to regulate pesticides designed to control specific things. The regulations were expanded to include the following:

1. Mammals, including but not limited to dogs, cats, moles, bats, wild carnivores, armadillos, and deer.
2. Birds, including but not limited to starlings, English sparrows, crows, and blackbirds.
3. Fishes, including but not limited to the jawless fishes such as sea lamprey, the cartilaginous fishes such as sharks, and the bony fishes such as carp.
4. Amphibians and reptiles, including but not limited to poisonous snakes.
5. Aquatic and terrestrial invertebrates, including but not limited to slugs, snails, and crayfish.
6. Roots or other plant parts growing where they are not wanted.
7. Viruses other than those in or on living man or other animals.

One might ask who was enamored of armadillos or English sparrows and got them included, but such a question misses the point that the law was being expanded in scope consistent with congressional interpretation of the public's desire for environmental safety.

A. Amendments

The Miller Pesticide Amendment, or PL-518, amended the Federal Food, Drug, and Cosmetic Act (FFDCA) of 1938. It was passed in 1954 to correct cumbersome enforcement procedures in the 1938 law. It was formulated by the Committee of the House of Representatives chaired by representative Delaney that was formed to investigate chemicals in food and cosmetics. The committee decided that a better way to establish tolerances on food crops was required and assumed the initiative to formulate a way. Congressman Miller of Nebraska formulated the recommendations in a bill known as the Pesticide Chemicals Amendment to the FFDCA. A pesticide chemical was defined as "any substance which alone, in chemical combination, or in formulation with one or more other substances, is an economic poison as defined by the FIFRA of 1947, as now or as hereinafter amended and which is used in the production, the storage, or the transportation of raw agricultural commodities." This definition through the use of the term *economic poison* related the Miller amendment to FIFRA.

The amendment established new procedures for obtaining tolerances. The HEW secretary was charged with establishing tolerances or maximum allowable limits of pesticides on raw agricultural commodities moving in interstate commerce. A raw agricultural commodity was defined as "any food in its raw or natural state including all fruits in a washed, colored, or otherwise treated state in their unspoiled form prior to marketing." This formalized the establishment of tolerances in the Federal Food and Drug Administration (FFDA) of HEW. The USDA had to certify to the FFDA that the chemical for which a petition for tolerance had been filed would be useful for the purposes described. The USDA had to express an opinion as to whether the tolerance requested reasonably reflected the residues likely to remain on the crop when the pesticide was used as directed. This change assigned agricultural functions to the USDA, an agricultural agency, and health functions to the FFDA under HEW, a health agency. Tolerances were obtained from FFDA and use clearance from USDA. Prior to filing a tolerance petition, the chemical must have been registered under the FIFRA. All registration functions are now handled by the Environmental Protection Agency (EPA).

The 1968 Color Additive Amendment subjected all color additives to the provisions for food additives, and the 1964 Seed Coloring Amendment subjected all seed colorings to the provisions for food additives. The most controversial amendment to the Federal Food and Drug Control Act (FFDCA) was the so-called Delaney Cancer Clause included with the 1958 food additive amendment. Widely and hotly debated, it stated that "no additive is deemed safe if found to induce cancer when ingested by man or animal or if it is found after tests which are found appropriate for the evaluation of the safety of food additives to induce cancer in man or animals." Much of the controversy concerning the use and misuse of pesticide chemicals has centered on the Delaney Cancer Clause. It prohibited setting of a tolerance in a processed food, although tolerances could be set in raw agricultural commodities. It is important to note that it says nothing at all about dose, nor does it mention a particular length of time within which cancer must be induced. It applies only to processed food, not raw agricultural commodities. After years of debate many (but not all) were pleased when the 38-year-old Delaney clause was removed in the 1996 Food Quality Protection Act (FQPA) signed into law by President Clinton on August 3. Since the Delaney clause was enacted (1958), chemical analytical technology has progressed so that it is now possible to routinely detect parts per billion (ppb) or trillion (ppt) amounts that are well below what could be detected in 1958 and pose no known human health hazard. The standard of reasonable certainty is now defined, in part, as “no more than a one in one million chance of getting cancer after a lifetime of exposure.” Replacement of Delaney standards with new health-based standards that do not distinguish between raw and processed agricultural commodities has not eliminated concern about health issues. The new standards may be just as tough or tougher than the old, widely discussed, standard.

The FQPA of 1996 included major changes to the FFDCA of 1938. EPA was required to consider children’s special sensitivity and exposure to pesticides, group compounds for tolerance with a common mechanism of action, consider cumulative exposure through contact with air, food, water, and other routes of exposure, and to reevaluate all existing tolerances within 10 years (ending in August 2006). The FQPA mandated testing for endocrine disruptors, compounds that block or mimic the effects of human hormones, such as estrogen (see Colburn et al., 1996). Tolerances for many pesticides are expected to be lowered, and some uses may be eliminated.

IV. THE ENVIRONMENTAL PROTECTION AGENCY (EPA)

In December 1970, the Environmental Protection Agency was created when the entire pesticide regulations division of the USDA and somewhat later, the pesticide office of the FFDA came to the EPA Office of Pesticides Program (OPP). This office contained the pesticides registration and enforcement divisions. There were five sections in the pesticides regulation division: efficacy, chemistry, human safety, fish and wildlife safety, and registration. The first four conducted scientific reviews prior to registration.

The pesticides enforcement division had a petitions control branch that reviewed chemistry and toxicology. In addition, they had the following groups: inspection services and imports, case review and development, control officer and prosecutions, and field enforcement staff. EPA pledged to Congress in 1993 that it would do all it could to significantly reduce pesticide use in the United States. It has worked to fulfill that pledge.

V. FEDERAL ENVIRONMENTAL PESTICIDE CONTROL ACT

On October 21, 1972, President Nixon signed into law the Federal Environmental Pesticide Control Act (FEPCA). This law made many changes as amendments to the FIFRA of 1947, which is still the primary law. The new law was designed to protect man and the environment and extended federal regulation to all pesticides, including those manufactured and used within a state.

Responsibility for use and misuse was now lodged with the pesticide applicator. In addition, no pesticide could be registered or sold unless its labeling was designed to prevent injury to man and any unreasonable effects on the environment. Future label evaluation by EPA had to consider the public interest, including benefits from pesticide use. However, under the 1947 FIFRA, ultimate responsibility for pesticide use and misuse was borne by the manufacturer who prepared the label. Under FEPCA, the amended FIFRA, manufacturers still had to establish safety and efficacy, but responsibility rests with the user if failure to follow label directions results in human or environmental harm. Violators could be prosecuted under civil or criminal law.

FIFRA required the registration of pesticides moving in interstate commerce. The amended FIFRA required registration of all pesticides regardless of their point of manufacture or use. All registered pesticides were classified for restricted or general use. General use or unclassified pesticides can be purchased and used by anyone who, it is assumed, will follow label directions. The restricted category includes all pesticides that demonstrate the potential for harm to human health or the environment even when used according to the label. The restricted classification must appear on the front label of the pesticide package. The FEPCA requires certification of commercial applicators that involves demonstration, on a written examination, of a minimum level of knowledge and competence about pesticides. A commercial applicator is one who may use or supervise the use of restricted use pesticides (RUPs). Private applicators are certified by participation in approved training programs. Most states also require a written test. A private applicator is a certified applicator who uses or supervises use of restricted use pesticides for purposes of producing any agricultural commodity on property owned or rented by the individual or an employer or on property of another person (if such application is without compensation other than trading personal services).

The FEPCA strengthened EPA enforcement procedures. All pesticide producing establishments had to be registered, and regular reports of sales and production were required. A pesticide's registration can also be revoked by EPA. Under the amended FIFRA, nonessentiality is not a sufficient reason to deny registration. This means that if one pesticide is already available for a specific use, registration cannot be denied to a new product. States may impose more stringent pesticide regulations than the amended FIFRA. In the past, some states had no pesticide laws, but the FEPCA required all to have them or federal regulations automatically applied.

EPA can cancel registration after five years even when continued use is requested by the manufacturer. EPA also has the power to reclassify, suspend, or cancel a pesticide if it causes unreasonable adverse effects on the environment when used as directed. Unreasonable adverse effects include any unreasonable risk to humans or the environment. The decision must be based on the economic, social, and environmental costs and benefits of pesticide use. If a use (or all uses) of a pesticide is suspended (it is taken off the market) and later canceled, the law provides indemnities to the manufacturer and other owners. Such indemnities are designed to protect the manufacturer that has met all legal requirements and may suffer large monetary losses when new knowledge demonstrates that continued use of the product may be hazardous.

The most recent change in federal legislation is the Pesticide Registration Improvement Act (PRIA) of 2004. The Consolidated Appropriations Act of 2004 established a new pesticide registration system. (PRIA is now Section 33 of FIFRA.) It created a registration service fee for applicants and established new tolerances for maximum residue levels in food and feed. EPA now has three registrations divisions: conventional chemical pesticides, biopesticides, and antimicrobial pesticides.

VI. PROCEDURAL SUMMARY

The 1988 FIFRA amendments focused on ensuring that previously registered pesticides met current scientific and regulatory standards. The procedure for pesticide registration can be summarized in two statements. First, the manufacturer must file with the Office of Pesticide Programs, Pesticides Registration Division (PRD) of the EPA for registration of a pesticide. The EPA has a total of 90 days segmented into two 45-day periods to determine the completeness of the application (first 45-day period) and the usefulness of the compound as requested on the label and to comment on the data. Second, the manufacturer must file with the Hazard Evaluation Division of the EPA for a tolerance or for an exemption from tolerance. EPA has 90 days to render an opinion on this petition. They can recommend a tolerance exemption, a petition withdrawal, a petition amendment, or a petition rejection. After the Hazard Evaluation Division has granted a tolerance, the Registration Division may register the label. In practice, these deadlines are often extended due to requests for additional information or submission of inadequate data.

Petitions must be supported by prescribed information including the identity and composition of the pesticide chemical, appropriate methods of analysis, complete information on proposed uses, full reports of investigations made on residues produced, and toxicity information. During preregistration, all other involved federal agencies can express an opinion regarding the use and registration of a pesticide. These agencies include the Forest Service, the US Department of the Interior, the Bureau of Land Management, and other conservation and wildlife interests (including private interests). These organizations cannot accept or reject a chemical, but their opinions are of great value to decision makers. Other federal agencies are involved in pesticide use but not in registration. They include the National Research Council that promulgates information on safe pesticide use, the Occupational Safety and Health Administration that protects workers who handle pesticides, and the Federal Aviation Administration that regulates aspects of safety for aerial pesticide application.

A certificate of usefulness may or may not be issued. If it is denied, the pesticide will not be registered and approved for use. If it is issued, the Tolerance Division has 90 days to act on a petition for tolerance and issue residue regulations in the Federal Register. If a tolerance is not established, the pesticide may fail to be registered. It is possible to obtain either without the other, but both are necessary for registration.

Under existing federal law, the EPA will register a pesticide only when the following criteria are met (Harrison and Loux, 1995):

1. The pesticide's composition must warrant the claims proposed by the registrant.
2. The proposed label must conform to FIFRA requirements.
3. The pesticide must perform its intended function without unreasonable adverse environmental effects.
4. The pesticide must not cause unreasonable adverse environmental effects when used in accordance with accepted practices.

In each case, the burden of proof is on the manufacturer (registrant). The EPA may waive the requirement to prove efficacy on the assumption that manufacturers will not be so foolish as to risk their reputation by marketing a product that does not do what they claim it will do.

A manufacturer may apply to EPA for an experimental use permit (EUP) before a pesticide is granted full registration. Such permits are usually granted for one year, and crops may be used or destroyed as determined by EPA when the permit is granted. EUPs permit the manufacturer to sell the product while gathering performance information under field conditions to support full registration.

Section 18 of FIFRA permits EPA to authorize use of a pesticide before full registration if an emergency condition can be established. Permits are granted only when the weed (or other pest) problem is urgent and nonroutine and no other registered pesticides will provide effective control and no other control measures are economically or environmentally feasible (Harrison and Loux, 1995).

A final procedural matter relates to the ability of states to regulate the sale or use of a federally registered pesticide under Section 24c of FIFRA. State regulatory agencies may register a federally approved active ingredient or product for a special local need that is not part of the EPA approved label.

VII. TOLERANCE CLASSES

All pesticides fall into one of four tolerance classes.

A. Exempt

Some pesticides are exempt because there is no known human or animal health concern. They are generally recognized as safe (GRAS) under Section 25b of the FIFRA and do not require a tolerance. A partial list of products in Section 25b includes castor oil, cinnamon, corn gluten meal, corn oil, cottonseed oil, lemongrass oil, linseed oil, mint oil, peppermint oil, potassium sorbate, sodium chloride, soybean oil, and white pepper. There are other exempted products.

B. Zero

If, because of toxicological characteristics, the PRD of EPA decides it is not in the public interest to accept any detectable residue of a given chemical, it can establish a zero tolerance that means none of the chemical is permitted in any crop. It is not possible to register a pesticide with a zero tolerance for use on food crops. This is a regulatory position and applies to pesticides even when no manufacturer ever applied for a tolerance. Zero tolerance used to mean that when used according to label directions, no detectable residue would remain. However, more sensitive methods of detection invalidated the concept. Today, no one knows what level will not be detectable tomorrow. Parts per trillion are not uncommon and smaller amounts can be found. As of 1966, a finite tolerance must be established, but zero can still be used. EPA applies the zero tolerance to pesticides but then refuses to register the pesticide for use on food crops.

C. Finite

A finite tolerance is used when chemical residues are known to exist. It is the tolerance under which most pesticides are registered. Any raw agricultural commodity moving in interstate commerce and found to have pesticide residues over the stated amount is subject to seizure by the FFDA. Before a finite tolerance can be obtained, two-year feeding studies on at least two species of mammals (usually rats and dogs) are used to establish no-effect levels.

D. Nonfood Crop Registration

When a pesticide is applied to soil many days before planting and has been proven to decompose or metabolize rapidly into natural substances, or if it is used in a way that presents no possibility of its remaining at harvest, it may be considered as a nonfood crop use. Such a chemical can then be registered without establishing a finite tolerance. Herbicides in this group could be applied to parking lots, but there could be reentry restrictions. Under this registration, range and pasture are considered food crops even though they are not consumed directly by humans because cattle or sheep are consumed by humans. Seed treatments have often been put in this group, as have applications of pesticides to dormant crops when the pesticide is known to disappear rapidly. Persistent compounds, on the other hand, require an established tolerance even if applied preplant or during the dormant season.

No residue registration was eliminated for pesticides in 1970. The concept was that if no residue could be detected with the best analytical method available at the time, a compound could be registered under the no-residue provision. The problem is that detection methods have improved so much that a compound that originally could not be detected by methods sensitive to a part per million can now be detected in parts per trillion or less. In 1967, no residue registrations were gradually converted, on petition of the manufacturer, to finite tolerances. If a manufacturer did not request a finite tolerance, the pesticide's uses were canceled.

VIII. THE PROCEDURES FOR PESTICIDE REGISTRATION

A complete registration petition contains a great deal of information necessary for full consideration of benefits and risks. At a minimum, the petition must contain:

A. A statement of active and inert ingredients in the product, chemical and physical properties of the compound in the formulation, the complete quantitative formula of the product, its environmental stability, and known impurities in the formulation.
B. Five copies of the proposed label, including the following information:
   1. Brand name
   2. Complete chemical name and physical and chemical properties
   3. Ingredients statement including samples of the chemical and its formulation(s)
   4. Directions for use, specifying crops or sites intended for treatment
   5. Amount(s) to be used
   6. Timing of application
   7. Any precautions or limitations on use
   8. Warning statement for protection of non-target species
   9. The antidote in case of human consumption
   10. Warning to keep out of reach of children
   11. Manufacturing details
   12. Net weight statement
   13. Restricted versus general use statement
C. Full description including the data of scientific tests used to determine effectiveness and safety.
D. Complete toxicity report of tests on lab animals, and the methods for obtaining the data. At a minimum, such tests must include items 1 to 11 following. Studies are often expanded to include data on oncogenicity, spermatogenicity, aspects of mutagenicity, and other risk related factors research may identify.
   1. Two-year rate feeding study to determine reproductive and carcinogenic effects
   2. Eighteen-month mouse feeding study to determine reproductive and carcinogenic effects
   3. Two-year dog feeding study
   4. Dominant lethal mutagenic possibilities in mice
   5. Teratogenic study in rabbits
   6. Three-generation rat reproduction study and reproduction studies in chickens
   7. Meat residue in cows, chickens, and swine; milk residue in cows; egg residue
   8. Ninety-day rate feeding study to determine mammalian metabolites
   9. Twenty-one-day subacute toxicity in rabbits, and oral and dermal LD_{50} in rats
   10. Eye and skin irritation
   11. Tests to determine effects on two species of fish and quail

E. Results of tests on the amount of residue remaining and the description of analytical methods. This is extremely critical for tolerances. Tolerances are set on the amount of residue remaining and not on the highest figure permissible from a health standpoint. EPA is interested in data that show the amount of residue on the crops and animals on which the pesticide will be used and in the soil (or other portion of the environment) that will be treated with the pesticide.
F. Practical methods for removing residues exceeding any proposed tolerance, including a description of the method.
G. Proposed tolerance for the pesticide and supporting reasons for the level requested.
H. Reasonable grounds in support of the petition including a summary of data in the entire petition and a summary of benefits when used in agriculture.

If there are no food residues and if no other residue exists, and if EPA's Pesticide Regulation Division (PRD) concludes that the pesticide is safe and conforms to the manufacturer's claims, then the Fish and Wildlife Service of the Department of the Interior and the Hazard Evaluation Division of EPA are notified of the intent to register. These agencies and others can concur or reject the petition. If they reject, a reevaluation must occur. When uses will result in residue at harvest of crops or slaughter of animals, registration is subject to the requirements of the Miller Amendment. In seeking to register such a compound, a petition proposing a tolerance or exemption must be submitted to EPA. It must provide information on the pesticide, its use, and reports of safety tests. The safety information must include results of animal susceptibility experiments, tests on residues, and the analytical methods employed, and practical methods for removing residues that exceed proposed tolerances. Table 18.1 summarizes the process.

The FIFRA, through its registration and enforcement features, provides the primary public protection against improperly labeled or adulterated pesticides. The law is also the primary effort to protect the health of users and consumers against potential adverse effects of pesticides. At the present time, there are 20,000 to 25,000 products made from one or more of 600 pesticidal chemicals. The Pesticides Registration Division of EPA:

1. certifies the chemical is useful for the use for which the label is requested, and
2. expresses an opinion as to whether the tolerance requested reasonably reflects the residues likely to remain on the treated crop.

The burden of proof is always on the applicant. EPA's Pesticide Tolerances Division establishes tolerances or maximum allowable limits of pesticide resi-

TABLE 18.1. A Summary of the US Pesticide Registration Procedure.

Submission of complete petition to EPA + registration fee	
↓	↓
Pesticide Tolerance Div. of EPA, 10 months to review residue, toxicology, and set tolerance	Pesticide Registration Div. of EPA, 6 months allowed to issue certification of usefulness
⬂	⬃
Publication of tolerances	
↓	
Label review by PRD	
↓	
Necessary modifications	
↓	
Final registration	

dues in or on raw agricultural commodities in interstate commerce. The government's role does not necessarily stop at this point. EPA and State officials collect unregistered pesticides, look for misbranded or adulterated products, and can take legal action against offenders. The FDA also has a program to monitor the nation's food supply for pesticide residues and a program of environmental monitoring for pesticide residues. This program was established under the Federal Food, Drug, and Cosmetic Act (FFDCA) of 1938. Under this program, the FDA's pesticide program regularly samples US food products. The most recent food and drug administration pesticide residue monitoring program was reported in 2003 (http://cfsan.fda.gov/~dms/pes03rep.html). The program monitored 7,234 samples, 2,344 domestic samples with at least one from every state, and 4,890 imported. No violative residues were found in grains, grain products, milk or dairy products, eggs, or fish and shellfish. More vegetable samples were tested than any others, and only 1.9% of 1,132 samples had violative pesticide residues. No detectable pesticide residue was found in 64% of the samples. Of 813 fruit samples, 2.2% had violative residues. A violative residue is one that exceeded a tolerance or was a residue of regulatory significance for which no tolerance had been established in the sampled food. In 2003, no violative residues were found in 97.6% of all domestic fruit and vegetable samples tested, and 62.6% of samples had no detectable residues. No violative residues were found in 94% of all imported foods sampled by the FDA's monitoring program.

States, through their Department of Agriculture, Environmental Agency, or other designated body have the power to register and regulate the intrastate use of pesticides. States are allowed to register additional uses of federally registered pesticides for special local needs (FIFRA, Section 24c registrations). States cannot invoke any regulations that are less stringent than the amended FIFRA, but can impose additional requirements on the registrant. Pesticides formulated and distributed within a state must be registered by the Federal EPA. State registrations cannot be obtained if EPA has already denied FIFRA registration for a particular use.

THINGS TO THINK ABOUT

1. Why does a nation bother to register pesticides?
2. What federal agency governs pesticide registration in the United States?
3. What federal acts govern pesticide registration in the United States?
4. What does it mean when a pesticide is registered?
5. Why is the pesticide label important?
6. What is the significance of the Miller pesticide amendment to the FIFRA?
7. What things must a manufacturer prove to register a pesticide?
8. What are the tolerance classes under which a pesticide may be registered in the United States?
9. What information must be included with a petition for registration and who bears the responsibility for preparing the information?

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CHAPTER 19

WEED MANAGEMENT SYSTEMS

FUNDAMENTAL CONCEPTS

- A weed management system can be designed for any crop-weed situation, but more research must be done to integrate available weed control techniques into management systems.
- There are six logical steps that are fundamental to all complete weed management systems.

LEARNING OBJECTIVES

- To understand the logical steps that are part of complete weed management systems.
- To know how to combine weed management and control techniques into a weed management system.
- To understand the design and implementation of weed management systems for a few crops and cropping situations.
- To appreciate the increasing role of molecular biology in weed management systems.
- To understand the complexity and role of computer-based decision-aid models in weed management.

I. INTRODUCTION

Weed control, an old practice, is a process of reducing weed growth to an acceptable level. To date there is no a clear definition of *weed management*. It is an evolving concept. When defined, it will include the dictionary sense of the term: "taking charge of and directing" the growth of weeds. It will also include "handling carefully"—a rarer definition of management that includes the concept of husbandry—that is, to manage economically and conserve.

Weed management has been defined as "an environmentally sound system of farming using all available knowledge and tools to produce crops free of economically damaging, competitive vegetation" (Fischer et al., 1985). This definition lacks the specificity of an economic threshold, and its use of the words "free of" implicitly advocates no yield loss (i.e., no economic damage). It could be interpreted as advocating a high level of weed control because it mentions crops free of economically damaging, competitive vegetation.

Fryer (1985) defined *weed management* as the "rational deployment of all available technology to provide systematic management of weed problems in all situations." Unfortunately, there is no agreement on what is rational or systematic. It is also not good to include the word defined in the definition, as if everyone already knew what it meant.

Weed management will be a systematic approach to minimize weed effects and optimize land use, and it will combine prevention and control (Aldrich, 1984). It will emphasize minimizing the affect of weeds but probably not eliminating all in a field. Weeds will be accepted as a normal and manageable part of the agricultural community, albeit a part one must learn to fight and live with. The objective of effective weed management will be to manipulate the crop-weed relationship so that growth of the crop is favored over the weeds.

Integrated weed management will be what is known as integrated pest management, or IPM, with the focus on weeds. IPM is "a decision support system for the selection and use of pest control tactics singly or harmoniously coordinated into a management strategy, based on cost-benefit analyses that take into account the interests of and impacts on producers, society, and the environment" (Norris et al., 2003, p. 11).

When research has provided an adequate base for integrated weed management systems, they will include the following components:

1. Incorporation of ecological principles
2. Use of plant interference and crop-weed competition
3. Incorporation of economic and damage thresholds
4. Integration of several weed control techniques, including selective herbicides
5. Supervised weed management frequently by a professional weed manager employed to develop a program for each crop-weed situation

Systems will be designed to prevent or reduce the probability that weed problems will develop and to anticipate future, perhaps inevitable, new weeds that are likely to appear. Systems will be designed to manage weeds that, if ignored, will reduce yield. Ecological considerations will include natural weed mortality, inter- and intraspecific competition, crop plant density, and genetic manipulation. The latter may develop populations that are more susceptible to control techniques, such as tillage and herbicides. Successful weed management will also include precise timing of cultural practices such as tillage to maximize benefit and careful selection of rate and application time of herbicides. The latter things are done now.

Weed scientists will develop Integrated Weed Management Systems (IWMS) (Shaw, 1982) for crops *and* specific weeds or weed complexes in crops. These systems will demand integration of the whole agricultural system, not just its parts, and will consider three choices: maximum short-term yield, maximum sustainable yield, or maximum yield sustainability (minimum risk; Weiner, 1990). Maximum yield sustainability characterizes third-world agriculture—systems dominated by low, stable (barring environmental disasters such as floods or drought), long-term production. Weiner (1990) and Jackson (1984) suggest that choosing maximum short-term yield "requires high input costs, high environmental costs, and high nutrient and capital fluxes." Both authors advocate low input, low environmental cost, low nutrient, and low capital flux agricultural systems. They suggest that option 2 is the most desirable, but it is also the one most likely to produce systems that integrate the fewest inputs to achieve the desired result. Results will always be important. One measure of the results of a weed management system is how well it manages the problem in the year it is first used. Another essential measure of the success of any weed management system is whether or not it reduces the likelihood of future problems. A primary question is, will there be fewer seeds or vegetative propagules after the management system is imposed than before? If the answer is yes, it is probably a good system.

Weed management systems will reduce weed problems, not eliminate them. The goal may best be described as stabilization of populations at a low level through management techniques that are economically and environmentally sound.

This chapter illustrates some principles and available components of weed management systems. Each system is incomplete, partially because the research base is still developing. It is also partially due to the fact that few management systems will ever be fully complete and fixed for all time. Weed problems will evolve as they always have, and management systems must be dynamic. This chapter will not include or discuss every weed problem in every crop or cropping situation. It will describe weed problems in several general situations and illustrate the techniques that can be integrated in management systems. The chapter is not a weed control guide or how-to manual. A longer discussion of weed management systems is available (Smith, 1995). It is important to know that weed management systems neither stand alone nor are imposed in isolation. They are part of agriculture and landscape management. Each must mesh with soil conditions, tillage practices, economic and political realities, and social and other aspects of plant culture. The principles developed in this chapter should be applied and adapted to weed management situations important in a region.

II. A METAPHOR FOR WEED MANAGEMENT

The necessity for weed management occurs when a place, a field, is selected for planting. The history of the place is important as a weed management system is developed. Past cropping sequences and weed control methods reveal the kinds of weeds to be expected. The way in which the soil and seedbed have been prepared will be important. Plowing the field exposes a different population of weed seed than disking or chiseling. The kind and timing of irrigation influence weed species. If the land has been observed carefully and edges, ditches, and fences have been kept clean of new sources of weed infestation, the weeds present will be different than if field sanitation has never been practiced. Past and present insect and disease management must be integrated with weed management and they influence each other. Many crop growers do all or some of these things, but few pay attention to their effects on the weed problem or the weed management program. More research is needed to determine specific effects of each necessary management practice on weeds.

Weed management systems can be compared to a carpenter's toolbox. A good carpenter's toolbox contains a large assortment of tools, many of which the noncarpenter doesn't know the purpose of. Almost everybody recognizes and knows something about the use of a hammer, a screwdriver, or a tape measure, but there are other tools whose purpose is a mystery to those who don't often use them. Many people would be pleased to have the toolbox of a good carpenter and would quickly use several tools. Other tools would be used later as knowledge developed or after someone explained their purpose and how to use them. Still other tools might remain interesting but unused. The purpose and use of some tools will be obvious. Others will look familiar but their use won't be obvious. There will probably be many with no clear purpose and one may even wonder who decided they should be in the box.

Like the carpenter's toolbox, there are some features common to all weed management systems that almost of us know how to use. Each weed management toolbox should have three compartments: weed prevention, weed control, and weed eradication. The prevention compartment will have the tools used to keep a weed species from occurring in a previously uninfested area. The compartment labeled *control* will be the largest, and many tools that belong there will also be found in one of the other compartments. Control tools are things used to reduce the weed population. The *eradication* compartment is the smallest one, or if not the smallest, the least used. The tools in it are not more complex than others, but they require great persistence and just don't seem to work as well as others do. They are designed for complete removal of a weed species and its propagules from an area.

Dewey et al. (1995) proposed that noxious weed management could be regarded as forest managers think of wildfire management. The area of range and forest land infested with noxious weeds grew from 2.5 million acres in 1985 to 8.4 million in 1994 and was projected to grow to 10 million in 2000. Dewey et al. (1995) regard weeds as a raging biological wildfire. All aspects of wildfire and weed management are similar except two. The first dissimilarity is that wildfires spread more rapidly than weeds do, even though their patterns of spread are similar. The second, more important, difference is that forest managers never fail to see a wildfire. Fires cannot be ignored, but weeds can. Weeds don't obviously destroy things, and because the occupied area increases slowly, they can be, and often are, ignored until they dominate large areas. Only then do people cry, "Why didn't someone do something?" It is too late then for other than expensive, time-consuming, and potentially environmentally harmful attempts to control. Action needs to be taken when fires and weeds begin. The next section describes the logical steps for developing a weed management system to take the necessary action.

III. THE LOGICAL STEPS OF WEED MANAGEMENT

Most toolboxes and good tools come with a set of instructions on purpose and use. Weed management tools also come with instructions. Presently, instructions are general but they will improve and become more specific as knowledge expands. At a minimum the instructions for weed management systems for nearly all areas and all cropping systems will include seven logical steps.[1]

A. Prevention

The first, most obvious, and perhaps the most frequently omitted step is prevention. Weeds that don't appear because clean seed is planted, machines are cleaned, and new cattle are separated (see Chapter 10, section II) don't have to be controlled. Early detection is part of weed prevention. Detecting a new weed does not prevent its arrival but quick action can prevent its spread.

[1]I am indebted to Dr. K. G. Beck, Professor of Weed Science, Dept. of Bioagricultural Sciences and Pest Management, Colorado State Univ. for the insights of these management steps.

Preventive action can be as simple as bending over and pulling the weed and removing it from the site.

B. Mapping

An accurate map of weed infestations should be made before a good management program can commence. Problems must be defined, by species, and located in the field or area to be managed before solutions are proposed. No one wants their physician to treat unspecified, unknown illnesses. An accurate medical diagnosis is expected before treatment. Weed management must be as careful. The best weed management systems will be designed to control specific weeds in specific places.

It is presently not technically feasible to map every weed. Major weed species should be known, and those species likely to become problems (e.g., parasitic weeds, perennials, hard to control annuals) should be located and the size of the infestation defined. Early detection of new weeds is part of mapping and prevention.

Weed scientists agree that weeds rarely, if ever, exist in a uniform density over a whole field. They exist in patches. In other words, weed populations have a spatial biology that must be defined for development of integrated management systems. The fact of variable spatial distribution has been neglected because available weed control technology prescribes uniform cultivation or broadcast herbicides on entire fields. Farmers and land managers know that fields and their weed populations are heterogeneous. Heterogeneity has increased as fields have grown larger and monoculture has increased (Mortensen et al., 1998). There is adequate justification for what Maxwell and Luschei (2005) call "site-specific weed management": "There is no need to attempt to control weeds where they are not present in crop production fields." Limiting weed control efforts to places where weeds are reduces the environmental effects of weed control techniques, saves money for weed managers, but may increase risk for growers who choose to manage conservatively for mean field conditions (Mortensen et al., 1998).

C. Prioritization

Money, time, technology, or labor are often lacking. It is not possible to do everything. The best weed managers will know as much as possible about the weed problems and select those to be managed. The species that pose the greatest threat to present or future land use should receive highest priority.

D. Development of an Integrated Weed Management System

When it is determined that management is necessary, one begins to look closely at the array of tools in the box to see what is available and if a particular tool or set of tools will be most effective for the weeds to be managed. The best weed management systems will not select a single technique. All appropriate tools will be examined, and an integrated approach including two or more tools or strategies will be selected. The ideal IWM system will employ what Liebman and Gallandt (1997) called “many little hammers” rather than a single hammer, no matter how effective it may be. Integration will consider cultural methods such as grazing management, fertility, irrigation practices, seeding rate, and use of competitive cultivars. Mechanical methods include tillage before and during the crop’s growth, mowing, burning, flooding, and mulching. Biological and chemical control will also be considered, but their use will shift from a “yes, provided that” to a “no, unless” attitude (Mortensen et al., 2000). All of these methods will be in the weed management toolbox. Some tools will be more numerous, more apparent, or easier to grab and are used more frequently. For several years, herbicides have been the method of choice in many situations. Other tools always seem to wind up on the bottom of the box and aren’t selected often. This could be because they are not as easy to use or because the knowledge of how to use them is not available. For example, soil fertility influences weeds and should be considered in weed management. The knowledge of how to manipulate fertility to complement weed management is not abundant. Figure 19.1 is a conceptual model of weed management systems. It is a glimpse into the weed management toolbox. After completing the preliminary steps shown in Figure 19.1, control options are selected to develop a system to manage weeds. When the methods are selected, weed managers must ask what *can* be done (a scientific question) and what *should* be done (a moral question). Some things that are scientifically possible may not be socially, culturally, politically, or environmentally desirable. For example, intensive tillage might increase soil erosion, or intensive herbicide use might pollute water or harm nontarget species. The best weed management systems will be integrated with other aspects of crop management (e.g., insect or disease control, fertility of the crop), the environment, and the area or field in which weeds are to be managed.

Integrated weed management systems supported by extensive research are now available for many cropping systems, but they are not widely used by growers (Norris, 1992). Perhaps the most important reason for lack of use is the difference between the goals and needs of agricultural researchers and those of producers (Norris, 1992). Producers want as much certainty of yield and profit as possible at reasonable cost in the current year. Researchers have

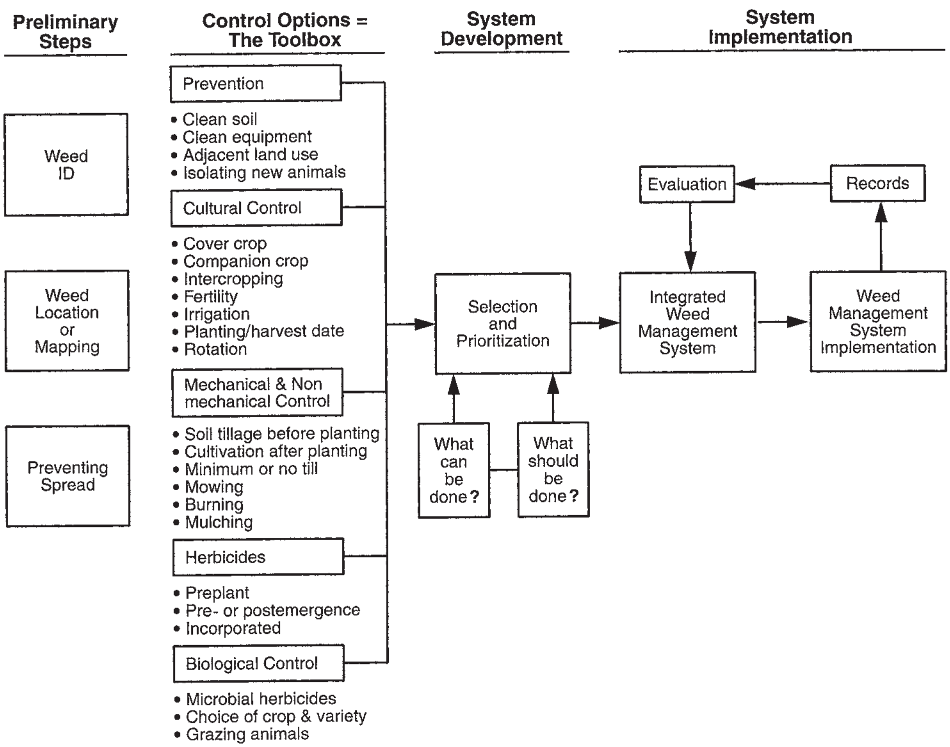

FIGURE 19.1. A conceptual model of a weed management system: the weed management toolbox. (Source unknown)

become more concerned about ecological effects of control techniques and long-term effects. A grower, quite understandably, needs to know what will solve the weed problem that exists or is anticipated in a year. What techniques can be combined to solve the problem and thereby optimize yield and maximize profit?

Weed control research, in recognition of the grower's need, has emphasized herbicide development and considered combinations with mechanical control (tillage), weed-crop competition, competitive cultivars, biological control, and, on occasion, allelopathic cover crops (Wyse, 1992). These aspects of control science and technology are necessary parts of integrated weed management systems, but they are not a sufficient base for system development. They must be combined with what Wyse (1992) calls the "principles-based research." Development of these principles demands a shift from weed control in a crop to a total systems approach to crop protection. Such an approach will begin to solve the "escalating economic and environmental consequences of combating agricultural pests" (Lewis et al., 1997). Weed control has been dominated by the search for "silver bullet" products to control weeds (Lewis et al., 1997; Mortensen et al., 2000). Such therapeutic interventions have been effective short-term (a crop year) techniques. Long-term control will be achieved by changing the approach to weed control to take advantage of natural preventive strengths (Lewis et al., 1997). Short-term therapies are not abandoned. They become supplements rather than primary defenses. The attitude is the "no unless" view expressed above. Some tools are not used unless they are the only alternative (Mortensen et al., 2000). The natural preventive strategies for weed management emphasize development of diverse systems that are biologically robust (Van Acker et al., 2001) that are "inherently less susceptible to weed invasion, proliferation and interference." The required data on "weed demographics and competition" include studies of (Buhler, 2001, modified from Wyse, 1992):

Seed and bud dormancy mechanisms
Seed germination, development, and production
Seed banks and emergence dynamics
Population genetics
Population shifts
Spatial distributions
Modeling of weed-crop systems
Weed-crop interaction studies

These kinds of studies will serve as the necessary foundation for development of weed control technologies that will reduce soil erosion and surface and groundwater chemical contamination, while maintaining an acceptable level of weed control (Wyse, 1992). The essence of these recommendations is that understanding the organism's biology and ecology is required before it can be controlled well with minimal or no undesirable environmental or social effects. Integrated weed management systems cannot be separate components of crop production. They must be regarded as part of the design of integrated cropping systems. Prevention rather than control becomes the key objective (Mortensen et al., 2000).

E. Implementation of Systematic Management

With a map that shows where the weeds are and an integrated crop management plan, managers can begin an integrated weed management program. Not everything has to be accomplished in one season or with one technique. Such plans will necessarily be crop, place, and possibly weed specific. The program will be systematic in that timely, planned management will be done over several seasons. The manager may decide to begin with control of perimeter weed infestations to prevent their spread and eliminate sources of future problems, unless those weeds are identified as hosts of beneficial insects that prey on harmful insects.

Another approach could be spot-treatment of developing parasitic or perennial weed infestations. Based on available techniques, their cost, environmental acceptability, and adaptability to the situation, the manager can choose among several courses of action (Dewey et al., 1995). If an infestation is small but the weed is very aggressive and likely to spread quickly, attempts to eradicate are often the best choice. A weed could be a serious threat but not easy to control. In this case it could be contained or confined with other tools to be employed when the weed threatens a crop. In some cases managers should opt to do nothing except monitor the weed regularly and evaluate management options.

F. Record Keeping and Evaluation

Records of what was done and its success must be kept (Figure 19.1). Good records allow the manager to repeat successes and learn from mistakes. Evaluation should be continuous and not just a week or month after control was done. Evaluation over two or three years is required to measure success and to observe what did *not* work well. For example, students are required to write final examinations at the end of classes. A better measure of learning (although one that would not be popular with students) might be an examination three to five years after completing a class. Such an examination would measure knowledge retention. It is the same with a weed management program. Success over time is more important than success in the short run. It is a bad mistake to develop a system and assume it works but to avoid doing regular evaluation (go out and look) to verify the system's success.

G. Persistence

Modern weed control has been available for several decades, but in spite of the successes that have been achieved, weeds are still a predictable threat in cropped fields and in many other places (Buhler, 2001). One should not assume that the weeds have won, only that they have adapted rapidly. Resistance to herbicides and weed population shifts are continuing challenges. Successful weed management is rarely achieved after application of one control technique in one season. Integration of techniques based on basic biological and ecological knowledge is required. The soil seed bank and new sources of infestation demand continued attention. Vigilance is the price of success. Weed management is not a one step (one control) process. Methods must be integrated over time to reduce or eradicate some weeds (e.g., parasitic weeds) and manage other populations to reduce yield loss and crop injury.

IV. WEED MANAGEMENT PRINCIPLES IN SIX SYSTEMS

There are as many weed management systems as there are cropping systems and weed complexes. The number of systems may equal the number of weed managers. Each manager puts unique touches on any system but each system shares some general characteristics. The feature that all systems share is integration of methods, which has led weed scientists to develop integrated weed management systems (IWMS). Not all systems include all possible methods of weed control, but all include, or at least recommend, consideration of all methods appropriate to the cropping system and the environment in which weeds are to be managed. Weed management systems have been reviewed (Smith, 1995). The review includes weed management systems for oil seed crops (Wilcut et al., 1995), grain crops (Donald and Eastin, 1995; also see Donald, 1990), pastures and hay crops (Smith and Martin, 1995), rangeland (Bovey, 1995), horticultural crops (Smeda and Weston, 1995, turfgrass (Bingham et al., 1995), and forest nurseries and woodland (McNabb et al., 1995).

Most weed management systems are based on herbicides as the primary control technique. This is primarily because herbicides work well, which is especially true if externalities are not considered.[2] Herbicides are generally reliable in that they do what they are advertised to do, they are selective, and relative to other methods they are not expensive. Recent thought about IWMS emphasizes two approaches (Mortensen et al., 2000). The first, often called the curative approach, emphasizes use of better application technology, improved application timing, site selective application (apply only where weeds are), lower doses, and use of herbicides with reduced or minimal environmental effects. However, herbicides are the primary tool. The second

[2]An externality is a cost that is not reflected in price or, more technically, a cost or benefit for which no market mechanism exists. In the accounting sense, it is a cost that a firm (a decision maker) does not have to bear or a benefit that cannot be captured. From a self-interested view, an externality is a secondary cost or benefit that does not affect the decision maker.

approach has reduced dependence on herbicides as its primary goal. The goal is not to control weeds but to prevent their appearance through development of integrated cropping systems. These systems emphasize techniques that reduce the fitness of weeds and kill or reduce their numbers through crop competition, rotation, planting time, companion cropping, mulches, and so on. When a weed's biology and ecology are understood, that knowledge can be used to manipulate crop-weed interactions to the benefit of the crop. The latter approach is taken by a review of ecological approaches to weed management (Altieri and Liebman, 1988).

The systems described herein should be thought of as generic management systems. It is assumed that weed identification, mapping, preventive measures, record keeping, and evaluation are part of each system. How these things are done differs with each system. Several research programs are now investigating studying methods to determine the easiest, most efficient, and cost effective way to sample an area to determine what weeds are present and where they are. The following examples focus on identifying components of integrated weed management systems. The examples are not complete, readily adaptable, prescriptive systems. They are intended to be a basis for discussion of such systems and their use and further development. Several weed management systems are covered well in Smith (1995), including those for oil seed crops (Wilcut et al., 1995) and pasture and hay crops (Smith and Martin, 1995), which are not included herein.

A. Small Grain Crops

Weed management systems for small grains, including winter and spring wheat, barley, oat, sorghum, and rice were reviewed by Donald (1990) and by Donald and Eastin (1995).

Prevention

Preventive strategies, the first phase of weed management in small grain crops, including wheat, oats, barley, and rye, are not complex; they are the basis of good farming practices. The first preventive step is identical for all crops and cropping systems: plant weed-free seed.

Custom combines and other itinerant machines are sources of weed seed and should be cleaned before leaving a farm and before moving from an area of known contamination to a weed-free area. Competitive weeds on field edges and roadsides should be managed because they are sources of new field infestations. Trucks or wagons used to transport grain should be covered to prevent wind dissemination of weed seed from uncleaned grain.

An ecological (integrated) approach to weed management in winter wheat developed by Anderson (2005) emphasizes prevention and aims to reduce herbicide use. The second approach suggested by Mortensen et al. (2000) includes three primary goals: enhancing natural seed loss through leaving weed seeds on the soil surface where viability loss is enhanced, reducing weed seedling establishment, and minimizing seed production by established weeds. Combining these goals mean growers may have to change the way crops are grown. Crop rotation, crop sequencing (fall and summer planting), and crop residue management may have to be changed and competitive crops will have to be included (Anderson, 1994, 2003).

Mechanical Methods

When preparing land for small grains, there is a wide choice of techniques. Traditionally, soil was plowed but that is dependent on prevailing weather, implements available, and grower preference. Preplant tillage ranges from plowing 8–16 inches deep, disking or field cultivating up to 6 inches deep, surface tillage 1–3 inches deep, or no tillage and direct planting. Each of these practices and their timing affect the type, presence, and abundance of weeds. No cultivation and a shallow, noninverting cultivation increase the incidence of perennial weeds and decrease annuals (especially broadleaved species). It is important to understand that soil tillage controls some weeds and creates an environment in which others flourish.

No tillage tends to increase the incidence of annual grass weeds such as wild oats, annual brome grasses, annual bluegrass, common rye, and jointed goatgrass. Plowing and disking help prevent spread of perennials but neither alone will control Canada thistle or field bindweed effectively. Plowing is 10 to 20% more effective than shallow cultivation or disking for control of perennials, but it returns previously buried roots and rhizomes to the surface, where, if they are not desiccated rapidly, they will produce new plants. After plowing or without plowing, early cultivation of land to be planted to small grains stimulates germination of seeds of annual weeds. The seedlings can be controlled by subsequent cultivation.

Cultivation of stubble in fields from which a small grain has been harvested can aid control of perennial grasses and prevent some annual weeds from producing seed. If stubble cultivation is done at the wrong time or with weeds that survive cultivation, the weed problem can worsen. For example, stubble cultivation soon after harvest could bury wild oats seed and reduce loss through natural causes (e.g., cold weather). Seedlings of winter annuals such as downy brome, easily survive shallow, noninverting tillage and partial burial.

Fallow (no-crop) or fallow combined with tillage is an effective weed management technique. Seedlings can be eliminated with cultivation. More than one cultivation may be required to control most emerged seedlings. No-till systems have enabled wheat producers in the semi-arid US central Great Plains to change the rotation from endless wheat-fallow to one that includes a spring-planted or warm-season crop (Anderson, 2005).

Cultural

For many reasons, farmers want to plant early, and the date of sowing affects weed management. The earlier a crop is planted, the less time is available for weeding of any kind before planting, which may increase the chance that weeds will germinate and grow with the crop. Seeding winter wheat at a higher rate reduces competitiveness of blackgrass and wild oats. Increasing crop density by using a higher seeding rate (see O'Donovan et al., 2006) or by narrowing row width tends to increase competitiveness of wheat and other cereals against spring grass weeds.

Delaying winter wheat planting until emerged weeds can be killed by a light tillage is an effective, inexpensive weed management technique. On the other hand, a quickly emerging, vigorous, dense crop stand is also an important weed management technique. For example, early planting of spring grains may allow crop development before foxtails germinate. Small grains are normally planted in 7-inch rows with adequate rain or irrigation and in about 14-inch rows on dry land. This accepted agronomic practice is usually not changed for weed management reasons even though row width and subsequent crop density affect weeds and their control.

Correct seed bed preparation for the soil and cultural system, cultivar selection; use of high-quality, clean seed; and careful attention to optimum fertility to produce rapid emergence of vigorous crop plants contribute to weed management. Many farmers save seed of small grains from year to year to save money. With no or poor cleaning of saved seed, weed seed can be planted (see Chapter 5).

As Italian ryegrass density increased, wheat yield decreased and semidwarf cultivars had lower yield than tall cultivars with the same density of Italian ryegrass (Appleby et al., 1976; Table 19.1). In Canada, green foxtail was more competitive in semidwarf than in tall spring wheat cultivars (Blackshaw et al., 1981). These data point out the importance of cultivar selection, crop canopy development, and crop competitiveness. Semidwarf cultivars have a more open crop canopy, permit more light to reach weeds, and allow Italian ryegrass to be more competitive. Cultivars are not often chosen for weed management, but their influence should not be ignored. Unfortunately, the basis for cultivar

TABLE 19.1. Yield of Four Wheat Cultivars Grown with Three Densities of Italian Ryegrass (Appleby et al., 1976).

Cultivar height	Ryegrass plants plants/sq yd	Wheat yield lb/A
Tall	0	3,096
	33.4	2,520
	82.8	2,232
Tall	0	3,924
	33.4	2,925
	89.4	2,709
Semidwarf	0	3,042
	32.6	2,214
	80.3	1,908
Semidwarf	0	3,465
	36.8	2,565
	82.8	2,115
LSD @ P = 0.05		423

competitiveness is too poorly understood, and it is a tool that cannot yet be used in weed management systems.

Crop rotation breaks a weed's life cycle by altering the crop it must associate with. It demands use of weed management techniques adapted to different crops. Rotation to another crop effectively manages winter annual grasses in winter grains or summer annual grasses in spring grains. Each crop has its own set of cultural practices that create habitats for certain weeds. Changing crops changes available habitats and weeds.

Fallow weed management must be done in winter wheat-fallow systems. Weeds such as downy brome, jointed goatgrass, and rye use moisture during fallow and the seed produced easily infests the next wheat crop. Their life cycles are similar to winter wheat, so inclusion of a spring crop (e.g., barley or corn) is a useful weed management technique. The spring crop may permit use of herbicides that cannot be used in winter wheat. Adding summer annual crops to a winter wheat-fallow rotation lengthens the time before the next wheat crop, reduces the annual weed problem, and increases weed seed mortality. To reduce the need for herbicides to control weeds during fallow, some producers are testing growing legumes such as dry pea or lentil for only six to eight weeks during fallow to suppress weed growth in spring (Anderson, 2005). After six to eight weeks legume growth is stopped by application of glyphosate. The goal is to gain nitrogen from the legume, reduce the need for another glyphosate application, and reduce the noncrop interval before winter wheat planting and thus the period for weed growth (Anderson, 2005).

Precise fertilizer placement is a regular practice in row crops but not in small grains, where it may have potential as a weed management practice. Placing nitrogen fertilizer in the crop seed row, away from weeds, achieved a small reduction in seed production of rye and jointed goatgrass. Greater reduction was obtained when fertilizer placement was integrated with an increased wheat seeding rate and a taller, more competitive cultivar (Anderson, 1994, 2003). In a barley-field pea-barley-field pea rotation in Alberta, Canada, fertilizer application timing had little effect on weed competition in barley, but spring compared to fall fertilizer application increased yield of field pea in two of four years (Blackshaw et al., 2005).

Biological

There are few biological weed control techniques available for use in small grains. Use of an endemic anthracnose disease to control Northern jointvetch in rice is one example (see Chapter 11). If developed, these agents will have to be integrated with other weed management techniques.

Chemical

Herbicides used in small grains are generally safe, efficient, and profitable, but like other methods, when used alone, they do not solve all weed problems. Herbicides must be regarded as one of the little hammers (Liebman and Gallandt, 1997) in an integrated weed management program. For maximum effectiveness, herbicides should be applied when weeds are young and have not yet affected crop yield.

Information on proper application of any herbicide is critical to successful use. Always read and follow label directions. If herbicides are mixed, follow label directions. Combining herbicides with different actions and activity can improve the weed control spectrum. When mixed, the rate of one or both herbicides may be reduced.

For the many weed problems in small grains, there are herbicides or herbicide combinations that provide good control and crop safety if they are properly applied at the right time and rate. Manufacturers determine rates that work across many environments and climatic conditions. These may not apply to all fields. Reduced rates may work well in some conditions, but local recommendations should always be sought and followed.

Most postemergence, foliar absorbed herbicides require actively growing weeds for maximum effectiveness. Weed growth is reduced by cool temperatures and drought. Herbicides with soil activity are less affected by temperature, but their activity is reduced in dry soil. A key to successful weed control with herbicides is early use when weeds are most susceptible.

Managers should know what weed is to be controlled before selecting an herbicide. The herbicide should be applied uniformly with a properly calibrated sprayer. Reading the part of the herbicide label specific to each crop-weed situation is essential. Local recommendations summarize the attributes of several herbicides that can be used for weed control in small grains in a state or region. These recommendations change as efficacy changes, resistance develops, or herbicides are removed from the market. Therefore, this book is not intended to and does not recommend herbicides. Specific label recommendations should be consulted and followed because approved uses vary from place to place.

B. Corn and Row Crops

One of every four US crop acres grows corn, and it has been selected as representative of the many row crops grown in the United States. Soybeans, dry beans, sugarbeets, cotton, tobacco, sorghum, peanuts, vegetables from broccoli to zucchini squash, and potatoes each have unique weeds, weed management requirements, and solutions. Examples from studies with few of these crops will be included. Because they are all annual row crops they share some weed management principles.

Corn, which most of the rest of the world calls maize, will be used to emphasize the shared principles of weed management. Less than 10% of the US corn crop is eaten by humans directly. Most is fed to animals, and much of the US crop is exported. Corn has over 3,000 uses in more than 1,200 food items ranging from corn syrup to margarine. Other uses include paper production, plastics, cleaning agents, cosmetics, additives for pesticides, and ethanol production for fuel.

Corn and several other crops are called row crops because they are planted in rows from 20 to 30 or more inches apart. Small grain crops are also planted in rows, but the rows are narrow and mechanical, inter-row cultivation is impossible. Rows were invented because of the necessity of cultivation for weed control. Weed management is only one reason crops are planted in rows. Rows make planting and harvesting easier, and modern equipment demands straight rows. Manufacturing facilities concentrate human power, talent, and resources in factories for mass production. Agriculture requires a different spatial geometry, and the advantages of concentration are limited. Spacing in rows is required for optimum yield per unit area for all row crops, and yield is not increased if plants become too crowded.

Prevention

Weed prevention strategies are similar for most crops. There is nothing sophisticated or mysterious about them. Most practices are just common sense and should be incorporated in all good weed management systems. See Chapter 10 for a discussion of preventive practices.

Mechanical

Not too many years ago, it was standard practice to moldboard plow the preceding fall or in the spring before planting corn. Plowing has not been abandoned as a weed management/seedbed preparation technique, but its use is diminishing. Plowing controls emerged weeds and buries weed seeds, while it brings other seeds to the surface where they can germinate. It, like many practices that affect seeds, controls and encourages weeds at the same time. As just discussed, plowing is usually followed by other tillage operations to prepare the seedbed. Disking and harrowing break down clods and make crop planting easier with traditional seed drills and corn planters. They also create ideal conditions for germination of weed seeds with, or just before, the crop. Plowing is a soil inverting operation, but chiseling is not, and fewer weed seeds are brought to the surface by the latter operation. Tillage operations, subsequent to plowing, are shallower and encourage germination of shallowly buried seeds but not those deeper in the profile. The effects of the two kinds of tillage on weed populations were discussed in Chapter 10.

The use of conservation or reduced tillage has expanded greatly in the last decade, and interest in adoption of some form of reduced tillage has expanded even faster. These systems range from surface disking to break up the residue of the preceding crop to no tillage at all with planting directly into the preceding crop's residue using specially designed no-till planters. In the first year or two after no-tillage is begun, weed problems decrease dramatically, but without careful management, weeds can increase in subsequent years. For example, in one experiment with monoculture corn and conservation tillage, all plots were weed-free the first year. In the second and third years, fall panicum dominated, and smooth pigweed dominated in the fourth and fifth years, reaching densities of 85% of total plot area (Coffman and Frank, 1992). The authors related the change of weed flora to continuous use of certain herbicides. Fall panicum dominated in plots treated with atrazine and a carbamothioate herbicide. A triazine-resistant biotype of smooth pigweed dominated in plots treated with atrazine plus cyanazine (Coffman and Frank, 1992).

Ridge-till systems are used to reduce soil erosion and the need for herbicides in some corn-soybean rotations. A special ridge-till cultivator makes ridges over the crop row during the final, summer cultivation of either crop. The ridges, disturbed at harvest and during spring planting, are leveled by moving some soil into the furrows. Immediately after smoothing, or "knocking off," the ridges, the crop is sown on the remainder of the ridge, and the ridges are gradually rebuilt, during cultivation, as the crop matures. The system was most effective in Minnesota when corn and soybeans were rotated (Forcella and Lindstrom, 1988a). Ridges crack, and weeds emerge when corn is grown continuously.

Ridge-tillage is used in corn-soybean rotations. It is not without problems. Knocking off ridges controls many weeds and ridging soil during the summer encourages germination of numerous weed seeds that can produce seeds to infest the next crop. Conventionally tilled corn had about 2/3 fewer weed seeds than ridge-tilled corn because of the large seed production by weeds that germinated when ridges were rebuilt (Forcella and Lindstrom, 1988b). Ridge tillage cannot be successful without herbicides to control late emerging weeds.

Studies in Indiana evaluated no-tillage, moldboard plow, and chisel plow systems in three rotation systems, each of which included corn (Martin et al., 1991). Net incomes for no-till systems on all farms were lower than incomes for moldboard or chisel plow systems due to slightly lower yields and higher herbicide costs. In general, farm incomes were higher with moldboard as opposed to chisel plow systems. It is important to note that these studies were done on highly productive, flat, well-drained soils that are not highly eroded. A different situation for any system will probably yield different results. Agriculture and agricultural research are definitely site specific, as are herbicide recommendations (Treadway-Ducar et al., 2003).

After land preparation, corn can be cultivated mechanically one or more times with various types of implements ranging from a straight shank to several different duckfoot-shaped tools. A rotary hoe can also be used to kill weeds between rows. Cultivation can move soil into corn rows and cover emerging seedling weeds, but it cannot till in the row. Newer cultivation implements operate close to the crop row and make herbicide banding (application in a narrow band just over the crop row) attractive. If all the weeds between rows are controlled mechanically, then herbicide quantity and cost can be reduced by applying the herbicide only in a band over the crop row. This requires more application skill and accuracy than broadcast application.

Postemergence flaming has been used selectively in corn and cotton but has never been used widely.

Cultural

Crop rotation can be a profitable and useful weed management technique. Corn is often grown in monoculture or in a limited rotation with soybeans or another row crop. Rotating to a small grain or hay crop, or both, in succession, often results in reasonable yields but lower than those in a corn-soybean rotation (Helmers, 1986). Rotational possibilities are limited by land, climate, market opportunities, and the availability of suitable rotational crops. Rotating corn with other crops is critical to managing weeds in systems attempting to reduce herbicide use. Introduction of crops with different life cycles and cultural practices deters growth of summer annual weeds with life cycles similar to corn, whose growth is encouraged by continuous or frequent corn crops. Rotation reduces annual grass weeds in corn in the central Great Plains of the United States (Wicks and Smika, 1990). Many annual grasses germinate in May and set seed by late August before corn is harvested. As just mentioned, rotating to winter wheat changes the times of tillage and crop presence and disrupts the life cycle of annual weeds.

It has also been shown that planting corn at higher densities (100,000 plants/ha) in a dry year in Ontario, Canada, or in narrower rows (38 vs. 76 cm) in a wet year provided greater weed suppression (Shrestha et al., 2001). Higher densities reduced early weed competition, and narrow rows reduced late-emerging weed species.

Biological

Currently there are no biological control agents used routinely in corn or other row crops. Because row crops usually have several weeds rather than just one, the specificity of a biological control organism may not fit the weed control need. Integrated weed control in soybean with a combination of the phytopathogenic bacterium (*Pseudomonas syringae* pv. *tagetis*), which attacked Canada thistle, a highly competitive soybean cultivar, and the herbicide bentazon was investigated (Hoeft et al., 2001). The bacterium was effective at reducing Canada thistle growth but less so than bentazon. The competitive soybean cultivar was not beneficial, and there was no synergy (added benefit) between the two control techniques.

Chemical

The main weed control technique that has to be integrated in most corn weed management systems is herbicides. Some, but not all, of the herbicides available for use in field corn may also be used in sweet or popcorn. Label and local recommendations must always be consulted before using any herbicide. The dominant herbicide families used for weed control in corn are triazine (atrazine), chloroacetamide (alachlor, metolachlor), phenoxy and benzoic acid (2,4-D and dicamba), and sulfonylurea. Herbicides in these families may be used alone but are most often used in combinations. Some state recommendations include over 30 soil-applied and a separate list of over 30 postemergence herbicides or herbicide combinations for weed control in corn. About a third of the soil-applied treatments combine atrazine with a chloroacetamide or a carbamothioate. Perhaps a half-dozen soil-applied herbicides are single applications of a chloroacetamide herbicide. The greatest variety of herbicides is found in the postemergence group. Much progress has been made in discovery of postemergence annual grass herbicides, including nicosulfuron, primisulfuron, and rimsulfuron and thifensulfuron, applied in combination. Each of these herbicides is applied at very low rates (grams per acre), and they have solved many postemergence annual grass control problems. Other new herbicides (e.g., halosulfuron, flumiclorac, and flumetsulam) control many annual broadleaved and grass weeds, including some (e.g, velvetleaf) not controlled well by other herbicides.

Integrated Strategies

Simulation models for weed management in corn (King et al., 1986; Lybecker et al., 1991) suggest that flexible weed management strategies, based on control variables, outperform fixed or prescriptive weed management programs. The variable used for deciding what and how much herbicide to use is weed seed number in soil. The models require knowledge of losses due to specific weed densities, percent emergence of weed seed from the soil seed bank, and the efficacy of each herbicide against each weed. The models don't consider the effect of weed escapes on the next year's crop, which in one study (Swanton et al., 2002) may not be important. A flexible strategy lowered total herbicide cost and the quantity of herbicide used, increased postemergence herbicide use, decreased preemergence herbicide use, and increased the farmer's gross profit margin (Lybecker et al., 1991, 1992). The models were developed for irrigated corn. To date, the models don't incorporate mechanical methods of weed control. They herald a new era of weed management when decisions will be informed by knowledge of weed seed in soil and the efficacy of different control measures. Weed management decisions have often been made on the basis of what someone thought the problem was going to be and have, therefore, been prophylactic rather than directed at a specific problem.

Integrated management of itchgrass in corn was studied in Costa Rica employing velvetbean as a leguminous cover crop, a preemergence herbicide (pendimethalin), and classical biological control with the head smut [*Sporisorium ophiuri* (P.Henn) Vanky], which is host specific for itchgrass (Smith et al., 2001). The head smut affects itchgrass seedlings as they emerge and leads to seed sterility rather than plant death. Thus, it is a preventive measure. Velvetbean planted at either of two densities between corn rows was very effective in reducing itchgrass populations from 54 to 17 plants per m^2.

Pendimethalin's contribution to weed control was modest. When the cover crop was effective and the head smut achieved 50% infection, significant income benefits were obtained by corn growers because the biological control was less expensive than the herbicide (Smith et al., 2001). Similar results were achieved in control of cogongrass in corn in Nigeria (Chikoye et al., 2001). Twelve months after planting corn with velvetbean as a cover crop, corn had an average of 65% less cogongrass biomass at three locations than weedy control plots without velvetbean. Corn grain yields were up 25 to 50% over the three locations. Similar results were obtained for cassava yield with velvetbean (Chikoye et al., 2001).

So far, weed management systems in cotton are dominantly curative (Mortensen et al., 2000) and emphasize herbicides. Burke et al. (2005) studied suitable soil-applied herbicides for use with glyphosate-resistant cotton. As herbicide inputs increased, cotton yield increased. Environmental concerns (soil erosion and pesticide use) have led to study of conservation tillage (reduced tillage) for cotton production. The curative approach demonstrated that optimum cotton yield was achieved with reduced tillage only when it was combined with broadcast application of preemergence or early postemergence herbicides (Toler et al., 2002).

Potato research has followed a similar curative approach. Systems that include a rye cover crop, reservoir tillage,[3] and herbicide banded over the crop row reduced preemergence herbicide use up to 2/3 and maintained tuber yield (Boydston and Vaughn, 2002).

C. Turf

Desirable turfgrass, usually divided into cool and warm season species, varies with climate, rainfall, and intended use. The United States has about 25 species that can be used for turf (Vengris and Torello, 1982). They are usually perennials that do well with continuous close mowing. Cool-season species grow best during cool (60° to 75°F), wet conditions in the spring and fall and may become partially dormant in the hot summer months. Warm-season species grow vigorously during hot, dry times when temperatures are above 80°F. Vengris and Torello (1982) list 108 weeds that invade turf. Those that occur most frequently in the United States and Canada are crabgrass, dandelion, annual bluegrass, common chickweed, plantains, and prostrate knotweed, but there are many others. Of the 108 common turf weeds, 17 are perennial

[3]Reservoir tillage, also called dammer tillage, is used in potatoes and carrots in the US pacific northwest. A rotating paddle wheel creates depressions about 10 inches deep (small water reservoirs) in the furrow between crop rows.

monocots, 11 annual monocots, 44 perennial dicots, 29 annual dicots, 4 winter annual dicots, and 3 biennials. Weed control on many turf sites is principally elimination of broadleaved species, and because of the variety of herbicides available, the task is not difficult. Weed management systems for turf were reviewed by Bingham et al. (1995).

Turf is no different from any other crop in the sense that prevention is an essential component of weed management. Preventive practices are used by turf managers when turf is established and during its life. Turf grasses are particularly poor competitors during establishment and elimination of weeds by thorough tillage prior to planting or use of preplanting herbicides is important. Imported topsoil is almost always contaminated with weed seeds and vegetative propagules, and delayed planting of turf species until some of these germinate and can be controlled is wise. Planting the correct turf grass or grass mixture is an obvious preventive strategy. Vigorous emergence and growth reduce weed growth. Grass seed must be of high quality (high percent germination), free of weed seed, and sown at the right time for the climate. Cool-season grasses do best when planted in the fall or early spring, and warm-season grasses do best when planted in spring or early summer.

Weeds in established turf can often be traced to wind-blown seed sources and poor management practices. Weeds most easily invade cool-season grasses such as Kentucky bluegrass, ryegrass, or fescue when the grass is mowed less than 1½ to 2 inches high. On the other hand, weeds most easily invade stoloniferous and rhizomatous bermudagrass turf when it is mowed too high (above 1 inch). Too little water may stress turfgrasses, and drought-tolerant broadleaved weeds will invade. Too much water will create ideal conditions for establishment of annual and winter annual grasses. Most turf is fertilized with a mix of nitrogen, phosphorus, and potassium to keep it vigorous and maintain desired color. Fertilization appropriate to the climate and turf species helps prevent weed invasion. Prevention can also be practiced by controlling turf wear from constant use of certain spots. Change of traffic or play patterns helps maintain a vigorous turf and prevent weed invasion.

The oldest method of weed control—hand-pulling—is still appropriate and common in turf. For a home lawn, it is efficient, even if not pleasant. For golf courses and public lawns, it is inefficient and not economical. In home lawns, hand-weeding will eventually control even the most persistent perennials for which there are no other selective control techniques. Tillage is not appropriate in established turf unless extensive renovation is undertaken. Scarification or vigorous raking is used to thin stoloniferous grasses and control some broadleaved species. If overdone, it thins turf and allows weed invasion. Aeration is used in many climates to reduce compaction and stimulate vigorous turf growth, thereby reducing weed competition.

Because turf is valuable, fumigation, although expensive, may be a desirable preplanting control strategy. Herbicides are used commonly in turf but are most appropriate after all preventive management techniques have been employed. There are at least 30 different herbicides that can be used in turf, but not all herbicides can be used with all turf species. For example, several herbicides (DCPA, dithiopyr, oxadiazon, pendimethalin, and prodiamine) control crabgrass in cool-season perennial turf grasses. All of them can be used on bermudagrass turf, but some hybrids and fine-leaved varieties can be injured (Elmore, 1985). Local recommendations should be consulted before application to bentgrass turf. There are no selective herbicides for removal of coarse-leaved, perennial grass weeds from perennial turf species—a major unsolved weed control problem. It can be accomplished by spot application of a translocated, nonresidual, nonselective herbicide such as glyphosate, but it will kill nearly all other plants it contacts. The most common herbicide used in turf is 2,4-D alone or in combination with other growth regulator herbicides to control broadleaved species. These injure seedling grasses less than four to six weeks old but control a range of annual and perennial broadleaved species without injuring most turf grasses. Because of the nature of plant growth and the translocation pattern in perennials, fall application is often the most effective. As in other crops, application when the crop is growing vigorously and the weeds are young is best.

Warm-season grasses in warm climates present a unique weed control situation. These grasses commonly are dormant during the winter and herbicides, such as paraquat, that would desiccate the bermudagrass foliage if applied when it is actively growing can be used to control cool-season grasses and annual broadleaved weeds that grow when the grass is dormant. Atrazine has been used in St. Augustine grass, although it would kill cool-season turf grasses. Postemergence application of the organic arsenical MSMA selectively controls weedy annual grasses in warm-season turf grasses. Local recommendations and turf managers should always be consulted prior to herbicide choice and application.

D. Pastures and Rangeland

Pastures and rangeland cover more than 40% of the world's agricultural acres. These diverse habitats exist in all topographies and climates and over most soil types. The desirable vegetation is equally diverse, ranging from short grass prairies of the mid-United States to the oak/pine associations found in western states to designed, planted, irrigated pastures of irrigated and rainfed areas. With the exception of intensively managed, planted pastures, rangeland and pasture may have over 100 species per square mile. These areas are often very large and hilly, or mountainous terrain makes access for mechanical or chemical weed control difficult if not impossible. Weed management systems for pastures and hay crops were reviewed by Smith and Martin (1995).

Controlled burning has been a common management technique to reduce competition from woody species and competition for water. It has some serious environmental drawbacks (smoke pollution, potential erosion of bare soil), and its intentional use has been reduced due to its environmental effects and the increasing number of homes in natural areas. Burning is often followed on large areas by reseeding, commonly by air. Biological control with grazing animals—managed grazing—is a desirable weed management technique. Goats are particularly good browse animals, but they have to be carefully managed so they don't compete with cattle or sheep. Some of the major successes in biological control of weeds with insects have been achieved on rangeland such as the use of *Cactoblastis cactorum* to control prickly pear and *Chrysolina quadrigemina* to control St. Johnswort (see Chapter 11).

Mechanical removal with bulldozers and by chaining is used on rangeland, but both are expensive and results are temporary. Mowing is a good technique for control of weeds in pastures but not on large areas of rangeland. Growth-regulator herbicides are used to control woody species such as big sagebrush or greasewood on rangeland.

A major problem in the arid western states is the perennial, herbaceous weed leafy spurge (see Chapter 11). Successful management has been accomplished when techniques have been integrated. Sheep or goats (biological control) will graze the weed early in the growing season to release desirable grasses from leafy spurge competition and make the leafy spurge more susceptible to fall-applied herbicides. Several insects have been released in the United States for biological control of leafy spurge. The leafy spurge hawkmoth (*Hyles euphorbiae*) eats leafy spurge leaves and bracts during its larval stage (Harris et al., 1985), but this feeding does not result in plant mortality. Alone, the hawkmoth is not an effective biological control agent (Coombs et al., 2004).

A root and stem-boring beetle (*Oberea erythrocephala*) imported from Italy, was established in Montana and North Dakota (Leininger, 1988). Adult beetles feed on leaves and stems, which does not result in plant death (Coombs et al., 2004). Stem girdling by the adults with subsequent egg laying usually results in shoot death. Larvae bore into stems and move to roots, where they mature and exist on carbohydrate root reserves. Boring allows other pathogens to enter. Adult and larval *Aphthona* spp. beetles (six species; two, *A. lacertosa* and *A. czwalinae*, have been released) feed on leaves and flowers, and the larvae bore into roots and feed on root hairs and young roots. They destroy vascular structure while feeding. Grass infested with leafy spurge will be favored by use of the cultural controls—fertilization and irrigation—if either is economically feasible. These strategies reduce competition and permit efficient grazing by animals such as cattle that do not eat leafy spurge. In the fall, leafy spurge can be sprayed with selective herbicides (chemical control). Neither herbicides nor grazing animals have greatly affected vitality or future performance of biological control insects. It is a certainty that this integration of methods will not eliminate leafy spurge in one season, but it will keep the population at a level that permits efficient land use. Persistence, defined as continued use of several techniques and continued evaluation, is required.

Perennial weeds such as Canada thistle are controlled better when herbicides and mowing are combined (Beck and Sebastian, 1993). Mowing improves pastures and stresses perennial weeds that may then be more susceptible to herbicides. The value of combining herbicides and mowing is illustrated well by control of the exotic invasive weed tropical soda apple in Florida (Mullahey et al., 1996). The perennial weed was first found in 1981 but not identified as an important invader until 1990. In 1990 it was estimated that it occurred on about 25,000 acres in south Florida. By 1993 it occupied 150,000 acres, and now it infests over 1,000,000 acres of Florida pasture land, where it flowers and sets seed throughout the year (Westbrooks, 1998). It has been found in seven other southern states (Westbrooks, 1998). Control has been best when plants are mowed or chopped 60 days prior to spraying with the growth regulator herbicide triclopyr. Mowing three times 60 days apart gave 83% control after 180 days. Mowing or chopping 60 days prior to triclopyr application was 93 to 100% effective 180 days after herbicide application. Further mowing is not required, but spraying escaped plants is recommended. Cattle ranchers are urged to isolate new cattle and monitor cattle movement between pastures because cattle eat the fruit, and seed easily passes through their digestive systems to reinfest pastures. Cattle isolation is a part of an integrated weed management system.

E. Perennial Crops

Perennial crops grow for several seasons and are then rotated (e.g., alfalfa) or for several years (e.g., apples or almonds), after which the trees are removed and another orchard is established on the same site. A diverse group of weeds succeeds in perennial crops including annuals, biennials, and perennials favored by perennial culture. Some perennial crops such as alfalfa, peppermint, asparagus, or strawberries are not commonly cultivated mechanically, and without good crop competition and weed management, perennials can invade and succeed. Cultivation can be a part of a weed management program in tree fruits and nuts that have wide rows and low crop density. Weed management options are limited because the crop's longevity precludes use of rotation and, in some crops, mechanical tillage. Cover crops and mulching are feasible in perennial crops and should be incorporated in weed management planning. Biological control must be chosen based on the weeds present and cannot be prescribed for all perennials.

Prevention

Vigilance is a prerequisite for a good weed management program. The manager must be aware of sources of weed infestation and take appropriate action to prevent invasion. In perennial cultures these could include screening of irrigation water to prevent import of weed seed, careful selection of clean mulch material, composting of manure to kill weed seed before spreading, mowing to prevent seed production, careful selection of adapted crop cultivars to maximize competitiveness, and planting weed free seed or seedling stock. The last two can only be done at planting, an opportunity that should not be lost. Site selection is a weed management technique. Perennial weeds are favored in perennial crops, sites without them should be selected, when possible, for initial planting. Annual weeds will be present on almost any site and some control can be achieved by preplant tillage, just as it can be before annual crops are planted. Perennials are not controlled easily by tillage and avoiding them is always good planning.

Cultural

Timing of planting is a cultural control and preventive technique. Planting should be done when a quick emerging (or establishing in the case of transplants), vigorous crop is ensured. For example, alfalfa planted in the fall in southern California becomes established and is a better competitor with weedy spring grasses than spring- or summer-planted alfalfa (Mitich, 1991). Planting time varies with climate and environmental conditions, but its role in weed management should not be ignored.

Irrigation timing is an important cultural practice that influences weeds. Barnyardgrass and yellow foxtail establish readily when alfalfa is stressed before or during harvest and water is applied when there is little alfalfa growth to shade soil. When water is applied near alfalfa cutting, weed invasion is reduced.

Grazing animals on perennial cropland contributes weeds in manure and overgrazing always encourages weed invasion. Grazing animals control some annual weeds.

For some short duration (three to five years) perennials (e.g., alfalfa), planting with a nurse or cover crop is a useful weed management technique. Crop yield may be reduced in the first year, but subsequent crops have lower weed populations.

Cover crops, ground covers, or grassed, mowed alleyways are part of good orchard management in many perennial row crops and fruit orchards. Groundcover species adapted to local environments should be selected based on local recommendations. Cover crops and groundcovers compete directly with weeds but should not compete with the crop. They may also have allelopathic effects. Regular mowing of grassed areas changes ecological relationships and affects weed populations. In orchards with grassed interrow areas, mowing is done between tree rows, whereas tree rows may be weeded with herbicides.

Mechanical

For alfalfa, peppermint, and similar crops that are not planted in wide rows and eventually cover the soil, cultivation is not possible. In tree crops, clean cultivation is a widely practiced weed management technique that precludes grassed alleyways or groundcovers. Clean cultivation is common in many nut orchards and is usually combined with chemical methods of weed control. It is a desirable management technique but increases the risk of soil erosion from water or wind.

Chemical

Herbicides for perennial crops are as diverse as the crops themselves. Because this is a book of principles rather than recommendations, the several herbicides available for perennial crops are not listed. Local recommendations should always be consulted for each crop. Many persistent herbicides including dinitroanilines (used in peppermint, spearmint, sugarcane), triazines (used in asparagus, alfalfa, citrus fruits, nuts, pineapple, sugarcane), and uracils (used in peppermint, spearmint, pineapple) are approved for use in perennial crops. Decisions on herbicide use must be based on the weeds to be controlled and how herbicides affect other weed management strategies (especially incorporation of a permanent ground cover). Herbicides are valuable tools in these crops and should be regarded as part of the overall weed management program but not a complete management technique.

Herbicides were essential parts of a program to manage leafy spurge on native rangeland (Masters and Nissen, 1998). Invasion of native range by leafy spurge was directly linked to past management practices that reduced native species diversity and opened niches for leafy spurge. Leafy spurge biomass was lowest in areas where tall grass (e.g., big bluestem, switchgrass) yield was highest. This was accomplished best by combining vegetation suppression with fall-applied herbicides, burning standing dead plant residue, and no-till planting of desirable native tall grasses in the spring. The same conclusion was reached for control of Russian knapweed on rangeland (Laufenberg et al., 2005). Herbicides were most efficacious when combined with revegetation in areas that lacked a diverse mixture of desired species.

F. Aquatic Weed Sites

Detailed recommendations for aquatic weed control can be found in McNabb and Anderson (1985) and in the complete manual of aquatic weed management with herbicides available from the Department of the Interior (Hansen et al., 1983). This section presents a view of several available techniques.

It is seldom necessary or desirable to remove all vegetation from water. The aquatic weed manager must decide if complete eradication is desirable or if some level of control is more appropriate. It may be possible to control one especially troublesome or dominant species and leave others undisturbed. Control can be infrequent by mechanical or chemical means, and it can be just removal of excessive growth for part of a season.

Classification of Weeds

A brief introduction to aquatic weeds was given in Chapter 3. It used the usual, and simple, classification of free-floating, submersed, and emersed weeds. Although those are useful divisions, the aquatic world is more complicated. A good explanation of the complexity is offered by McNabb and Anderson (1985), who subdivide the usual categories to provide more information about habit of growth and plant type (Table 19.2). The aquatic weed manager must know exactly what weed is to be controlled or managed and its method of reproduction. Algae reproduce asexually by cell division. Completely submerged aquatic plants reproduce by fragmentation, vegetatively by rhizomes and runners, and by specialized submerged buds (turions) and tubers. Submersed plants that have some floating leaves such as American pondweed reproduce by seed, as do emerged plants. Free-floating plants (e.g., waterhyacinth) reproduce by seed and asexually or clonally by fragmentation, and some reproduce by spores and clonally (e.g., salvinia). With dual modes of reproduction, some weeds cannot be managed by preventing seed production, as is the case with terrestrial annuals. If the manager doesn't know the plant's growth habit and method(s) of reproduction, poor or no control may result from improper choice of methods.

Prevention

Preventive strategies depend on knowledge of the factors affecting growth of aquatic vegetation. These include light, nutrients, water depth, water flow rate,

TABLE 19.2. Classification of Aquatic Weeds (McNabb and Anderson, 1985).

Type of plant	Growth habit	Examples
Algae	Unicellular or microscopic colony	
	Free-floating attached to substrate	Phytoplankton diatoms
	Filamentous-green	Cladophora
	Colonial—attached or floating	Spirogyra
	Blue-green	Nostoc
Vascular plants	Completely submerged	Sago pondweed, hydrilla
		Eurasian water-milfoil
		Some mosses
	Submersed with floating leaves	Waterlilies
		American pond-weed, arrowhead
	Emergent	Cattail, bulrush
		Several grasses
	Free-floating	Waterhyacinth
		Duckweed, azolla
		Salvinia (a fern)

the growth medium (water or soil) and its nutritional status, dissolved gases, and temperature. While the last two are important, there is little that can be done to change them. Light can be managed by control of water depth. Water management to control weeds by reducing water depth through intentional drawdown manages some weeds effectively. It has little effect on floating vascular plants or algae but will aid control of rooted species. It is not permanent because other weeds adapt to new water levels, but it can help manage current weed problems. Eurasian watermilfoil, arrowhead, and water lilies can be managed by a drawdown of water (decreasing water level), but most pondweeds, cattails, and rushes are not affected. Drawdown can be done at any time, but most irrigation structures were not designed to facilitate the technique, and it is not used widely. If the manager understands the biology of the weed to be controlled, drawdown can be timed to stop production of reproductive structures. The opposite technique—ponding or deepening water—can be used to manage some aquatic species.

Apparent water depth for plants is also affected by turbidity. Turbid, or more nearly opaque, water provides less light to submerged species. If turbidity can be tolerated, it can be created by stirring or intentional incorporation of silt or other soil particles. Turbidity can also be created by fertilization to promote algal "blooms" or abundance. This technique can cause other problems because algae may be toxic or otherwise undesirable. Fertilizer stimulates algal growth that shades plants that root underwater and do not emerge. A bloom must be maintained through a growing season to achieve control. Careful monitoring is required. More commonly, nutrients from surrounding fields or other sources encourage growth of weedy plants and worsen the weed problem. Dredging or reshaping a pond to remove shallow areas reduces light on the edges and reduces growth of submerged or emersed weeds.

Moving irrigation water inevitably brings weeds with it (see Chapter 5). Prevention of water movement to ponds and lakes is nearly impossible. Animals, birds, and humans transport seeds and vegetative reproductive organs to water and, with the exception of humans, cannot be prevented easily, if at all.

Mechanical

Mechanical methods of weed control adapted for use on aquatic sites frequently require large, specially adapted machinery. Aquatic weeds can be mowed with floating mowers, but these are expensive, and there is a problem of disposal of the mowed, inevitably smelly, vegetation. Repeated mowing is required, and the method is not adapted to large areas. As is true for terrestrial, perennial weeds, mowing may release dormant, vegetative buds and actually worsen the weed problem unless it is done frequently or integrated with another method. It is only appropriate for rooted plants. Floating plants could be collected by a large mower that collected what it removed (Figure 19.2), their control would be an incidental similar to physical removal of terrestrial vegetation. Removal is a good technique for floating plants. The biomass of aquatic plants is often quite high, and large equipment is needed to collect them. The method is only appropriate for small to medium lakes or straight waterways. Vegetative reproducers will quickly repopulate an area, and disposal of collected biomass is a problem.

Physical disruption of rooted plants by chaining or dredging is a good technique for straight irrigation ditches. It immediately reduces clogging by weeds but the relief is only temporary for plants that grow back from severed roots. Dredging or reshaping a ditch or pond can be more effective if roots and vegetative reproductive organs are removed, but it is expensive.

Burning is used in much of the western United States each spring to remove plant residue from irrigation ditches. It is more for sanitation and good housekeeping than weed control. Temperatures are not high enough to kill buried seeds or vegetative organs. If young seedlings are emerging they will be controlled but the main benefit is sanitation.

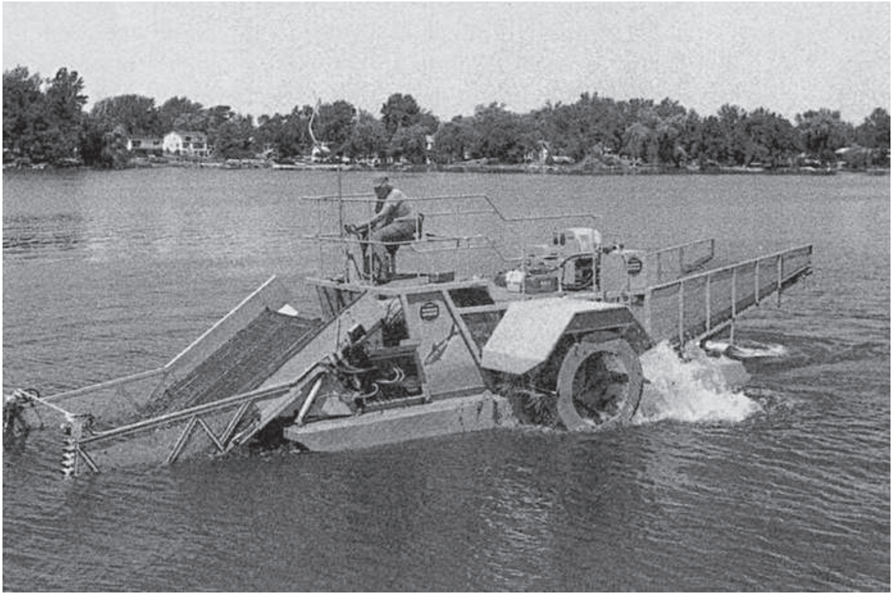

FIGURE 19.2. A weed mower for aquatic weeds.

Biological

The same criteria for success of a biological control organism apply to aquatic and terrestrial environments (see Chapter 11). *Agasicles hygrophila*, a South American flea beetle, has been used to clear southern US waterways of alligatorweed, a free-floating plant. *Cercospora rodmanii* has shown great promise for control of waterhyacinth in tropical and semitropical waterways (Strobel, 1991). Although *Agasicles* has been very successful, there are no other examples of a widely adapted, successful insect or pathogen control for aquatic plants. Other organisms have been used for control for aquatic plants. They include the sea manatee, a large aquatic mammal, and two fish, the grass carp or white amur (*Ctenopharyngodon idella*) and tilapia (*Tilapia melanopleura*). These eat aquatic vegetation but are generally nonselective, and that is not regarded as a serious disadvantage. Survival and reproduction are problems with any biological control organism. The manatee has no known enemies except man and a pathogen that reduced their population in 1996. Manatees survive well in warm fresh water but do not reproduce well.

Fish provide an alternative crop in many aquatic environments. Tilapia are intolerant of cold water and are therefore, adapted only to subtropical and tropical climates. The grass carp reproduces well in cold water and can grow to marketable size, but its reproductive ability limits its acceptability in many places (it is not approved for use in California; McNabb and Anderson, 1985). On the other hand, failure to reproduce keeps a population under control and prevents escape of an otherwise desirable control organism.

Chemical

Aquatic plants are susceptible to a wide range of herbicides, but there are few herbicides available for use in water. However, herbicides are the most common method of weed control in the United States. These apparently contradictory statements are explained by the multiple uses that water has and the fact that it moves. Herbicides offer the same advantages in the aquatic environment that they do in field crops. They are selective, easy to apply, act quickly, are relatively inexpensive, and can be used where other methods don't work well. Nevertheless, their use is limited in aquatic sites. Limitations on herbicide use exist because water has multiple uses. Aquatic herbicides are applied directly to emerged plants or to water. Some herbicides can be applied to exposed soil after water is drawn down or removed. In all cases, water's multiple uses must be considered. Label and local recommendations must be consulted prior to use. There are very few herbicides for aquatic use, and restrictions limit use of approved herbicides.

McNabb and Anderson (1985) developed a decision-making scheme for integration of methods. The first question in all cases is "What will the water be used for?" The answer determines control options, and other questions can only be considered after the first has been answered. They divide water into three categories: industrial, potable or recreational, and irrigation. Their scheme integrates all control methods through a series of logical questions regarding the possibility of nutrient control, drawdown of water level, and control of downstream flow through ponding or temporarily holding water. Their scheme is presented for one situation in Table 19.3.

Compared to terrestrial crops, herbicide choices for aquatic weed control are limited. Some aquatic weeds can be managed by skillful combination of preventive and control techniques in an integrated system.

G. Woody Plants

Woody plants are perennials that produce secondary growth in the form of wood. Some are useful for their wood. Others provide browse grazing for animals, shade, shelter, medicinal extracts, and aesthetic benefits. Many become undesirable (weedy) when they dominate an area to the exclusion of desirable vegetation. Woody plants and their management have been dealt

TABLE 19.3. Decision Scheme for Control of Attached Submersed Weeds Where Water Is Potable.

Potable Water		
Can nutrients be reduced?		
Yes		No
Can water be held temporarily?		Is drawdown possible?
Yes	No	Excavate
Compatible herbicide	Herbicide with potable use	Dredge
Excavate	Mechanical removal	Foliar herbicide for
Dredge	Herbivorous fish	plants with floating
Line pond bottom	Reduce light	leaves
Foliar herbicide	Plant beneficial competitive	Yes
Soil incorporated herbicide	plants	Soil incorporated herbicide
		Line bottom

with in detail in a major book by Bovey (2001) and in reviews by Bovey (1995) and McNabb et al. (1995). Interested readers are referred to those works for complete coverage of woody plant management.

V. MOLECULAR BIOLOGY IN WEED MANAGEMENT

The primary, perhaps only, role of molecular biology on weed management has been the development of herbicide-resistant crops. Many regard herbicide-resistant technology as the next advance in weed science after the development of herbicides. It is important to understand as Gressel (2000) points out, "No solution in agriculture has ever been forever." Evolution is operative, and major changes are often not even observed until they have occurred. Nature changes, weeds change, and their management must also evolve. The technology of molecular biology offers several important advantages (Lyon et al., 2002):

- Improved weed control, particularly of difficult to control weeds.
- Improved ability to control weeds not controlled by available herbicides or other control techniques for a crop.
- A lengthened application time for the herbicide to which the crop has been made resistant.
- Improved crop safety because the crop is resistant.

There are equally important concerns:

- The eventual need to control weeds that become resistant to the herbicide to which the crop has been made resistant.
- The introgression of transgenes into related weeds.
- Overreliance on a single herbicide will lead to weed species shifts to resistant or more difficult to control species. Weed scientists must recognize that reliance on herbicides in large monocultures predictably led to development of herbicide resistant weeds (Gressel and Segal, 1978; Powles and Holtum, 1994). It is a good lesson but one that seems to be difficult to learn: overreliance on any agricultural technology tends to lead to its failure.
- The development of multiple resistant weeds that are resistant not just to the herbicide the crop is resistant to but also to other herbicides with similar modes of action.
- Public concerns fall into one of two groups:
  1. A genetically modified food crop may, for a usually unknown or unspecified reason, be harmful to those who consume it.
  2. A genetically modified food crop may be harmful to the environment. In this regard it is worthy of mention that genetically modified sugarbeet has been shown to have beneficial effects in research in England: crop yield increased as much as 9%, weed seed production declined as much as 16 times, and 43% less herbicide was required (*Economist*, 2005).

Gressel (2000) mentions another gain from the advent of molecular biology. It is the positive effects on basic biological science. He suggests that in the long run it would be good to focus molecular biology research on ways to accomplish weed control without, or with fewer, chemicals. It is also true that molecular biology research to date has focused largely on crops of importance to developed country agriculture (corn, soybean, canola, etc.). Eventually one hopes the work will give proper emphasis to the crops that feed most of the world (several vegetables, pigeon pea, cassava, millets, etc.), but that may not offer as much, or perhaps any, major profit potential to corporations.

Martinez-Ghersa et al. (2003) note that there was (in 2003) no evidence of production cost reductions or yield increases from molecular biological research. Weed control is easier and perhaps more efficient, and while that is an important accomplishment, it is all that has been accomplished. Research could be conducted, and I expect it is, to make crops more competitive with weeds for light, nutrients, or water (Gressel, 2000). Allelochemical interference by crops could be enhanced. It is theoretically possible to make biocontrol agents more virulent yet unable to spread (Gressel, 2000). Gressel also proposes that research could devise ways to make weeds less competitive through genetic modification with deleterious transposons.

Research on molecular biology applicable to agriculture and specifically to weed science will continue, and new applications will be developed. Martinez-Ghersa et al. (2003) correctly note that scientific questions have dominated the field (What *can* we do?), but ethical considerations (What *should* we do?) are essential to proper development of the technology. I have dealt with ethical matters elsewhere and refer interested readers to that work for consideration of the ethics of molecular biology in agriculture (Zimdahl, 2006).

VI. WEED MANAGEMENT DECISION AIDS[4]

Weed-crop competition was the first process of weed biology that weed scientists modeled and modeling research continues. Accurate yield loss estimates are needed to create weed management decision aid models and to evaluate economic thresholds. Weed management models tend to be in one of two broad categories (Lundkvist, 1997; Swinton and King, 1994). Models of weed competition are research models (to develop an understanding of processes) or practical models (decision aid or weed management tools).

1. Research models attempt to quantify the effects of the density of one species, usually a crop, on its own yield or biomass production and on the yield or biomass production of a competing weed species (Lundkvist, 1997; Radosevich, 1987).
2. Practical models incorporate scouting or economic thresholds and purport to be decision aids for weed management (Wilkerson et al., 2002).

Lundkvist (1997) concluded that although research models had clarified principles, practical models were still only potential tools, a situation that still prevails. They remain potential primarily because of the regional nature of crops and the weeds that infest them. Models and integrated weed management systems must reflect regional crop and weed diversity and the diversity of ecosystems in which crops are grown. This is a daunting task (see Gunsolus et al., 2000).

Wiles (personal communication) noted that models of crop-weed competition can also be categorized as conceptual, simulation (generally used synonymously with analytical), and empirical (generally used synonymously with mechanistic or ecophysiological). Conceptual models are research tools, developed to provide insight into the competitive process. Most practical models are empirical, and much can be and has been learned from empirical modeling of weed-crop competition (Cousens, 1985b).

[4]Much of the material in this section has been excerpted with permission from Zimdahl, R.L. 2004. *Weed-Crop Competition: A Review*, 2nd ed. Blackwell Publishing. Ames, IA. 220 pp.

Coble and Mortensen (1992) reported the four most common definitions of threshold used in weed science. The threshold to be determined depended on the response measured; it is not a fixed definition. The most common adjectives were *damage, economic*, *period*, and *action*. Damage is used to define the weed population that caused a yield reduction. The *economic* threshold (Jordan, 1992) is the weed population at which the cost of control is equal to the increase in crop value from control. The economic threshold is further complicated because it may be used for single- or multiple-season effects. A *period* threshold implies that there are times in the growth of a crop when weeds are more damaging. The *action* threshold is often related to the period threshold and is the point at which control is initiated. Action is usually based on cost but may include risk aversion, desire for clean fields (the neighbor's opinion effect; Wilkerson et al., 2002), or other considerations. All models, independent of the threshold used, give primary emphasis to aiding the decision to use or not use an herbicide—the putative aim of all models. Some models also incorporate mechanical and cultural methods (Wilkerson et al., 2002), but models and modeling used in weed science emphasize decisions about herbicide use. Attempts to determine the economic threshold have been most common.

Zanin and Sattin (1988) conducted four tests to determine the economic threshold for velvetleaf in corn and velvetleaf seed production with different levels of infestation with and without a corn crop. The economic threshold was calculated with Cousens's (1985a) model and varied from 0.3 to 2.4 plants m^{-2}. Corn reduced velvetleaf seed production by 50%. But even when only four to five velvetleaf m^{-2} competed with corn, velvetleaf still produced 8,000 to 10,000 seeds m^{-2}. Zanin and Sattin (1988) questioned the value of a threshold density for weed management when one must consider velvetleaf's ecological characteristics that permit great seed production at low density. Cardina et al. (1995) found the single-year economic threshold for velvetleaf in corn ranged from 0.4 to 14 velvetleaf m^{-2} in conventional tillage and 0.13 to 3.13 m^{-2} with no tillage. Cardina et al. (1995) also questioned the value of the economic threshold because of seasonal variation and high seed production from subthreshold velvetleaf populations. Economic thresholds that were predicted using yield goal information deviated from the actual threshold values by −43 to +30%.

Roberts and Hayes (1989) proposed a decision criteria model for johnsongrass control in soybean, based on actual data, which describe the relationship between johnsongrass density and soybean yield loss. When these data are combined with the cost of control and the expected soybean price, the result can be used to show the weed density threshold at which johnsongrass control becomes profitable. Toler et al. (1996) tested an additive response model and a product response model to predict yield reductions due to johnsongrass and smooth pigweed interference in soybean. Both models predicted higher soybean yield losses than were observed. When growing conditions were favorable and the competitive effects of weeds were low, both models adequately predicted soybean yield decline. If the weather was dry, the product response model was superior. Smooth pigweed was 80% of the biomass when species were grown together (Toler et al., 1996). The modeling was complicated by the fact that as johnsongrass density increased, the reduction in soybean yield was linear, whereas an exponential response characterized the decrease in soybean yield due to smooth pigweed.

Practical application of single-season economic thresholds for postemergence weed control decisions have been frustrated by the variable effect of differences in climate between growing seasons, different soils, and variable crop-weed interactions (McDonald and Riha, 1999), the same factors that plague developers of quantitative models. Simulations showed that when weeds do not emerge before corn, corn will only suffer a yield reduction in 2 of every 10 years (McDonald and Riha, 1999). Therefore, economic thresholds based solely on the level of weed infestation (the weed density) are inherently flawed (McDonald and Riha, 1999). McDonald and Riha (1999) advocated shifting the focus from measuring weed density to assessing the competitive status of the crop indirectly with climate information which would alleviate many of the problems of inaccuracy associated with present threshold management strategies. This view is supported by the work of McGiffen et al. (1997), who found that economic thresholds for foxtail interference in corn are not constant but vary with weather, cropping system, and soil type. McGiffen et al. (1997) offered the pessimistic view that widespread management of weeds with economic thresholds is an unrealistic goal until the stability (i.e., accuracy across years and regions) of interference models improves. Jasieniuk et al. (1999) expressed the same view based on a multistate, multiyear study of crop yield loss-weed density relationships between wheat and jointed goatgrass. Site-to-site and year-to-year variation in winter wheat and jointed goatgrass yield loss parameter estimates demonstrated that management recommendations made by a bioeconomic model cannot be based on a single yield loss function with the same parameter values for different winter wheat producing regions. Jasieniuk et al. (1999) advocated that models would be improved when yield loss functions incorporating time of emergence and crop density are built into the model's structure. Subsequently, Jasieniuk et al. (2001) evaluated three models that empirically predict crop yield from crop and weed density for their fit to 30 data sets from a multistate, multiyear winter wheat-jointed goatgrass study. They used seven criteria to evaluate the models to determine which one best fit the objectives of a bioeconomic model that seeks to identify economic optimum weed management recommendations. The earlier paper (Jasieniuk et al., 1999) used the rectangular hyperbolic model proposed by Cousens (1985a). The later paper (Jasieniuk et al., 2001) compared three candidate modifications of Cousens's (1985a) model. The first involved the use of two linked hyperbolic equations derived from Cousens's (1985a) hyperbolic model. The second modification was first proposed for aboveground biomass by Baeumer and de Wit (1968) and, as mentioned by Jasieniuk et al. (2001), was applied to marketable yield by Weiner (1982), and was the best compared to six other models for predicting barley and winter wheat yield (Cousens, 1985b). The third modification involved the use of a model derived from "a crop density-yield loss model" proposed by Martin et al. (1987), who modified Cousens (1985a) hyperbolic model. The conclusion of this very detailed manuscript is that no one model was superior unless one selected and defined the criteria of evaluation—that is, they defined what made the model superior. The common choices are the proportion of regressions that converge on a solution and more readily exhibit asymptotic behavior or statistical significance and a linear relationship between yield and crop density under the constraint of limited data. Thus, work goes on to develop the best model that combines reliability across years and locations with statistical reliability and conformity to biological reality.

Several weed management models are available and are beginning to be used, albeit not extensively, to help choose weed management methods. For example, three computer-based models have been developed for corn, cotton, peanut, and soybean (Bennett et al., 2003). HADSS (Herbicide Application Decision Support System) was designed for office, desktop use; Pocket HERB is designed for on-site, field use; and WebHADSS uses field-specific information to estimate crop yield loss if no weed control is done to compare and eliminate inappropriate herbicides and to estimate yield results after recommended treatments. Each model is a curative, herbicide-based system. Each system has been modified for use in several southern states and in Canada (Weaver et al., 1999) for site- and weed-specific conditions. Even with the significant research effort that has been devoted to development of decision aid models, they are often not superior to farmer decisions. Swinton et al. (2002) compared three models (Michigan WEEDSIM/GWM, CORNHERB, and SOYHERB) in Michigan and found no model was statistically superior to weed management decisions made by farmers unaided by decision aid models. Development of decision aid models "has been and will continue to be, an evolutionary process" (Bennett et al., 2003). Models and modelers will evolve and models will improve. They are helpful and will become more so. Whether their time and trouble will be cost effective for growers remains to be determined. As Masin et al. (2005) point out for WeedTurf, there is a "possibility of developing interactive computer software to determine the critical timing of weed removal and provide improved recommendations for herbicide application timing."

Whether models will ever be superior to the knowledge and experience of growers remains to be determined.

Norris (1999) conducted an extensive survey and concluded that in spite of the abundant literature on the effects of weed density and duration on competition (an abundance supported by Zimdahl, 2004), improved computer technology, and the new decision aid models, the information on weed crop competition has had almost no effect on weed management practice. Norris (1999) strongly argued for greater emphasis on weed biology and research to understand the mechanisms of competition. His plea has not resulted in a significant change in the type of research weed scientists do. Norris's view is supported by arguments presented by Wilkerson et al. (2002), who note that models may not be necessary because farmers want a weed-free crop and herbicide-resistant crops have eliminated the need for models. In addition, an expert can usually make a good and much quicker recommendation without collecting the data models required, and even with the required data, the model may not change the recommendation of experience and expertise. Norris (1999) also advocated a no-seed production threshold. That is, no weeds are allowed to produce seed, and thus the future problem is reduced and gradually may be eliminated. A model is not needed to justify a no-seed production threshold. Zero is a difficult goal, and achieving it is a decision that may not be aided by today's models. Work by Maxwell and Ghersa (1992) with a theoretical model to assess the relative importance of weed competition and seed dispersal on long-term crop yield losses also supported the no-seed threshold concept. Simulations using extant data of green foxtail competition in spring wheat showed that seed dispersal from the invading weed might have more influence on yield than the relative competitive ability of the weed. Maxwell and Ghersa (1992) also suggested that if the weed was uniformly distributed at a high density, seed dispersal was less important relative to competitive ability.

Jones and Medd (2000) support Norris's (1999) concept of no-seed production as the proper goal. They suggest that although economic thresholds are strongly embedded in weed management, perhaps because profit is a primary goal, they may not be the best approach. Jones and Medd (2000) suggest a population management approach that includes the "intertemporal effects" of management decisions. The proper focus, in their view, is to manage weed populations over time rather than to minimize the effect of weeds in one crop in one year, which is what most economic thresholds and the associated models advocate. The goal, consistent with Norris' recommendation, is to deplete the seed bank over time. Jones and Medd (2000) tested this approach using wild oat invasion of spring wheat in Australia and found the economic benefits from the population management approach were significantly greater than the typical economic threshold approach. Sattin et al. (1992) found that the economic threshold for velvetleaf in corn varied between 0.3 and 1.7 plants

m^{-2}. Their findings agree with those of Jones and Medd (2000) that the proper focus is one that includes measurements over time. Therefore, one must conclude that a single-season economic threshold is not the best model or management strategy.

VII. SUMMARY

There are few fully integrated weed management systems. Each developing system must be adapted to local environmental, economic, and farming realities and therefore, no single system will be appropriate for a crop everywhere it is grown. For many years, herbicides will continue to be important components of most weed management systems. Their use may be reduced as integrated systems become more common and effective. Research is being done to develop effective, integrated weed management systems that minimize cost, optimize weed control and are sustainable with changing economic conditions. These systems will not solve all weed management problems. Integrated systems will stabilize weed populations at a low level by employing an array of control techniques. Systems will evolve and change over time because of failure to prevent invasion by new weeds, development of resistance to one or more control techniques, development of a population not controlled and, in fact, favored by a given management system. Weeds will never be eliminated, but they can be managed.

THINGS TO THINK ABOUT

1. What are the basic weed management techniques that should be considered for weed management systems?
2. Describe the components of a good weed management system.
3. Can you design a weed management system that includes several techniques for a crop of your choice?
4. What things other than weeds must be considered in the design of a weed management system?
5. What information is essential to create better weed management systems?
6. Explain the role of biological control in present weed management systems.
7. Explain the role of herbicides in present weed management.
8. Explain the role of mechanical methods in weed management systems.
9. How can cultural control techniques be incorporated in weed management systems?
10. Discuss the role of models and modeling in weed management.

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CHAPTER 20

Weed Science—The Future

FUNDAMENTAL CONCEPTS

- Weed science has a rich, productive history, and weed management will continue to contribute to production agriculture and other disciplines where weeds occur.
- There are many new research areas in weed science that will create a challenging future.

LEARNING OBJECTIVES

- To know the promising areas for weed science research.
- To understand that weed science is an evolving discipline.
- To understand that research opportunities in weed science and potential contributions to food production and alleviation of world hunger are great.
- To understand the opportunities and problems related to use of biotechnology in weed science.
- To understand the opportunities and problems of transgenic crops in weed science.

But you who seek to give and merit fame,
And justly bear a critic's noble name,
Be sure yourself and your own reach to know,
How far your genius, taste, and learning go;
Launch not beyond your depth, but be discreet,
And mark the point where sense and dullness meet.

An Essay on Criticism, Part I
by Alexander Pope

Those who have read to this final chapter know that the end is near, but the end of the book is not the end of the story. This book has presented a short, accurate history of weed science and described the present situation and now it is time to think a bit about the future. Sir Winston Churchill said he always "avoided prophesying beforehand, because it is a much better policy to prophesy after the event has already taken place." The Danish humorist Victor Borge, echoing Churchill's words, said, "Prophecy is a difficult business, especially of the future." However, when the past is known and the present is understood, it is tempting to try to glimpse the future. What follows will be only a glimpse because the future cannot be predicted with absolute confidence, although some trends can be seen. This will be, one hopes, not beyond my depth and not dull. To begin, I assert that weed science is young among the agricultural sciences, has an enviable record of achievement, and has a promising future.

The practice of weed control was a recognition of necessity by farmers who had been controlling weeds long before herbicides were invented. The advent of herbicides changed the way weed control was done but didn't change its fundamental purpose: to improve yield of desirable species. Herbicides replaced human, animal, and mechanical energy with chemical energy. No other method of weed control, before herbicides, was as efficient at reducing the need for labor or as selective. People with hoes could discriminate between weeds and crops, and weed selectively. Mechanical and cultural methods, although effective, were not selective enough. Herbicides prevented weeds, reduced the growing population, and selectively removed weeds from crops. Other methods could do these things but not as well, as easily, or as cheaply. Weed control in the world's developed countries now depends on herbicides as the primary technology. This situation will prevail well into the 21st century.

I. RESEARCH NEEDS

There are at least three important problems that have and may continue to hinder progress in weed science. The *first* problem is the assumption that anyone can control weeds. Those who make this assumption understand neither the complexity of weed problems nor their solutions. They do not know how much specialized, sophisticated knowledge is required to control weeds correctly. Those who have studied weeds and their control know how wrong this assumption is. The *second* problem is that weeds are such steady components of the environment. They lack the appeal and urgency of sudden, serious infestations of other pests. Other pests *are* serious, but that does not mean they are more serious than weeds or deserve more attention. If a problem is always there, it doesn't receive the attention or funding that new, obvious, but perhaps no more serious problems receive. A reasonable analogy can be drawn with thoughts about world hunger. Famines receive the greatest attention but persistent, widespread hunger and malnutrition are the most serious aspects of world hunger.

The *third* problem is a lack of people and research funds. A great deal of research is done by large herbicide development and sales corporations. It is good work, but it is inevitably oriented toward sales. Research on weed biology, ecology, seed dormancy, and other problems that lead to basic understanding rather than immediate control is done by too few scientists. Public funding of agricultural research and specifically weed research is not growing. There continues to be a rapid increase in the research capability of private sector corporations, and the publicly funded agricultural research and development system is and, it seems, will remain, a minor component. Private sector research increasingly induces the nature of public sector research rather than the opposite (Buttel, 1985). Thus, weed science has few scientists, and too few of them work on long-term, sustainable approaches to weed management.

This chapter will deal with the future of weed science in terms of research possibilities rather than in terms of what will be accomplished. It is a chapter of conjecture, not one of prophecy. It might be best conceived as a proposal of what ought to be done. It may not be exactly what will be done because research does not always follow a straight path, and other developments may change what ought to be done. For example, environmental legislation that mandated reduced herbicide use could rapidly change the way agriculture is practiced. A description of research needs is a safer prophetic stance. It describes what could be done rather than what the situation will be several years hence. This approach, of course, reduces the possibility that the prophet will be wrong.

A. Weed Biology

Weed Biology and Seed Dormancy

Weed scientists know that dependence on herbicides is equivalent to treating the symptoms of a disease without actually curing the disease, but there has been little choice. Agriculture would be far better served if weed scientists learned how to control weed seed dormancy and seed germination so weed problems could be prevented, rather than controlled after they appear. No one knows enough about weed seed dormancy, and much research remains to be done to reach the prevention goal.

Empirical herbicide testing has made it easy to control weeds without studying their biology. Any attempt to control must know what weeds are to be controlled and where they are growing. That is, control is not blind. There is an object to be controlled, and it is known. But, with herbicides, it has been necessary to know something (what is that weed?), but not much about the weed. In general, herbicide development has neither exploited weak points in a plant's life cycle nor has it used specific physiological knowledge for control purposes. The safest approach has been to aim for, although it is rarely achieved, complete control of weeds in a crop. As knowledge grows, scientists find that some weeds are not injurious in some crops and control is not necessary. Some plants that are now considered weeds may be beneficial and should not be controlled. To acquire the necessary information about the entire life cycle of a weed, including knowledge of the dormancy of its seeds and vegetative reproductive organs, must be known. A marvelous series of projects could be developed on the biology of perennial weeds. These projects should include those mentioned by Wyse (1992):

Regulation of weed seed dormancy
Regulation of bud dormancy of perennials
The development and loss of reproductive propagules of perennials
Weed population genetics
Modeling of crop-weed systems

Several research programs are oriented toward modeling crop-weed systems. Models take several forms and several are available (see Chapters 6 and 19). Models attempt to combine effective use of several tillage techniques aided by computer technology to find weed control strategies that minimize herbicide use. Models routinely include knowledge of the size of the soil seed bank, rate of seed emergence, and seedling survival. It is only logical to assume control and management methods will improve as knowledge of weed biology and seed dormancy improves.

Weed-Crop Competition and Weed Ecology

Much of the basic information required to develop computer-based models of weed-crop systems that lead to best use of available weed control techniques has come and will continue to be derived from weed biology and ecology research. What plants compete for and when competition is most severe between crops and weeds are known in sufficient detail to be useful in development of weed management systems. The old, but still used, period threshold concept of weed competition (Dawson, 1965) affirms that weed competition is nearly always time dependent. Seedling weeds in the crop very early in the season (i.e., at emergence) are less detrimental than those that compete with the crop later on. This principle led to timely use of herbicides and other techniques for weed management. Some crop cultivars are more competitive than others, and this needs to be considered in developing weed management systems and as a basis for cooperative work with plant breeders.

Weed populations change with time, and the reasons are beginning to be understood. One reason is the development of weeds that are resistant to some herbicides, often after less than only a few years, use in one field (see Chapter 12). Active research on why resistance occurs is coupled with development of techniques to combat it. The chances of selection for resistance are increased when a persistent herbicide with a single site of action is used for several years. When resistance has developed, it has not led to totally unmanageable weed populations because other weed control techniques (e.g., cultivation or crop rotation) are available. Other reasons weed populations change with time are found in the study of weed ecology, a relatively new area of emphasis in weed science. Understanding why populations change and the weed management implications of population shifts is important to development of successful, sustainable weed management systems.

Even the casual observer of the world of weeds will recognize that weed problems change. The weeds most difficult to control in most crops today are not those that were important 10 or 20 years ago. That is evidence that weed scientists have developed successful solutions to weed problems. It is also evidence that nature abhors empty niches. When successful control efforts have reduced the population of a species they have inevitably left space unoccupied and resources unused. Other species move into empty niches created by successful weed control.

Solutions to this dilemma take two forms. The first solution is to reduce the attractiveness of the niche. Farmers typically overprovide for crops. Fertilizer placement and precise rate recommendations have reduced surplus nutrients, but whole fields are irrigated and light cannot be controlled. If water could be placed (e.g., drip irrigation) as precisely as fertilizer and only what was needed was provided, the attractiveness of the niche and the success of potential invaders could be reduced. This is a preventive approach to weed management. The second approach has an element of prevention. Few look carefully, but some of the important problem weeds of the next decade are already in fields or lurking on the edges. If they were identified and their weedy potential determined, weed scientists could try to predict which ones would be successful invaders, and they could then be controlled or managed before they invaded. More basic biological-ecological knowledge is essential to either approach. Without this knowledge, weed science may be doomed to endure the Red Queen effect (a character in Lewis Carroll's classic book *Through the Looking Glass*). The Red Queen tells Alice, "In this place, it takes all the running you can do to keep in the same place." Weeds and our ability to control them, especially with herbicides, seem to be evolving at about the same rate. In trying, and often succeeding, to eliminate weeds from fields, weed scientists have created, in a sense, better, more ecologically successful weeds as well as negative environmental effects of dominant control technologies.

B. Allelopathy

Allelopathy could be discussed with herbicide technology (the following section). It is a well-known plant phenomenon that has been studied for a long time but has not been commercially exploited (see Chapter 8). It is intriguing that plants have natural chemical defenses that could be discovered and exploited as herbicides. It is one of those things that seems to be forever just beyond our grasp. Maybe there has been too little research. Maybe the responsible chemicals are very common in nature, not selective enough, or not active enough for commercial use. Maybe some observed effects are not allelopathy at all. The lure remains. It will take time and good research to discover if a natural herbicide (an allelochemical) can be found and developed for commercial use and to ask if they are, in any way, environmentally superior to synthetic organic herbicides.

C. Biological Control

What if the agrichemical industry had never developed? Just suppose that someone had discovered an organism in 1944 that selectively controlled annual broadleaved weeds in small grains. What would weed science be like? Would we use as many herbicides as we now do? Would our environmental problem be what to do with mutating organisms rather than polluting chemicals? Interesting questions make nice debate topics, but they don't always solve problems. Biological control is still in its infancy compared to other control methods (see Chapter 10). Its theoretical potential, unrealized in all but a few cases, has had little effect on integrated weed management systems for agronomic or horticultural crops. Future research may discover specific biological control organisms and combinations of organisms that are effective and safe and can be integrated with other methods of weed management in crops. There aren't many now.

Those who understand the techniques of biological weed management readily acknowledge that it is not devoid of environmental concerns. However, the "massive accumulation of environmental problems—air pollution, acid rain, the greenhouse effect, ozone depletion—suggests that few of our citizens and virtually none of our politicians have seriously considered that the very meaning of progress in the future must be different" (Bellah et al., 1991). What the public may regard as the thoughtless exploitation of the earth at the expense of future generations will not be tolerated, and weed management may have to rethink and redefine what proper weed control is.

D. Weed Control and Bioeconomic Models

Rotation of crops is an effective way to reduce weed competition and will be a more important part of future weed science research. Future rotations may include use of more smother and green manure crops to keep land covered and protected from wind and water erosion more of the year. It is well known that rotations reduce soil erosion and manage weeds, but the research has not been done so that one can say exactly what weeds will be managed effectively and how rotations can be used to greatest advantage. Rotational research will have to include research on the relative competitiveness of crop cultivars and weeds.

Cultivation, from plowing to inter-row tillage, has been part of growing crops and weed management for years, but it has been employed without knowing its full potential in integrated management systems. Cultivation will continue to be part of many crop and weed management systems, but its potential to encourage soil erosion must be recognized. Worldwide 2 billion hectares of soil (greater than the area of the United States and Canada combined) have been degraded (Cummings, 2006). Sir Albert Howard's 1940 book *An Agricultural Testament* criticized the rise of what he called "scientific agriculture." Following the work of Leibig in the mid-19th century, many thought that all plants needed from soil was the correct quantities of nutrients. Without Liebig's work and the development of nitrogen fertilizer, it is highly probable that 40% of humanity would not be here.

Howard was concerned with the success of farmers and with feeding people, but he was more concerned with the health of the soil upon which, in his view, the health of a nation depended. To reduce soil health to a few chemical inputs was the worst of reductionist science (Shapin, 2006). In Africa, the site of the some of the world's most persistently hungry people and difficult weed problems, 3/4 of arable land is severely degraded (Cummings, 2006). The cost of soil erosion is estimated to be US $400 billion annually (Cummings, 2006). Weed management has a role in solving this problem. It may be possible, as unlikely as it may seem, to farm land without creating a weed problem (Faulkner, 1943). Soil tillage routinely buries weed seeds for future recovery and growth. That does not seem to be good weed management.

Research will have to be done to determine the effect of cultivation timing with different types of implements on specific weeds. Much of the work will emphasize modeling of the crop-weed system to determine optimum timing for different weed management techniques during the crop's life (Wyse, 1992).

E. Bioeconomic Models

Models and modeling were discussed in Chapter 6. In the early 1980s, two decision-aid, computer-based models were available. By the early 1990s, 21 mostly crop-based, weed control-management, decision-aid computer-based software models were available to researchers and farmers (Mortensen and Coble, 1991).

Available models will be refined and new models will be developed. Some weed scientists suggest the ideal is a mechanistic weed-crop competition model that considers and responds to changing environments. The essential knowledge of weed biology to construct such models is not yet available (Schweizer et al., 1996). In most models, weed density is the sole variable used to estimate crop yield loss. Future models will incorporate a variable for relative time of crop and weed(s) emergence, crop density, climate variation, method and amount of fertilizer applied, and weed density (O'Donovan, 1996). Rather than just predicting crop loss, as important as that is, future models will also enable realistic monitoring of weed population development and long-term implications of failure to control, or to say it another way, the long-term implication of seed production by uncontrolled weeds (O'Donovan, 1996).

As more biological knowledge of weeds becomes available, as weed seed sampling techniques improve, and as models improve, they will be used by decision makers. Weed management decisions guided by models will lead away from prophylactic control methods. Such methods have accounted for the clear and repeatable success of ridding a farm of weeds for a season. They have not provided long-term control of weeds in several crops in economically efficient, environmentally sound ways. Models and modeling have emphasized herbicides that have been profitable and efficacious. These will continue to be important criteria but long-term weed management success will become a more important criterion of success. As new knowledge is incorporated, computer-based, weed management decision-aid models will provide greater assurance of achieving profitability and appropriate long-term weed management. Some of the knowledge required to develop better models is shown in Table 20.1.

F. Herbicide Technology

Herbicides are the most successful weed control technology ever developed. They are selective, not too expensive, fairly easy to apply, have persistence that can be managed, and many formulations and kinds are available. In spite of their many advantages, herbicides are far from perfect even in the eyes of

TABLE 20.1. Some Examples of Knowledge Required to Develop Improved Weed Management Systems and Decision Aid Models (Buhler et al., 1997).

Management goal	Research needed
Management decision aids = models seed bank	Relationship of the size of the weed to final weed population
	Emergence rate of individual weed species
	Determination of economic optimum thresholds for control
	Interaction of management practice and weed seed production
	Effect of weed density on control
Prediction of seedling emergence	Mechanisms of dormancy
	Determination of interaction of environmental conditions, seed germination, and dormancy
Effect of management on weed seed	Effect of crop rotation of weed seed bank size
	Effect of living and dead mulches
	Rate of seed predation and decay
	Rate of seedling mortality
	Light requirement for seed germination
	Role of tillage and cultural practices

their staunchest advocates. Ideal herbicides, which would have the following characteristics, are not available:

1. Effective on a spectrum of weeds or able to control a single species selectively.
2. Very selective in at least one major crop and some minor crops.
3. Not toxic to nontarget species, not just to humans.
4. Persistent in soil but not beyond the period of intense weed competition.
5. Easily and quickly degraded to innocuous breakdown products by soil microorganisms or nonenzymatic soil processes.
6. Applied postemergence to avoid the prophylactic nature of preemergence use.
7. Active at very low rates (mg or g/ha = ounces or fractions of an ounce per acre).
8. Not leachable and not volatile.

There are some herbicides that meet *nearly* all of these criteria, but none is perfect, and much remains to be done to develop better herbicides. There is no adequate justification for abandoning herbicides for weed management. There is adequate justification for reducing their use for weed management.

Study of Plant Biochemistry and Physiology

It is known that dichlobenil and isoxaben affect a plant's ability to synthesize cellulose. However, neither was developed to do so. It is serendipitous that they interfere with a specific plant process. There are four ways to discover new herbicides (Beyer, 1991; Evans, 1992).

Method 1. Random selection of chemicals submitted to targeted biological screening tests. This method relies on carefully developed, targeted biological screening techniques to detect chemicals with activity and selectivity. Candidate chemicals are obtained from a company's several divisions or purchased. This is often referred to as the "blue sky" approach (Evans, 1992).

Method 2. Screening of chemical derivatives of herbicides with known activity. Once activity is found in Method 1, derivative or chemical analog development ensues and further screening attempts to gain more activity or greater or different selectivity.

Method 3. Development of leads taken from natural products that display biological activity. Nature can be viewed as an intense arena of complex chemical activity. Allelopathy is only one arena of chemical activity. Biologists and chemists can find clues in this chemistry that could lead to successful herbicides. There have been few successes (Evans, 1992). Natural products are inherently complex, and the chemicals frequently have insufficient potency or the wrong activity or selectivity to provide strong leads for chemical synthesis (Evans, 1992).

Method 4. Rational design based on biochemical principles and knowledge of plant physiology and biochemistry. The most intellectually attractive concept is biorational design. The organism to be controlled is considered to be a target, and an enzyme that is essential to its survival is chosen for direct attack. Candidate chemicals are developed to inhibit an essential plant function, based on biochemical knowledge of the target site. To date there has been little success, but the technique is advancing rapidly (Evans, 1992).

Scientists know how to use all four techniques. In practice the first two have provided almost all presently available herbicides. Method 1, in which a large number of chemical compounds are screened for possible activity, is the most common method of herbicide discovery. The screening process includes structural relatives of compounds with known activity and chemical structures with unknown activity. Method 4, biorational design, has become increasingly feasible and useful. Combination of biological performance, toxicological properties, and environmental behavior with computer analysis will make this a powerful technique for herbicide development. The broad screen (Method 1) has been very successful. The herbicide industry will likely base future screening programs on greater understanding of plant biochemistry and physiology (Method 4). It is a certainty that future screens will more precisely target specific plant processes as the biochemistry of those processes becomes known.

Rate Reduction and Precise Application

Sulfonylurea and imidazolinone herbicides (see Chapter 12) reduced herbicide rates by an order of magnitude; from kilograms to grams per hectare (pounds to ounces per acre). That is a desirable direction from an economic and an environmental perspective. Further reductions are possible when there is more information on threshold levels for phytotoxic activity. Most herbicides are now broadcast over the entire target area. A few may be banded over the plant row. These methods require enough herbicide to satisfy the soil's adsorptive requirements and must account for dilution in soil. When knowledge of precise thresholds is combined with precise application, a further reduction in rate will be achievable. The essential question is "What is the minimum amount that can be applied to achieve the desired control level?"

Soil Persistence and Controlled Soil Life

It is at once a major problem and a significant advantage that herbicides persist in soil. Excessive persistence may affect succeeding crops, lead to contamination of ground- or surface water, or cause undesirable residues in crops. Some persistence is good because it gives weed control over time and avoids the necessity of repeated herbicide applications and the necessity of using other weed control methods in the crop. Regulating or controlling soil life is a desirable goal for future herbicide development. If nonpersistent herbicides could be given a few weeks of persistence and the soil life of herbicides with long persistence but desirable activity and selectivity could be shortened, it would be good. If these things are achieved, it will probably be through controlled release formulations that have already achieved some success (e.g., encapsulated alachlor). The technology for these formulations is a special challenge in the complex soil environment.

Formulation Research

A few decades ago, only a few formulations were available (see Chapter 16). Most herbicides were emulsifiable concentrates, solution concentrates, or wettable powders. A few granular formulations were available, but application technology limited their use. Today formulation chemists have reduced dust, foaming, and storage problems, made handling easier and safer, and improved efficacy. Users can choose from all the previous formulations and several improved ones. Further improvement will occur to make formulations safer and easier to use. Controlled release formulations could reduce volatility, leaching, and use rates, and increase selectivity. They could give nonpersistent herbicides a desirable soil life without fear of residual carryover to the next crop.

Perennial Weeds

There are some herbicides that control perennial broadleaved or grass species. Perennial members of the *Cyperus, Cynodon, Sorghum, Cirsium, Convolvulus*, and *Eltrygia* genera are not generally controlled selectively by available herbicides. Few herbicides that are sufficiently active on perennial weeds are also selective enough to be used in most crops, and several persist in soil. It is relatively easy to control the emerged shoots of perennial weeds but far more difficult to ensure translocation of an adequate amount of the herbicide throughout the extensive root, root runner, rhizome, or stolon system of a perennial weed. Selectivity is a greater problem than activity. A continuing problem for turf managers is selective control of coarse-leaved perennial grasses (e.g., quackgrass or tall fescue) that infest fine-leaved turf species (e.g., Kentucky bluegrass).

Aquatic Weeds

The difficulty of controlling aquatic weeds is related to their habitat not their life cycle. Seventy percent of the earth's surface is covered with an interconnected water system. All waters flow to the sea and all contaminants can be carried along as dissolved solutes or adsorbed to eroded soil. Almost all water contamination is, in the minds of most people, unacceptable. Because of heightened and enlightened concern about environmental quality, the unacceptability of contaminating water has resulted in legislation to prevent, control, and punish water pollution. Only a few herbicide active ingredients can be used in aquatic systems. Present and future herbicides must be compatible with all other actual and potential uses for water. This is a very difficult requirement, and extensive and expensive research will be required if acceptable weed management techniques are to be developed. In the aquatic environment, it is likely that proof of safety will be demanded by an anxious public. Reasonable assurance or reasonable doubt will not suffice. Because of these appropriate concerns, the aquatic environment is a likely site for development of nonchemical control techniques.

Parasitic Weeds

Parasitic weeds are present in the United States. Unless one has them, they are not regarded as major problems in most US states. They are major problems in several of the world's developing countries (see Gressel et al., 2004). Few selective herbicides or other control techniques are available (see Chapter 3). Research has not focused on them because they are very difficult problems and because herbicide development and developers have concentrated on large acreage crops of the developed world. It takes only a little experience with parasitic weeds to recognize how devastating they can be and how large crop yield losses can be. Third World farmers stop growing susceptible crops, abandon fields, and are often defeated by parasitic weeds. Developing reliable, affordable management techniques for parasitic weeds would be a significant scientific contribution and a major contribution to development of agriculture in the world's poor countries. Imaginative and scientifically sound biotechnology solutions may help to solve parasitic weed problems. One approach to the *Striga* problem in Africa was mentioned in Chapter 3. It involves applying very low doses of an appropriate herbicide to maize seed after the maize plant has been rendered resistant to the herbicide through now standard transgenic techniques (Gressel et al., 2004). It remains to be seen if the herbicide industry, governments, or other research agencies will be adequately funded and thereby encouraged to pursue the work and relieve a major Third World (particularly African) weed problem.

Packaging and Labeling

Major herbicide manufacturers have developed safe packaging and are concerned about personal safety of users. Systems that minimize human exposure are available and will become more common. Manufacturers and users are working together to minimize the hazards of herbicide handling and container disposal. Safe efficient herbicide delivery systems will be needed, and they will demand adaptations in formulations and application methods.

Herbicide labels and use instructions in the world's developed countries are explicit, readily available, and contain adequate instructions for all approved uses. Sadly, the same is not true in much of the rest of the world. Manufacturers are well aware of the problem. Labels have to be developed that are clear, simple, adequate to the task, but not too complex. When potential users may be illiterate, clear instructions are imperative. It is a difficult challenge to create instructions that combine the need for clarity and accuracy in view of the growing complexity of herbicide chemistry and use.

The Agricultural Chemical Industry

Innovation and progress in herbicide development depend on the agrichemical industry, where consolidation has led to domination by a few large, world-oriented European and US companies. The industry is growing less rapidly than it once did because of greater market saturation in the developed countries and limited prospects for quick expansion in the large, diffuse market in the world's developing countries. The trend toward no- and minimum tillage, evolving soil tillage practices, genetic modification to create herbicide resistance in crops, and the changing weed spectrum in crops will together and individually affect the herbicide market.

Mergers among agrichemical companies began in 1986, when DuPont bought Shell's pesticide division, and the agricultural groups of Dow and Eli Lilly merged their agricultural chemical divisions into a new company: DowElanco. The French firm Rhone-Poulenc bought Union Carbide's agrochemical business, which had previously absorbed AmChem (that previously had purchased the herbicide business begun by American Paint Co.). These units all merged with AgrEvo, which had been formed from NOR-Am and Hoechst-AG to form Aventis in 1999, which merged with Bayer Crop Science in 2002. The American division of Britain's Imperial Chemicals Co. (ICI) bought Stauffer Chemical group from Cheeseborough-Ponds, and the Swiss company Sandoz bought VS Crop Protection (Velsicol). Sandoz Agrochemical and Ciba combined to form Novartis, which merged in 2000 with AstraZeneca to form Syngenta. In the same year, BASF bought the agricultural division of American Cyanamid. For a complete summary of herbicide company genealogy prepared and maintained by A. P. Appleby, Professor Emeritus of Oregon State University, see cropandsoil.oregonstate.edu/herbgnl.descr.html.

To the outsider it seemed that boards of directors must have said, "Let's either get big or get out." As reported in Chapter 12, there has been no negative effect on the availability of herbicides. It remains for historians to ascertain the effect of these mergers on agriculture. There is a downward price pressure due to patent expirations, market saturation, and competition. The cost of development for a single herbicide (that must pay for all failures) is estimated to be greater than $40,000,000. The agricultural chemicals business is not one for the timid. Costs of herbicide development are increasing, and new, profitable herbicides are rarer and more expensive. Biorational approaches that consider biological efficacy, toxicology, and environmental interactions and, presumably save money, will dominate design of new herbicides. These approaches will be combined with more specialized chemical, biological, and safety testing to determine mode of action, use, economic benefit, and environmental acceptability.

The green or environmental movement has helped create ever more restrictive herbicide legislation and regulation, which the public thinks is justified. Some feel there is more emotion and law than science in decisions that affect herbicide use and development and govern environmental decisions. Regulations that are too restrictive, it is claimed, suppress herbicide development.

These brief comments on the agrichemical industry are included to give the reader insight into the business side of agriculture that is often not noticed by those who control weeds. Business decisions in corporate executive offices may have a much greater affect on future weed management programs and the direction of weed science than anything that occurs in a research laboratory.

G. Biotechnology and Herbicide-Tolerant Crops

All major herbicide companies have research programs to incorporate herbicide tolerance in crops (so-called transgenic crops). Success has been achieved with several herbicides. The work has focused on major crops: corn, soybean, wheat, rice, cotton, and tobacco (Duke et al., 1991). The technology for agricultural crops was introduced in the mid-1980s. From then to 1994, more than 1,500 approvals for field testing of a wide range of transgenic organisms were granted, and 40% of them were for herbicide tolerance (Hopkins, 1994). Between 1996 and 1999, the world's commercial area (albeit dominantly in the United States) planted with transgenic crops increased from 1.7 to 39.9 million hectares (James, 1999) and to 81 million hectares (200 million acres) in 2004, a steady double-digit growth rate. By 2005, 8.3 million farmers (http://www.isaaa.org; accessed August 2006) grew transgenic varieties on more than 90 million hectares (222 million acres) of land in 21 countries. Transgenic crops (GMOs) have been one of the most rapid instances of technology adoption in agricultural history. Soybeans are the most common genetically modified crop. Corn is second with more than 21 million hectares (51.8 million acres) of corn modified to resist an herbicide or produce insecticides in 2005, up from 300,000 hectares (741,000 acres) in 1996 (Halweil, 2006).

More than 7 million of the 8.5 million adopters are small-holder farmers in the world's developing countries (Chassy et al., 2005). For example, transgenic cotton was first planted in China in 1998 and now is 50% of the cotton acreage. Yields improved 10 to 30%, pesticide use declined 50 to 80%, and farmer profit increased (Chassy et al., 2005). In fact, insecticide use in agriculture has declined due to transgenic crops (Chassy et al., 2005; www.ers.usda.gov/publications/aer810/; accessed July 2006). But Lang (2006) warns that all is not rosy. Cotton resistant to bollworm was planted widely, worked well, and failed. After 7 years of use, bollworms resistant to the Bt cotton have not appeared, but secondary pests have appeared in abundance. Farmers are now spraying cotton up to 20 times a season to control the secondary pests (e.g., mirids) that formerly were controlled by the insecticides used to control bollworm.

Because the transgenic crops have been available for some time, it is not unreasonable to ask why they are discussed in a chapter on the future of weed science, as well as in the preceding chapter. The reason is that although we know what has been done with agricultural biotechnology and herbicide-resistant crops, the technology is so new and changing so rapidly that we do not—perhaps cannot—know what might be done. That is, the direction of research is clear, but the final destination is not. We cannot be sure what new possibilities will be discovered as the technology of herbicide resistance continues to develop rapidly. Adoption of molecular-based methods in weed science research will bring a new dimension to the science and can have "far-reaching benefits in agriculture and biotechnology" (Marshall, 2001). One potential benefit of genomics research is the discovery of new targets for herbicide action (Hess et al., 2001). Other benefits may include identification and use of genes that contribute to a crop's competitive ability (e.g., early shoot emergence, rapid early growth, fast canopy closure, production of allelochemicals). Genomics may also discover genes that contribute to weediness (see Chapter 2), a plant's perennial growth habit, seed dormancy, and allelopathy (Weller et al., 2001).

There are three physiological mechanisms for natural or induced tolerance or resistance to an herbicide:

1. reduced sensitivity at a molecular site of action,
2. increased metabolic degradation, and
3. avoidance of uptake or sequestration (hiding) after uptake (Duke et al., 1991).

Each of these has potential use in development of resistance in crops. Several examples of herbicide resistant crops are shown in Table 20.2. Most of those modifed to be resistant to glyphosate and glufosinate are commercially available and grown. Some of the crops listed in Table 20.2 have been created but are not currently sold in the United States. Roundup Ready™ soybeans, corn, cotton, and canola have achieved commercial success in the United States and Canada. Other glyphosate-resistant crops are being developed by Monsanto.

Criticism of herbicide-resistant crops is common and is usually related to all or some of four perceived risks (see Zimdahl, 2006, for a discussion of ethical concerns).

Public health. Concern has been expressed about water or food contamination from increased herbicide use. Additional concern centers on use of herbicides in crops that do not metabolize the herbicide. Therefore, the unaltered herbicide could be consumed by people. As biotechnology and herbicide-resistant crops develop, it is important to remember that no technology is ever proved to be perfectly safe. The nature of science and its reliance on probability prevent absolute verification of safety. Science cannot prove a

TABLE 20.2. Some Herbicides and Crops That Have Been Modified to Be Resistant to Them. Not All Herbicide-Resistant Crops in This Table Are Currently Marketed in the United States (Duke et al., 1991; Hopkins, 1994; Hubbell and Welsh, 1998; www.agbios .com/dbase.php; Accessed September 2006).

Herbicide	Crop
Atrazine	Canola
Bromoxynil, Ioxynil	Canola, cotton, potato, tobacco, tomato
Glufosinate	Alfalfa, barley, canola, corn, cotton, peanut, rice, soybean, sugarbeet, sugarcane, tobacco
Glyphosate	Alfalfa, canola, corn, cotton, creeping bentgrass, lettuce, soybean, sugarbeet, tobacco, tomato, wheat
Imidazolinones	Canola, corn, cotton, potato, sunflower, tobacco, wheat
Sulfonylureas	Canola, corn, flax, grape, tomato, tobacco
2,4-D	Corn, cotton, potato, tobacco

negative. Scientists look for evidence of harm, and if none is found, conclude that there is none or that it must be looked for in a different way (Anonymous, 2005). Second, this technology, like all technologies (e.g., herbicides, cell phones, computers), has both its good and bad uses. We must be cautious about demonizing the potential but unknown bad effects of legitimate uses by good people and weigh them carefully against illegitimate uses by bad people.

Environmental concern. Environmental concern is related to herbicide use. Hubbell and Welsh (1998) suggest that transgenic crops have the potential to create a more sustainable agricultural system than present chemically based systems but will fail "in enabling a fully sustainable agriculture." They claim that genetic traits[1] that have a higher potential of enabling truly sustainable agricultural systems have not been developed for three main reasons.

1. The lack of EPA and USDA regulatory policies that specifically promote sustainable traits.
2. An agricultural biotechnology industry that is dominated by agricultural chemical companies.

[1]Hubbell and Welsh (1998) divide these genetic traits into three categories: transitional, compatible, and sustainable. Transitional traits reduce environmental damage (glyphosate tolerance); compatible traits are those with limited future value but during their useful lives they enhance use of sustainable practices (crops that substitute for toxic chemicals); and sustainable traits are those that encourage use of sustainable practices (there are presently no transgenic crops in this category—examples include plants that make efficient use of natural fertilizers, conversion of annuals to perennials, or enhancing the nitrogen fixing ability to reduce fertilizer use).

3. Patent law and industry policies that prevent farmers from saving transgenic seed and thus tailoring transgenic crops to their local ecological conditions.

Social concern. Social concern is related to the following:

1. Fear the technology will favor large farms and lead to loss of more small farms and small-scale farmers. It is estimated that as many as 1.4 billion small-scale farmers grow 15 to 20% of the world's food from seed saved from the previous year's harvest. Much of this food, grown by women, is not sold. It is eaten or bartered and is often omitted from production figures. Loss of the ability to save seed may drive these farmers out of farming (Sexton, 2004).
2. Cost of food production and food cost to the consumer will rise.

Weed control concerns. There are three concerns related to weed control:

1. *Development of herbicide resistance.* Herbicide resistance among weeds may become more widespread because of continued use of an herbicide to which a crop is resistant (see Sandermann, 2006).
2. *Resistant gene flow to sexually compatible plants.* This is acknowledged as a potential risks of introducing any genetically engineered (transgenic) crop variety. The risk is transfer of desired herbicide resistance from the crop to a weed where undesirable resistance persists by natural selection. It is worth noting that this has happened when genes from herbicide resistant canola moved to a nonweedy relative in the mustard family and then to wild mustard in a short time.[2] The risk may be especially high where the crop and weed are closely related and can interbreed—for example, red rice and rice or johnsongrass and grain sorghum.
3. *Resistant crop plants becoming hard-to-control volunteer weeds.* This has not been shown, but Keeler (1989) urged caution and pointed out the example of wild proso millet that emerged as a weed in the 1970s after over 200 years of successful cultivation of proso millet in North America without its becoming a weed. Keeler (1989) used wild proso millet to emphasize how much we do not understand about weed evolution.

The quite legitimate concerns of epistasis and pleiotrophy must also be recognized. *Epistasis* is the suppression of gene expression by one or more other genes, and *pleiotrophy* is defined as a single gene exerting simultaneous effects on more than one character. In short, the rules of ecology apply: It is impossible to do just one thing. When science manipulates a genome, any genome,

[2]*Denver Post*, April 14, 1996, and *New York Times*, March 7, 1996.

specific outcomes are intended, and even when these are achieved, other, unplanned things may also occur. Genetic engineering, with the best intention to do a good thing, may do unexpected things that could be good or bad.

Another common critique of herbicide resistant crops is that the technology will promote the use of herbicides, not decrease it, while continuing to develop what many view as an unsustainable, intensive monocultural agriculture. It is also suggested that herbicide-resistant crops will reinforce farmers' dependence on outside, petroleum-based, potentially polluting technology. An associated concern is that there is no technical reason to prevent a company from choosing to develop a crop resistant to a profitable herbicide that has undesirable environmental qualities such as persistence, leachability, harm to nontarget species, and so on. It is undoubtedly true that nature's abhorrence of empty niches will mean that other weeds will move into the niches created by removal of weeds by the herbicide used in the newly resistant crop. In other words, herbicide resistance will solve some but not all weed problems. Weeds that are not susceptible to the herbicide to which the crop is resistant will appear. Weeds are not conscious, but they seem to be clever.

Development of herbicide-resistant crops is proceeding rapidly, and there are important advantages that provide good reasons for their development. Many argue that the technology will provide lower-cost herbicides and better weed control. These are powerful arguments in favor of the technology because both can lead to lower food costs for the consumer. It is also true that herbicide-resistant crops are providing solutions to intractable weed problems in some crops. Glyphosate resistance has been created in several crops. It is an environmentally favorable herbicide, and therefore, many (e.g., Hubbell and Welsh, 1998) argue that it is better to use it in lieu of other herbicides that are not environmentally favorable. An important argument in favor of the technology is that it has the potential to shift herbicide development away from initial screening for activity and selectivity and later determination of environmental acceptability to the latter occurring first. Resistance to herbicides that are environmentally favorable but lack adequate selectivity in any crops or in a major crop so their development will be profitable could be engineered and the herbicide's usefulness could be expanded greatly. This has important implications for minor crops (e.g., vegetables, fruits) where few herbicides are available because the market is too small to warrant the cost of development. If resistance to an herbicide already successful in a major crop (e.g., cotton) could be engineered into a minor crop, manufacturers and users would benefit.

Biotechnology was discussed by Christianson (1991), a self-acknowledged outsider, and his view is quoted here to present an alternative view of this research:

> I think it would be a pity if the power of the use of mutants and mutation to uncover and describe physiology and development were limited, in the hands of weed scientists, to the isolation and description in yet another species of yet more genes that confer resistance to yet another herbicide.

The central issue for weed science is understanding the nature of weeds: What makes a weed a weed (see Chapter 9)? How can weeds consistently come out ahead when matched up against the finest commercial varieties that plant breeders develop? Weeds persist, they spread, and they outcompete crop plants, reducing yields when left uncontrolled. The nature of the "competitive ability" that weeds possess seems an interesting target for research and an appropriate target for analysis through generation of mutants. The 1950s gave us catchy phrases that still resonate: Better living through chemistry; atoms for peace. We don't hear similar things now. Chernobyl, Three Mile Island, napalm, Agent Orange, space shuttle crashes, and ozone destruction dominate the public's thoughts. Human drug disasters have soured the public on the efficacy and trustworthiness of science and scientists (Lemonick, 2006). It is in this context that public doubts about genetic modification of anything are raised, and it is in this context that these doubts must be addressed. Weed scientists and others involved with GMOs often think if we can just educate the public about our science (William et al., 2001), then they will understand. Education is important, but a conversation among equals may be a better course, especially in a time when science has made mistakes and is regarded with some well-founded suspicion.

Transgenic crops are a controversial research area that is developing rapidly (see Hileman 1995; Zimdahl, 2006). It is not the purpose of this text to analyze the controversy in depth. Others have done this (Duke, 1996; Zimdahl, 2006). Scientific journals and popular press articles too numerous to mention are available. Much more work will be done and discussed but, it is important to realize that the technique is already widely promoted, accepted, and used.

H. Organic Agriculture

To borrow from G. K. Chesterton, who spoke of Christianity, organic agriculture within weed science, with some exceptions, hasn't been tried and found wanting, but it has been found difficult and left untried. Evans (2002, p. 14) said it differently but gave us the same message:

> Because weeds are inextricably both products of psychology and ecology, weed problems are best addressed by considering not only the agroecosystems that produce them but also the culture that informs how we think and farm. Recognition of this point is potentially threatening and subversive for it challenges the very

> social structure of farming upon which employment of weed scientists depends. They are, in effect, servants of large-scale, single-crop, commercial agriculture and if that were to disappear so too would a large proportion of their jobs.

Weed scientists have been conditioned to take pride in and seek to achieve crop fields where no weeds exist, just the crop (Harker, 2004). This may be the wrong goal. The goals of organic agriculture may have something to teach us about what Evans (2002, p. 51) calls a "blindly oppositional attitude" that led scientists to "frantically search for immediate solutions to an ever-worsening" weed problem. That search often obscured the need for different approaches to weeds and to needed changes in North American farming systems. Herbicides helped weed scientists to define weeds as the enemy, and only in the 1990s did this begin to change. The overuse of herbicides led weed scientists to neglect other weed management strategies (environmental awareness, herbicide resistance, pesticide reduction; Harker, 2004), which organic agriculture has encouraged thought about. The demands and popularity of organic agriculture may compel weed scientists to broaden their horizons and consider other weed management tools more carefully.

I. Engineering Research

The preceding section described research needs for herbicides. No matter how selective or active, herbicides have to be applied in the environment to function. The herbicide in the package is interesting but not functional. The Weed Science Society of America published a monograph on applying herbicides (McWhorter and Gebhardt, 1987). The monograph points out that over 90% of all herbicides applied annually in the United States were sprayed with sprayers that had the same four basic components—tank, pressure regulator, pump, and nozzles—that were on the sprayers when the herbicides were first sprayed. The technology has evolved, and application equipment is more precise, more durable, and more flexible than older pieces of equipment. But must herbicides be sprayed? Is there a better way? Some of all sprayed herbicides never hits the target. Can spray that doesn't hit the target be recovered and reused or at least handled so it doesn't reside in the environment without fulfilling its intended purpose? Low-volume and ultra-low-volume application techniques are available but not widely used. There is potential for decreasing the volume of spray required.

Sprayers are being developed that use remote sensing technology to sense weed presence and just spray where weeds are. Other techniques sense variations in soil type and adjust herbicide concentration to account for differences. Automated detection and identification of weeds remain as the greatest obstacle to development of practical, affordable, site-specific weed management systems (Brown and Noble, 2005). However, before site-specific systems can be perfected, affordable techniques to sample weed populations must be developed (Wiles, 2005). Sampling to determine the location of the problem is a fundamental principle of integrated weed management. Broadcast herbicide application reduces or eliminates the need to know where the problem is or where it may be. It is assumed to be everywhere, and that is not true. Sampling is a decision-making tool that has not been fully exploited by weed science primarily because there are no simple, affordable methods for weed seed sampling.

In addition to affordable sampling techniques, other research necessary to perfect remote sensing technology includes: the need for artificial lighting, definition of spectral band requirements, techniques for rapid image processing, multiple spatial resolution systems, and techniques for dealing with multiperspective images (Brown and Noble, 2005). For example, leafy spurge can become, and in many places is, a major problem on western US range lands. It can be detected easily by extensive, expensive ground surveys. Use of Space Imaging's 4-m multispectral Ikonos imagery was effective for detecting leafy spurge patches under some circumstances, but in areas with a high forb component, identification of leafy spurge was not as effective (Casady et al., 2005). Shaw (2005) evaluated use of remote sensing data for weed management and saw it as an area of "tremendous opportunity." He predicted that proper use of remote sensing would result in reductions in inputs, reduced environmental liability from applying herbicides to entire areas rather than just to weed patches, increased crop yield due to better management, and early detection and more effective management of invading species. A less sanguine appraisal of the profitability and economic feasibility of site-specific weed management was based on the advantages of reduced herbicide use and the additional costs of scouting for weeds, preparing treatment maps, and patch herbicide application (Swinton, 2005). Ecologically based, site-specific weed management may offer revenue gains to farmers compared to broadcast herbicide applications because while herbicides are very effective for weed control, further yield gains from their use are unlikely. Therefore, revenue gains, if any, will come from higher crop prices or environmental stewardship payments from government programs, which presently do not exist (Swinton, 2005). Policymakers and consumers may be willing to pay for increased freedom from the perceived and real environmental risks of herbicides. No one knows if this is true or if such policies can be developed and implemented.

Remote sensing techniques will be pursued and aided by global positioning technology that will permit more precise herbicide application on weed patches. The goal is to improve application accuracy and operator safety, while maintaining environmental quality and protecting crop yield.

Herbicide application is not the only area in which engineers can contribute to improved weed management. The effects of tillage over time on weed populations are not known. There is room for improvement in methods of mechanical control of annual and perennial weeds in crops. Cultivators are available to weed the entire area between crop rows and leave only a narrow band over the crop row. This is a vast improvement over a person with a hoe or an animal-drawn cultivator. Further research will reveal even more specialized tillage and cultivation methods for weeds in crops.

Tillage research has shown that much is unnecessary and, in fact, complicates weed management. Tillage exposes weed seeds to sunlight and encourages germination (see Chapter 9). No-tillage leaves seeds buried and prevents or inhibits germination. The best tillage for weed management may be none. That does not mean that weeds will not be present. No-tillage creates a niche for weeds that do well without tillage. It will change, but not eliminate, the need for weed management.

J. Vegetation Management, Integration of Methods, and Remote Sensing

In science, as in most human activities, movements occur, directions change, and progress may result. Some movements are called bandwagons. Each has associated words and phrases that define and identify it, called buzzwords. Each movement makes its contribution to the parade of ideas and contributes to the general cacophony of competing ideas, which, one hopes, will yield a harmonious new paradigm. Some ideas assume a position at the head of the line. It is too soon to tell if integrated weed management will be just another interesting, but temporary movement or if it is assuming a position of centrality and leadership. Integrated pest management (IPM) has endured as a good alternative to previous pest management systems, especially for insect control. It has been challenged because from 1968 to 1992, when US interest in IPM grew steadily, pesticide use in US crops increased 125% (Gardner, 1996). Many see IPM as a buzzword that hasn't changed pest control. If integrated weed management systems are to endure, change will be required. The direction and scope of change may determine the enduring success of the concept and practice of integrated weed management. Historians tell us, after the fact, what things have endured and why and why other ideas were only temporary phenomena. Judgments from the present are often flawed because one is so close that subjectivity dominates. The perspective of time is often a prerequisite to objectivity.

Will integrated weed management be regarded as just another buzzword that, like Andy Warhol's remark about people, had its 15 minutes of fame?

The idea makes so much sense that it is likely to endure. It is not perfect, but it is better than anything else we have. The evidence in this book is sufficient to demonstrate that weed management systems for crops are incomplete. They are developing, but the research gaps identified herein and summarized in Table 20.1, preclude defining complete systems. Several good research questions remain:

1. What seeds emerge first from complex soil seed banks?
2. What percentage or seeds, for each species, emerge each year?
3. What is the precise percent control for different weed control techniques for different weeds at different growth stages?
4. If soil seed bank composition is known, can the weed complex be predicted for a crop?
5. How do weed management techniques affect other pests and other pest control techniques?

It is likely that successful integrated weed management systems will be developed most rapidly within the opportunities and constraints of agricultural industrialization. Industrialization is a process whereby agricultural (or any industry's) production is structured under the pressure of increasing levels of capital and technology in a way that allows management systems to integrate each step in the economic process to maximize efficiency of capital, labor, and technology (Keeney, 1995; Urban, 1991). A primary question is whether this process is compatible with, and capable of achieving, a sustainable agriculture (Keeney, 1995). Keeney thinks that if agriculturalists, environmentalists, and government work together, a sustainable rural landscape can be achieved. If they do not, "today's haphazard and divisive times" will continue. Urban (1991) believes that the industrializing forces of consumer desires and demand, prescription agricultural products, molecular biology, and the changing nature of future farmers combine to make agricultural industrialization inevitable. Thus, the demise of the Jeffersonian agricultural heritage of the farmer is inevitable, and these changes will affect weed science.

Integrated control will no longer be able to limit its focus to weeds and weed control. To be successful, the focus should be the total vegetation complex or better, habitat management rather than weed control in a year in a crop. Perhaps it is most correct to say that industrialization will change the scale of concern. Sustainable integrated weed management systems must extend concern to environmental quality and future generations. These are large-scale concerns. Small-scale concerns such as how to control weeds in a crop in a year have dominated and future agricultural systems require change. Environmental concerns demand large-scale thought. Small-scale thought suffices for individual concerns. Large thoughts are needed for large systems. Everything needs to be integrated to have a complete crop management system. It won't be easy to do, but it is necessary.

K. Other Research

There are several other research areas that should be included in planning for weed science. These are less well developed than those that preceded but may be just as important:

1. What is the value and what are the advantages and disadvantages of monoculture?
2. What is the role of companion cropping and regular inclusion of cover crops in weed management?
3. What are the long-term effects of soil erosion after regular plowing and cultivation? One effect is all too apparent in the brown color of a country's rivers. Weed scientists were not too concerned with long-term effects when the science was developing. Weeds decreased crop yield; a detrimental long-term effect. The vision didn't extend much farther. Solving the weed problem was a sufficient challenge. Any technology, used for enough time, has demonstrable environmental and social effects. A longer-term view will help reveal these effects and compel their consideration before widespread use is achieved.
4. Weed science must begin to work more closely with economists who ask—What does it cost and what is it worth? What is it worth to do the work to develop a more competitive cultivar, to deplete the soil seed bank, to have assurance of 80 or 100% weed control? What will it be worth to be able to predict weed problems? No one knows but the answers are important to complete weed management systems.
5. How will nanotechnology and nanobiotechnology affect weed science. This is the integration of biological materials with synthetic materials to build new molecular structures. Synthetic biology goes beyond moving existing genes (biotechnology) to creating new ones that are programmed to perform specific tasks. Nano biotechnology operates at the nano scale of living and nonliving parts. It has enormous potential for both good and harm (Shand and Wetter, 2006). Syngenta already sells two pesticide products that contain nanoscale active ingredients that prevent filter clogging and are readily absorbed by plants (Shand and Wetter, 2006, p. 82).

II. POLITICAL CONSIDERATIONS

Weed scientists and most people engaged in agriculture are not, by nature or choice, good politicians. Most agriculturalists consider a career as a politician to be more noble than, say, being a shoplifter but still not unlike the telemarketers who always call at supper-time to tell that you *really* should replace all the windows in your house. Failure or inability to consider the fact that we live in a political world and are affected by it is a prescription for disaster. Political considerations affect our lives daily. A major political creation, in many countries, is cheap food, especially in urban areas. Most enjoy the benefit of this, often unstated, government policy. It affects the way we practice agriculture and manage weeds. If the government removed itself from agricultural policymaking and the market, weed management systems would have to change to fit a new system. Given agricultural and environmental history, concern about environmental pollution from agriculture is a fairly recent political development. It wasn't too long ago that pesticide use in agriculture meant prosperity and progress rather than environmental pollution and corporate irresponsibility. For example, a study commissioned by the American Farm Bureau, an organization noted for its defense of agriculture (King, 1991), showed that only 15% of the American public was in favor of abolishing pesticide use in agriculture. However, 66% of the people surveyed thought pesticide use should be limited in the future, and 38% thought farmers were using more pesticides than they had in the past. Such information and concern has political meaning and consequences. Such data are ignored or dismissed only by those who willfully ignore the effects of political action. Political acts change many things and agriculture has to recognize and work in a political milieu or suffer the consequences of regulation by those who do.

III. CONCLUSION

The American author and farmer Wendell Berry (1981b) has written often and eloquently about problems facing American agriculture and about their solutions. He advocates solving for pattern. Berry says that "to the problems of farming, then, as to other problems of our time, there appear to be three kinds of solutions." The first kind causes a ramifying series of new problems. The only limitation on the new problems is that they "arise beyond the purview of the expertise that produced the solution." That is, those who are encumbered by the new problems are not those who devised solutions for the old problem. This kind of solution shifts the burden away from those who created the problem.

The second kind of solution is one that immediately worsens the problem it is intended to solve. These are often quick fix solutions that take the form of questions such as, What herbicide will kill the weed? Adopting this kind of problem solving leads to the need for more quick fix solutions. Everyone who has tried to fix something is familiar with this kind of solution. What was tried first didn't work, and some study (but perhaps little knowledge) revealed that loosening another bolt or screw would do it. Alas, loosening that screw was the wrong thing to do because it loosened other things, and suddenly parts are everywhere, and neither the source of each part nor a way to fit them back together is known. These solutions are common.

The third and most desirable solution creates a ramifying series of solutions. Parts don't fly off in all directions; they fit together. These solutions make, and keep, things whole. For Berry (1981b) a good solution is one that acts constructively on the larger pattern of which it is a part. It is not destructive of the immediate pattern or the whole. People who devise the best solutions recognize the pattern in which they must fit and work to create a set of solutions that maintain the essential pattern. Good solutions solve for the whole system not for a single goal or purpose.

Those who will create the next generation of weed management systems for simple and complex weed problems will do well to remember Berry's admonition as they search for the best solutions. One must know the whole system and devise solutions that create more solutions that maintain the pattern or make it better. Weed scientists should view the agricultural system the same way a good family physician views patients: as a family, not as individuals. It is the entire system and not just the weeds that must be managed.

M. S. Swaminathan, the creator of India's green revolution, former director General of the Int. Rice Research Institute, and recipient of the first World Food prize, delivered the B. Klepper endowed lectureship at the 2005 meeting of the Tri-Societies (Agronomy, Soil Science, and Crop Science). He said, "The most cruel form of inequity is malnutrition." This is a large-scale concern. Contributing to the elimination of hunger in the world is a proper goal for weed science. It is a goal consistent with the Millennium goals of the UN (Sachs, 2005, pp. 211–212). Two of the goals are relevant to agriculture and worthy of the attention of weed scientists. These large-scale goals include (1) eradicating extreme poverty and reducing hunger by half by 2015 and (2) ensuring environmental sustainability. In his *Recollected Essays*, Berry (1981a, p. 98) writes eloquently about a vison of the future that is shared by those who want to create alternative futures, including alternative, improved agricultural systems. His words are a good place to end thoughts about the future of weed science. I leave it to readers to determine if the book has launched beyond its author's depth:

> We have lived by the assumption that what was good for us would be good for the world. We have been wrong. We must change our lives so that it will be possible to live by the contrary assumption that what is good for the world will be good for us. And that requires that we make the effort to know the world and to learn what is good for it. We must learn to cooperate in its processes, and to yield to its limits. But even more important, we must learn to acknowledge that the creation is full of mystery; we will never clearly understand it. We must abandon arrogance and stand in awe. We must recover the sense of the majesty of the creation, and the ability to be worshipful in its presence. For it is only on the condition of humility and reverence before the world that our species will be able to remain in it.

THINGS TO THINK ABOUT

1. Why are herbicides the primary weed control technique in the world's developed countries?
2. What are the major problems that impede progress in weed science?
3. Name several important future research problems.
4. Why is understanding weed-crop competition crucial to the future of weed science and weed management?
5. Why are studies of seed dormancy and seed germination so important to weed management?
6. What will be the future role for bioeconomic models of weed-crop competition, and what parameters should new models incorporate?
7. What are the characteristics of an ideal herbicide?
8. Why are perennial weeds so hard to control?
9. Why are parasitic weeds so hard to control?
10. What are the major problems with herbicide use for aquatic weed management?
11. Why is there concern about packaging and labeling of herbicides?
12. What has been the recent evolutionary trend in the agrichemical industry?
13. Why are herbicides sprayed?
14. In what areas can engineering research contribute to weed management?
15. Why are political considerations important to weed science?
16. What is solving for pattern and how does it relate to weed science and weed management?

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APPENDIX A

List of Crop and Other Plants Cited in Text

(Alphabetized by common name)

COMMON NAME	SCIENTIFIC NAME
alfalfa	*Medicago sativa* L.
almonds	*Prunus dulcis* (Mill.) D.A. Webb
apple	*Malus* spp.
artichoke	*Cynara scolymus* L.
asparagus	*Asparagus officinalis* L.
azalea	*Rhododendron* spp.
bahiagrass	*Paspalum notatum* Fluegge
banana	*Musa paradisiaca* L.
barley	*Hordeum vulgare* L.
bean	*Phaseolus* spp.
begonia	*Begonia* spp.
bell pepper	*Capsicum annuum* L.
berseem clover	*Trifolium alexandrinum* L
big bluestem	*Andropogon gerardii* Vitm.
blackberries	*Rubus allegheniensis* Porter
black currant	*Ribes nigrum* L.
black walnut	*Juglans nigra* L.
blueberries	*Vaccinium angustifolium* Ait.
bluebunch wheatgrass	*Agropyron spicatum* (Pursh) Scribn. & Sm.
blue grama	*Bouteloua gracilis* Lag.ex
broadbean	*Vicia faba* L.
broccoli	*Brassica oleracea* L.—Botrytis group
Brussels sprouts	*Brassica oleracea*—Gemmifera group
buckwheat	*Fagopyrum esculentum* Moench.

cabbage	*Brassica rapa* L.
camellia	*Camellia* spp.
canola = rapeseed	*Brassica napus* L.
carnation	*Dianthus caryophyllus* L.
carrot	*Daucus carota* L.
cassava = manioc	*Manihot esculenta* Crantz
celery	*Apium graveolens* L.
centro	*Centrosema pubescens* Benth
cherry	*Prunus* spp.
cherry, wild	*Prunus* spp.
Chinese cabbage	*Brassica rapa* L.
clover	*Trifolium* spp.
coconut	*Cocos nucifera* L.
coffee	*Coffea arabica* L.
clover, crimson	*Trifolium incarnatum* L.
common rye	*Secale cereale* L.
corn = maize	*Zea mays* L.
cotton	*Gossypium hirsutum* L.
cottonwood	*Populus deltoides* Marsh
cowpea	*Vigna unguiculata* (L.) Walp.
crambe	*Crambe abyssinica* Hochst.
cranberry	*Viburnum opulus* L.
crested wheatgrass	*Agropyron desertorum* (Fisch. ex Link) Schult.
crimson clover	*Trifolium incarnatum* L.
crownvetch	*Coronilla varia* L.
cucumber	*Cucumis sativus* L.
date	*Balanites aegyptiaca* (L.) Del.
Douglas fir	*Pseudotsuga menziesii* (Mirbel) Franco
durum wheat	*Triticum durum* Desf.
egusi melon	*Citrullus lanatus* L. subsp. *mucospermus*
fava bean	*Vicia faba* L
fescue	*Festuca* spp.
field pea	*Pisum sativum* L.
flax	*Linum usitatissimum* L.
foxtail millet	*Setaria italicum* (L.) Beauv.
grapes	*Vitis* spp.
groundnut = peanut	*Arachis hypogaea* L.
guayule	*Parthenium argentatum* A. Gray

hairy vetch	*Vicia villosa Roth*
hops	*Humulus lupulus* L.
hyacinth bean = lablab	*Lablab purpureus* L.
Idaho fescue	*Festuca idahoensis* Elmer
iris	*Iris psuedacorus* L.
jute	*Corchorus olitorius* L.
Kentucky bluegrass	*Poa pratensis* L.
lentil	*Lens culinaris* Medik.
lettuce	*Lactuca sativa* L.
lily-of-the-valley	*Convallaria majalis* L.
lima bean	*Phaseolus limensis* L.
macadamia	*Macadamia* spp.
maize = corn	*Zea mays* L.
maple	*Acer* spp.
mistletoe	*Arceuthobium* spp.
mung bean	*Vigna radiata* (L.) Wilczek var. radiata
muskmelon	*Cucumis melo* L.
narcissus	*Narcissus poeticus* L.
oak	*Quercus* spp.
oats	*Avena sativa* L.
oleander	*Nerium oleander* L.
onion	*Allium cepa* L.
orange	*Citrus sinensis* (L.) Osb.
orchardgrass	*Dactylis glomerata* L.
pangolagrass	*Digitaria decumbens* Stent
peanut	*Arachis hypogaea* L.
pearl millet	*Pennisetum glaucum* L.
peppermint	*Mentha piperita* L.
peppers	*Capsicum* spp.
pigeon pea	*Cajanus cajan* (L.) Millsp.
pine	*Pinus* spp.
ponderosa pine	*Pinus ponderosa* Dougl.ex P. & C. Laws.
potato	*Solanum tuberosum* L.
potato bean = groundnut	Apios *americana* Medik.

princess feather	*Amaranthus hypochondricus* L.
proso millet	*Panicum miliaceum* L.
psoralea	*Psoralea* spp.
radish	*Raphanus sativus* L.
rapeseed = canola	*Brassica napus* L.
raspberry	*Rubus* spp.
red clover	*Trifolium pratense* L.
red currant	*Ribes sativum* Syme
red maple	*Acer rubrum* L.
rhodendron	*Rhododendron* spp.
rhubarb	*Rheum rhaponticum* L.
rice	*Oryza sativa* L.
ryegrass	*Lolium* spp.
sainfoin	*Onobrychis viciifolia* Scop.
satsuma orange	*Citrus nobilis* Lour.
sava medic	*Medicago scutella* L.
side-oats grama	*Bouteloua curtipendula* (Michx.) Torr.
silk-cotton tree	*Ceiba pentandra* (L.) Gaertner poll.
slender wheatgrass	*Agropyron desertorum* (Fisch. ex Link) Schult.
smooth bromegrass	*Bromus inermis* Leyss
snapbean	*Phaseolus vulgaris* L.
snapdragon	*Antirrhinum majus* L.
snowberry	*Symphoricarpos* spp.
sorghum	*Sorghum bicolor* (L.) Moench
soybean	*Glycine max* (L.) Merr.
spearmint	*Mentha spicata* L.
spinach	*Spinacia oleracea* L.
squash	*Cucurbita* spp.
strawberry	*Fragaria vesca* L.
subterranean clover	*Trifolium subterraneum* L.
sudangrass	*Sorghum sudanense* (Piper) Stapf
sugarbeet	*Beta vulgaris* L.
sugarcane	*Saccharum officinarum* L.
sweet potato	*Ipomoea batatas* Lam
switchgrass	*Panicum virgatum* L.
tepary bean	*Phaseolus acutifolius* A. Gray
timothy	*Phleum pratense* L.
tobacco	*Nicotiana tabacum* L.

tomato	*Lycopersicon esculentum* Mill.
trillium	*Trillium* spp.
tropical kudzu	*Pueraria phaseoloides* (Roxb.) Benth.
velvetbean	*Mucuna cochinchinensis* (Lour.) A. Chev.
watermelon	*Citrullus lanatus* (Thunb.) Matsum. & Nakai
wheat	*Triticum aestivum* L.
white ash	*Fraxinus americana* L.
white clover	*Trifolium repens* L.
wild winged bean	*Psophocarpus palustris* Desv.
willow	*Salix* spp.
yellow indian grass	*Sorghastrum nutans* (L.) Nash
zucchini squash	*Cucurbita maxima* L.

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APPENDIX B

List of Weeds Cited in Text

(Alphabetized by common name)

COMMON NAME	SCIENTIFIC NAME
African mile-a-minute	*Mikania cordata* (Burm. f.) B.L.Robins.
ageratum	*Ageratum* spp.
alder	*Alnus* spp.
alder, red	*Alnus rubra* Bong.
alkaliweed	*Cressa truxillensis* H.B.K.
alligatorweed	*Alternanthera philoxeroides* (Mart.) Griseb.
amaranth	*Amaranthus* spp.
American black nightshade	*Solanum americanum* Mill.
American pondweed	*Potamogeton nodosus* Poir.
annual ryegrass	Probably—*Lolium temulentum* L. (poison Ryegrass)
annual sowthistle	*Sonchus oleraceus* L.
arrowgrass	*Triglochin maritima* L.
arrowhead	*Sagittaria sagittifolia* L.
artichoke thistle	*Cynara cordonculus* L.
aspen = quaking aspen	*Populus tremuloides* Michx.
autumn olive	*Elaeagnus umbellata* Thunb.
azolla = pinnate mosquitofern	*Azolla pinnata* R. Brown
barnyardgrass	*Echinochloa crus-galli* (L.) Beauv.
bearded sprangletop	*Leptochloa fascicularis* (Lam.) Gray
bentgrass	*Agrostis* spp.
bermudagrass	*Cynodon dactylon* (L.) Pers.
bigleaf maple	*Acer macrophyllum* Pursh
big sagebrush	*Artemesia tridentata* Nutt.
bindweed	*Convolvulus* spp.
birdsrape mustard	*Brassica rapa* L.

bitterbush	*Eupatorium oderatum* L. = *Chromolaena odorata* (L.) R.M. King & M. Robinson
bittercress	*Cardamine* sp.
blackgrass	*Alopecurus myosuroides* Huds.
black henbane	*Hyoscyamus niger* L.
black medic	*Medicago lupilina* L.
black mustard	*Brassica nigra* (L.) W.J.D. Koch
black nightshade	*Solanum nigrum* L.
bluegrass	*Poa* spp.
blue pimpernel	*Anagallis coerulea* Nathh.
bouncing bet	*Saponaria officinalis* L.
brackenfern	*Pteridium aquilinum* (L.) Kuhn
branched broomrape	*Orobanche ramosa* L.
Brazilian peppertree	*Schinus terebinthifolius* Raddi.
Brazilian satintal	*Imperata brasiliensis* Trin.
broadleaf filaree	*Erodium botrys* (Cav.) Bertol.
broadleaf plantain	*Plantago major* L.
brome	*Bromus* spp.
buckhorn plantain	*Plantago lancolata* L.
buffalobur	*Solanum rostratum* Dun
bulbous buttercup	*Ranunculus bulbosus* L.
bull mallow	*Malva nicaeensis* All.
bull thistle	*Cirsium vulgare* (Savi) Tenore
bulrush	*Scirpus* spp.
burning nettle	*Urtica urens* L.
burcucumber	*Sicyos angulatus* L.
bursage	*Ambrosia* spp.
buttercup	*Ranunculus* spp.
buttercup oxalis	*Oxalis pes-caprae* L.
California sagebrush	*Artemesia californica* Less.
California chapparral = whiteleaf sage	*Salvia leucophylla* Greene
California peppertree	*Schinus molle* L.
camelthorn	*Alhagi pseudalhagi* (Bieb.) Desv.
Canada thistle	*Cirsium arvense* (L.) Scop.
catchweed bedstraw	*Galium aparine* L.
catclaw mimosa	*Mimosa pigra* L.
catnip	*Nepeta cataria* L.
celosia	*Celosia argentea* L.
charlock	*Brassica* spp.
chicory	*Cichorium intybus* L.

Chinese tamarisk	*Tamarix chinensis* Lour.
Chinese tallow	*Sapium sebiferum* (L.) Roxb.
chokecherry	*Prunus virginiana* L.
coat buttons	*Tridax procumbens* L.
cocklebur	*Xanthium* spp.
coffee senna	*Cassia occidentalis* L.
common crupina	*Crupina vulgaris* Cass.
common elodea	*Elodea canadensis* L.C.Rich
common foxglove	*Digitalis purpurea* L.
common groundsel	*Senecio vulgaris* L.
common hempnettle	*Galeopsis tetrahit* L.
common lambsquarters	*Chenopodium album* L.
common mallow	*Malva neglecta* Wallr.
common milkweed	*Asclepias syriaca* L.
common mullien	*Verbascum thapsus* L.
common plantain	*Plantago* spp.
common pokeweed	*Phytolacca americana* L.
common purslane	*Portulaca oleracea* L.
common ragweed	*Ambrosia artemisiifolia* L.
common reed	*Phragmites australis* (Cav.) Trin. ex Steud.
common rye	*Secale cereale* L.
common St. Johnswort	*Hypericum perforatum* L.
common sunflower	*Helianthus annuus* L.
common tansy = tansy ragwort	*Tanacetum vulgare* L.
common teasel	*Dipsacus fullonum* L.
common velvetgrass	*Holcus lanatus* L.
common vetch	*Vicia sativa* L.
common waterhemp	*Amaranthus rudis* Sauer
coontail	*Ceratophyllum demersum* L.
corn cockle	*Agrostemma githago* L.
corn marigold	*Chrysanthemum segetum* L.
corn speedwell	*Veronica arvensis* L.
cottonwood	*Populus* spp.
cowcockle	*Vaccaria pyramidata* Medicus
cowpea witchweed	*Striga gesnerioides* (Willd.) Vatke
crabgrass	*Digitaria* spp.
creeping buttercup	Ranunculus *repens* L.
creeping woodsorrel	*Oxalis corniculata* L.
cress	*Lepidium sativum* L.
curly dock	*Rumex crispus* L.
cutleaf groundcherry	*Physalis angulata* L.

daisy fleabane = annual fleabane	*Erigeron annuus* (L.) Pers.
dallisgrass	*Paspalum dilatatum* Poir.
dalmatian toadflax	*Linaria dalmatica* (L.) Mill.
dandelion	*Taraxacum officinale* Weber in Wiggers
darnel = poison ryegrass	*Lolium temulentum* L.
dayflower	*Commelina* spp.
devil's-claw	*Proboscidea louisianica* (Mill.) Thellung
diffuse knapweed	*Centaurea diffusa* Lam.
dock	*Rumex* spp.
dodder	*Cuscuta* spp.
downy brome	*Bromus tectorum* L.
dropseed	*Sporobulus* spp.
duckweed	*Lemna* spp.
dwarf mistletoe	*Arceuthobium vaginatum* M. Bieb.
dyer's woad	*Isatis tinctoria* L.
eastern black nightshade	*Solanum ptycanthum* Dun
eclipta	*Eclipta prostrata* L.
Eurasian watermilfoil	*Myriophyllum spicatum* L.
European blackberry	*Rubus fruticosus* L.
European buckthorn	*Rhamnus cathartica* L.
false flax	*Camelina* spp.
fall panicum	*Panicum dichotomiflorum* Michx.
fescue	*Festuca* spp.
field dodder	*Cuscuta campestris* Yuncker
field horsetail	*Equisetum arvense* L.
field pennycress	*Thlaspi arvense* L.
field pepperweed	*Lepidium campestre* (L.) R.Br.
field violet	*Viola arvensis* Murr.
fireweed	*Epilobium angustifolium* L.
flaxweed = flatseed falseflax	*Camelina alyssum* (Mill.) Thell
flixweed	*Descurainia sophia* (L.) Webb. ex Prantl
Florida beggarweed	*Desmodium tortuosum* (Sw.) DC.
Florida pusley	*Richardia scabra* L.
foxtail barley	*Hordeum jubatum* L.
foxtail millet	*Setaria italica* (L.) Beauv.
fringed sagebrush	*Artemesia frigida* Willd.
fumitory	*Fumaria officinalis* L.
galinsoga	*Galinsoga* spp.
garden cress	*Lepidium sativum* L.

garden spurge	*Euphorbia hirta* L.
garlic mustard	*Alliaria petiolata* (Bieb.) Cavara & Grande
giant foxtail	*Setaria faberi* Herrm.
giant ragweed	*Ambrosia trifida* L.
giant reed	*Arundo donax* L.
giant salvinia	*Salvinia auriculata* Aubl.
globe fringerush	*Fimbristylis miliacea* (L.) Vahl
goldenrod	*Solidago* spp.
goosegrass	*Eleusine indica* (L.) Gaertn.
gray rabbit brush	*Chrysothamnus nauseosus* (Pallas) Britt.
greenflower pepperweed = peppergrass	*Lepidium densiflorum* Schrad.
green foxtail	*Setaria viridis* (L.) Beauv.
green sorrel	*Rumex acetosa* L.
groundcherry	*Physalis* spp.
ground ivy	*Glechoma hereracea* L.
groundsel	*Senecio* spp.
guayule	*Parthenium argentatum* A. Gray
Guineagrass	*Panicum maximum* Jacq.
hairy fleabane	*Conyza bonariensis* (L.) Cronq.
hairy nightshade	*Solanum sarrachoides* Sendtner
hairy vetch	*Vicia villosa* Roth
halberdleaf orach	*Atriplex patula* var. *hastata* (L.) Gray
halogeton	*Halogeton glomeratus* (Stephen ex. Bieb.) C.A. Mey
hayfield tarweed	*Hemizonia congesta* DC.
heath	*Erica scoparia* L.
hedge bindweed	*Calystegia sepium* (L.) R.Br.
heliotrope	*Heliotropium* spp.
hemp dogbane	*Apocynum cannabinum* L.
hemp sesbania	*Sesbania exaltata* (Raf.) Rtdb. Ex A.W.Hill
henbit	*Lamium amplexicaule* L.
hoary cress = whitetop	*Cardaria draba* (L.) Desv.
horsenettle	*Solanum carolinense* L.
horseweed	*Conyza canadensis* (L.) Cronq.
hydrilla	*Hydrilla verticillata* (L.f.) Royle
Indian balsam	*Impatiens glandulifera* Royle
Indian tobacco	*Lobelia inflata* L.
Italian ryegrass	*Lolium multiflorum* Lam.

itchgrass	*Rottboellia cochinchinensis* (Lour.) W.D. Clayton
ivyleaf morning glory	*Ipomoea hederacea* (l.) Jacq.
Japanese brome	*Bromus japonicus* Thunb. ex Murr.
Japanese honeysuckle	*Lonicera japonica* Thunb.
Japanese knotweed	*Polygonum cuspidatum* Seib. & Zucc. = *Fallopia japonica* (Houtt.) Ronse. Ducr.
Japanese stiltgrass	*Microstegium vimineum* (Trin.) A.Camus var. *Imberbe* (Ness) Honda
Java plum	*Szygium cumini* (L.) Skeels
Jerusalem artichoke	*Helianthus tuberosus* L.
jimsonweed	*Datura stramonium* L.
johnsongrass	*Sorghum halepense* (L.) Pers.
jointed goatgrass	*Aegilops cylindrica* Host
junglerice	*Echinochloa colonum* (L.) Link
junipers	*Juniperus* spp.
karibaweed	*Salvinia molesta* Mitch.
kikuyugrass	*Pennisetum clandestinum* Hochst. ex Chiov.
klamath weed	See common St. Johnswort
knapweed	*Centaurea* spp.
kochia	*Kochia scoparia* (L.) Schrad.
kudzu	*Pueraria montana* var. *lobata* (Willd.) Maesen & S.Almeida
ladysthumb	*Polygonum persicaria* L.
lantana	*Lantana* spp.
large crabgrass	*Digitaria sanguinalis* (L.) Scop.
larkspur	*Delphinium* spp.
leafy spurge	*Euphorbia esula* L.
little mallow	*Malva parviflora* L.
longspine sandbur	*Cenchrus longispinus* (Hack.) Fern.
Madagascar periwinkle	*Catharanthus roseus* (L.) G.Don
mallow	*Malva* spp.
marestail	*Hippuris vulgaris* L.
marshpepper smartweed	*Polygonum hydropiper* L.
Mediterranean sage	*Salvia aethiopis* L.
meadow barley	*Hordeum brachyantherum* Nevski
meadow foxtail	*Alopecurus pratensis* L.

meadowsweet	*Spirea latifolia* (Ait.) Borkh.
Mediterranean sage	*Salvia aethiopis* L.
medusahead	*Taeniatherum caput-medusae* (L.) Nevski
melaleuca	*Melaleuca quinquenervia* (Cav.) Blake
mesquite	*Prosopis* spp.
miconia	*Miconia* spp.
mock bishop's weed	*Ptilimnium capillaceum* (Michx.) Raf.
monkshood	*Aconitum napelus* L.
monochoria	*Monochoria vaginalis* (Burm.f.) Kunth
morning glory	*Ipomoea* spp.
mugwort	*Artemesia vulgaris* L.
mulberry weed	*Fatousa villosa* (Thunb.) Nakai.
mullein	*Verbascum* spp.
multiflora rose	*Rosa multiflora* Thunb. ex Murr.
musk thistle	*Carduus nutans* L.
mustard	*Brassica* spp.
needle-and-thread grass	*Stipa comata* Trin. & Rupr.
netseed lambsquarters	*Chenopodium berlandieri* Moq.
nettle	*Urtica spp.*
nightshade	*Solanum* spp.
Northern jointvetch	*Aeschynomene virginica* (L.) B.S.P.
nostoc	*Nostoc* spp.
nutsedge	*Cyperus* spp.
oak	*Quercus* spp.
oakleaf goosefoot	*Chenopodium glaucum* L.
Ohio buckeye	*Aesculus glabra* Willd.
oldfield cinquefoil	*Potentilla simplex* Michx.
oldfield toadflax	*Linaria canadensis* (L.) Dumont
orange hawkweed	*Hieracium aurantiacum* L.
orchardgrass	*Dactylis glomerata* L.
orobanche	*Orobanche* spp.
Palmer amaranth	*Amaranthus palmeri* S.Wats.
pangola grass	*Digitaria decumbens* Stent
paragrass	*Brachiaria mutica* (Forsk.) Stapf
parthenium ragweed	*Parthenium hysterophorus* L.
passionflower	*Passiflora* spp.
peppergrass = greenflower pepperweed	*Lepidium densiflorum* Schrad.
perennial pepperweed	*Lepidium latifolium* L.

perennial ryegrass	*Lolium perenne* L.
perennial sowthistle	*Sonchus arvensis* L.
Persian speedwell	*Veronica persica* Poir.
phragmites	See common reed
pigweed	*Amaranthus* spp.
pinnate tansymustard	*Descurainia pinnata* (Walt.) Britt
pitted morning glory	*Ipomoea lacunosa* L.
plains pricklypear	*Opuntia polyacantha* Haw.
plantain	*Plantago* spp.
poison hemlock	*Conium maculatum* L.
poison ivy	*Toxicodendron radicans* (L.) Ktze
poison oak	*Toxicodendron toxicarium* (Salisb.) Gillis
poison ryegrass = darnel	*Lolium temulentum* L.
pondweed	*Potamogeton* spp.
poppy	*Papaver* spp.
prickly lettuce	*Lactuca serriola* L.
pricklypear cactus	*Opuntia littoralis* (Engelmann) Cockerell
prickly sida	*Sida spinosa* L.
princess feather	*Polygonum orientale* L.
prostrate knotweed	*Polygonum aviculare* L.
prostrate pigweed	*Amaranthus graecizans* auctt., non L.
prostrate spurge	*Euphorbia supina* Raf.
prostrate vervain	*Verbena bracteata* Lag. & Rodr.
puncturevine	*Tribulus terrestris* L.
purple moonflower	*Ipomoea alba* L.
purple loosestrife	*Lythrum salicaria* L.
purple nutsedge	*Cyperus rotundus* L.
quackgrass	*Eltrygia repens* (L.) Nevski
queen-of-the-meadow	*Filipendula ulmaria* (L.) Maxim.
rabbitbrush	*Chrysothamnus* spp.
ragweed	*Ambrosia* spp.
rattail fescue	*Vulpia myuros* (L.) K.C.Gmel.
red morning glory	*Ipomoea coccinea* L.
redrice	*Oryza sativa* L.
redroot pigweed	*Amaranthus retroflexus* L.
red sprangletop	*Leptochloa filiformis* (Lam.) Beauv.
redtop	*Agrostis gigantea* Roth
reed canarygrass	*Phalaris arundinacea* L.
rice flatsedge	*Cyperus iria* L.
rigid ryegrass	*Lolium rigidum* Gaudin

roughstalk bluegrass	*Poa trivialis* L.
rubber vine	*Cryptostegia grandiflora* R. Br.
rush	*Scirpus* spp.
Russian knapweed	*Acroptilon repens* (L.) DC.
Russian olive	*Elaeagnus angustifolia* L.
Russian thistle	*Salsola iberica* Sennen & Pau
rye	*Secale montanum* Guss. origin of *S. cereale* L.
ryegrass	*Lolium* spp.
Sacramento thistle	*Cirsium vinaceum* (Woot. and Standl.)
sage	*Artemesia* spp.
sago pondweed	*Potamogeton pectinatus* L.
Syrian sage	*Salvia syriaca* L.
sagebrush	*Artemisia* spp.
Sakhalin knotweed = S. knotgrass	*Polygonum sachalinense* F. Schmidt ex Maxim.
saltbush	*Atriplex* spp.
salt cedar = tamarisk	*Tamarix ramosissima* Ledeb.
saltgrass	*Distichlis spicata* (L.) Greene
salvinia	*Salvinia molesta* Mitch.
sandbur	*Cenchrus* spp.
sand dropseed	*Sporobulus cryptandrus* (Torr.) Gray
sand sagebrush	*Artemesia filifolia* Torr.
scotch broom	*Cytisus scoparius* (L.) Link
scotch thistle	*Onopordium acanthium* L.
sensitiveplant	*Mimosa pudica* L.
sessile joyweed	*Alternanthera sessilis* (L.) R.Br. ex DC.
shattercane	*Sorghum bicolor* (L.) Moench
shepherd's purse	*Capsella bursa-pastoris* (L.) Medieus
showy crotalaria	*Crotalaria spectabilis* Roth
showy milkweed	*Asclepias speciosa* Torr.
sicklepod	*Senna obtusifolia* (L.)
signal grass	*Brachiaria* spp.
silverleaf nightshade	*Solanum elaeagnifolium* Cav.
skeletonleaf bursage	*Ambrosia tomentosa* Nutt.
slender foxtail	*Alopecurus myosuroides* Huds.
slimleaf lambsquarters	*Chenopodium leptophyllum* (Moq.) Nutt. ex S.Wats.
smallflower galinsoga	*Gallinsoga parviflora* Cav.
smallflower morning glory	*Jacquemontia tamnifolia* (L.) Griseb.
smallflower tamarisk	*Tamarix parviflora* DC.

smallflower umbrella sedge	*Cyperus difformis* L.
smooth dock	*Rumex* (species unknown)
smooth pigweed	*Amaranthus hybridus* L.
soft brome	*Bromus mollis* L.
sorghum-almum	*Sorghum almum* Parod.
sour paspalum	*Paspalum conjugatum* Bergius
southern crabgrass	*Digitaria ciliaris* (Retz.) Koel
southern sandbur	*Cenchrus echinatus* L.
sowthistle	*Sonchus* spp.
spiny amaranth	*Amaranthus spinosus* L.
spotted cat's ear	*Hypochoeris radicata* L.
spotted geranium	*Geranium maculatum* L.
spotted knapweed	*Centaurea maculosa* Lam.
spotted waterhemlock	*Cicuta maculata* L.
sprangletop	*Leptochloa* spp.
spreading dayflower	*Commelina diffusa* Burm. f.
spurred anoda	*Anoda cristata* (L.) Schlecht.
St. Augustine grass	*Stenotaphrum secundatum* (Walt.) Ktze.
star chickweed	*Stellaria pubera* Michx.
sterile oat	*Avena sterilis* L.
stinkgrass	*Eragroatis cilianensis* (All.) E. Mosher
stinkweed	*Pluchea camphorata* (L.) DC.
sulfur cinquefoil	*Potentilla recta* L.
sumac	*Rhus* spp.
sumac, smooth	*Rhus glabra* L.
sweetclover	*Melilotus* spp.
tall fescue	*Festuca arundinacea* Schreb.
tall oatgrass	*Arrhenatherum elatius* (L.) Beauv. ex J. & C. Presl
tamarisk = salt cedar	*Tamarix ramosissima* Ledeb.
tares = common vetch or darnel	*Vicia sativa* L. *Lolium temulentum* L.
Texas panicum	*Panicum texanum* Buckl.
toadflax	*Linaria* spp.
toothed spurge	*Euphorbia dentata* Michx
torpedograss	*Panicum repens* L.
trailing crownvetch	*Coronilla varia* L.
travelersvine clematis = old man's beard	*Clematis vitalba* L.
tree cactus	*Opuntia megacantha* Salm-Dyck
tree of heaven	*Ailanthus altissima* (Mill.) Swingle

tropic ageratum	*Ageratum conyzoides* L.
tumble mustard	*Sisymbrium altissimum* L.
tumble pigweed	*Amaranthus albus* L.
velvetleaf	*Abutilon theophrasti* Medikus
Venice mallow	*Hibiscus trionum* L.
vetch	*Vicia* spp.
Virginia pepperweed	*Lepidium virginicum* L.
volunteer rye	*Secale cereale* L.
waterhemlock	*Cicuta* spp.
waterhyacinth	*Eichhornia crassipes* (Mart.) Solms
waterlettuce	*Pistia stratiotes* L.
watershield	*Brasenia schreberi* J.F.Gmel.
wavyleaf thistle	*Cirsium undulatum* (Nutt.) Spreng.
western ragweed	*Ambrosia psilostachya* D.C.
white mustard	*Sinapis alba* L.
whorled milkweed	*Asclepias verticillata* L.
wild buckwheat	*Polygonum convolvulus* L.
wild garlic	*Allium vineale* L.
wild marigold	*Tagetes erecta* L.
wild melon	*Cucumis melo* L.
wild milograss	*Panicum* spp.
wild mustard	*Sinapis arvensis* L.
wild onion	*Allium canadense* L.
wild proso millet	*Panicum milaceum* L.
wild radish	*Raphanus raphanistrum* L.
wild tomato	*Solanum triflorum* L.
winged waterprimrose	*Ludwigia decurrens* Walt.
witchgrass	*Panicum capillare* L.
witchweed	*Striga asiatica* (L.) Ktze.
wood sorrel	*Rumex* spp.
wooly cupgrass	*Eriochloa villosa* (Thunb.) Kunth
yarrow	*Achillea millefolium* L.
yellow charlock	*Brassica arvensis* Ktze = *Sinapis arvensis* L.
yellow-devil hawkweed	*Hieracium floribundum* W. et G.
yellowflag iris	*Iris pseudacorus* L.
yellow foxtail	*Setaria glauca* (L.) Beauv.
yellow hawkweed	*Hieracium pratense* Tausche
yellow mustard	*Brassica hirta* Moench

yellow nutsedge	*Cyperus esculentus* L.
yellow rocket	*Barbarea vulgaris* R. Br.
yellow starthistle	*Centaurea solstitialis* L.
yellow sweetclover	*Melilotus officinalis* (L.) Lam.
yellow toadflax	*Linaria vulgaris* Mill.
yucca	*Yucca* spp.

GLOSSARY OF TERMS USED IN WEED SCIENCE*

Achene A small, dry, thin-walled fruit that does not split open when ripe, such as on a dandelion.

Absorption The process by which herbicides are taken into plants, by roots, or foliage (stomata, cuticle, etc.). *See* Adsorption.

Acid equivalent (ae) The theoretical yield of parent acid from an active ingredient in acid-based herbicides.

Acre A common unit of land measure, equal to 43,560 square feet or 0.405 hectares.

Acropetal Toward the apex; generally upward in shoots and downward in roots. *See* Basipetal.

Active ingredient (ai) Chemical(s) responsible for herbicidal effects.

Adjuvant An ingredient that facilitates or modifies the action of the principle ingredient; an additive.

ADP (adenosinediphosphate) An adenosine-derived ester formed in cells, converted to ATP for energy storage.

Adsorption Chemical or physical attraction of a substance to a surface; can refer to gases, dissolved substances, or liquids on the surface of solids or liquids. *See* Absorption.

Adventitious Having plant organs such as shoots or roots that are produced in an abnormal position or at an unusual time of development.

Aliphatic Derived from straight chain hydrocarbons.

Allelopathy Adverse effect of one plant or microorganism on another caused by release of a chemical from living or decaying organisms.

Allelopathy, true Allelochemicals that enter the environment through volatilization or root exudation and move through soil by leaching.

*A glossary of terms also appears on pages 457–462 of Vencill, W.K. (Ed.) 2002. *Herbicide Handbook* 8th Ed. Weed Sci. Soc. America, Lawrence, KS.

Allelopathy, **functional** Toxins resulting from transformation after release by the plant or during decomposition of plant residues.

Allopatry Occurring in separate, widely differing geographic areas. *See* Sympatry.

Angiosperm A plant that has seeds born within a pericarp.

Annual A plant that completes its life cycle in one year (i.e., germinates from seed, grows, flowers, produces seed, and dies in the same season); examples: redroot pigweed, common ragweed, mustards, foxtails, large crabgrass.

Apoplast The continuous, nonliving, cell wall phase that surrounds and contains the symplast.

Aquatic weed A weed that grows in water. There are three kinds: (1) submerged—grow beneath the surface (e.g., sago pondweed, elodea, watermilfoil); (2) emerged—grow above the water (e.g., cattails and water lilies); and (3) floaters—float on the surface (e.g., waterhyacinth).

Aromatics Compounds derived from the hydrocarbon benzene.

ATP (adenosinetriphosphate) An adenosine-derived nucleotide. The primary source of energy through conversion to ADP.

Band application Application to a continuous restricted band such as in or along a crop row rather than over the entire field.

Basal treatment Herbicide applied to the stems of woody plants at and just above the ground.

Basipetal Toward the base; generally downward in shoots and upward in roots. *See* Acropetal.

Bed A narrow flat-topped ridge on which crops are grown with a furrow on each side for drainage of excess water, or an area in which seedlings or sprouts are grown before transplanting.

Biennial A plant that completes its growth in two years: The first year it produces leaves and stores food; the second year it produces fruits and seeds (e.g., wild carrot, bull thistle).

Biological control Controlling a pest with natural or introduced enemies.

Blind cultivation Cultivating before plant emergence.

Broadcast application Application over an entire area rather than only on rows, beds, or middles.

Broadleaved plants In general, used as an antonym to grass plants.

Brush control Control of woody plants.

Bulb A subterranean leaf bud with fleshy scales or coats.

Calibration A series of operations to determine the amount of solution (volume) applied per unit area of land and the amount of pesticide to add to a known volume of diluent.

Capitulum A dense head-like cluster of stalkless flowers.

Carrier Liquid or solid material added to a chemical compound to facilitate its application. (Usually water, but diesel oil has been used with water for brush control.)

Cation exchange capacity The total exchangeable cations a soil can adsorb; expressed as moles or m/moles of negative charge per kg soil (or other exchange material, e.g., clay).

Chlorosis The loss of green foliage color.

Clay (1) soil consisting of particles <0.002 mm diameter; (2) soil textural class; soil containing >40% clay, <45% sand, and <40% silt.

Cleistogamous Having small, unopened, self-pollinated flowers.

Compatibility The quality of two compounds that permits them to be mixed without effect on the properties of either.

Compensation point The light intensity at which the rate of photosynthesis and the rate of respiration in a leaf are equal.

Competition The active acquisition of limited resources by an organism that results in a reduced supply and consequently reduced growth of other organisms.

Concentration The amount of active ingredient in a given volume of diluent. Recommendations for concentration of herbicides are normally based on the weight or volume of active ingredient or product per unit volume of diluent.

Contact herbicide An herbicide that kills primarily by contact with plant tissue rather than after translocation.

Corm The enlarged fleshy base of a stem, bulb-like, but solid.

Cotyledon First leaf, or pair of leaves, of the embryo of seed plants.

Culm The stem of sedges and grasses.

Defoliator or defoliant Causes foliage to fall from plants.

Desiccant Promotes dehydration of plant tissue and may lower moisture content of seeds to facilitate harvest.

Dicot Abbreviation of *dicotyledon*. A member of the Dicotyledoneae. One of two classes of angiosperms (see Monocotyledoneae), usually characterized by having two seed leaves (cotyledons), net leaf venation, and a root system with a taproot.

Diluent A liquid or solid to dilute an active ingredient in the preparation of a formulation.

Dioecious Having male and female reproductive organs on separate plants; literally = two houses.

Directed spray Precise application to a specific area or plant organ, such as a row or bed or just plant leaves or the base of stems.

Dormant Condition in which seeds or other living plant organs are not dead but do not grow; state of suspended animation.

Dormant spray Chemical application in winter or very early spring before plants have begun active growth.

Drift Movement as a liquid.

Ecosystem Ecological entity composed of the biotic community and nonliving environmental phases functioning together in an interacting system.

Edaphic Of or pertaining to soil.

Emergence Appearance of a plant above the soil.

Emersed plant Rooted or anchored aquatic plant that grows with most of its stem tissue above the water surface.

Emulsifiable concentrate (EC) Single-phase, liquid formulation that forms an emulsion when added to water.

Emulsifier A material that facilitates suspension of one liquid in another.

Emulsion A mixture in which one liquid is suspended in minute globules in another liquid without either losing its identity (e.g., oil in water).

Encapsulated formulation An herbicide enclosed in capsules (or beads) to control rate of release of active ingredient and thereby extend period of activity.

Epinasty Increased growth on one surface of plant organ or part, causing it to bend.

Eutrophication A term used to designate a body of water in which the increase of mineral and organic nutrients has reduced the dissolved oxygen, thus creating an environment that favors plant over animal life.

Exchange capacity The total ionic charge of the soil adsorption complex.

Field capacity The percent water remaining in soil after free drainage has ceased.

Floating plant Free-floating or anchored aquatic plant adapted to grow with most vegetative tissue above the water surface; plants rise and fall with water level.

Flowable Two-phase formulation containing solid herbicide suspended in liquid that forms a suspension when added to water.

Formulation A pesticide preparation supplied by a manufacturer. The process of preparing pesticides for commercial use.

Fumigant A volatile liquid or gas used to kill insects, nematodes, fungi, bacteria, seeds, roots, rhizomes, or entire plants. They are usually applied in an enclosure of some kind or to covered soil.

Germination The activation of metabolic sequences culminating in renewed growth of the seed embryo, which is morphologically observable as radicle protrusion through the seed coat.

Granular A dry formulation consisting of discrete particles usually $< 10\text{mm}^3$, designed to be applied without water.

Growth regulator A substance effective in minute amounts for controlling or modifying plant processes.

Growth stages of cereal crops (1) Tillering—when additional shoots are developing from the crown; (2) Jointing—when stem internodes begin elongating; (3) Boot—when leaf sheath swells due to the growth of developing spike or panicle; (4) Heading—when seed head emerges from the sheath.

Hard water Water that contains minerals, usually calcium and magnesium sulfates, chlorides or carbonates, in solution to the extent of causing a curd, or precipitate, rather than a lather when soap is added.

Harvest index The amount (weight) of grain versus total plant foliar dry weight.

Herbaceous plant A vascular plant without woody tissues.

Herbicide A chemical used for killing or inhibiting the growth of plants; phytotoxic chemical (from Latin *Herba*, meaning "plant," and *caedere*, meaning "kill").

Hectare An area of land equal to 10,000 square meters or 2.47 acres.

Hormone A growth-regulating substance occurring naturally in plants or animals; refers to certain manmade or synthetic chemicals with growth-regulating activity; more correctly called *synthetic regulators*, not *hormones*.

Hypocotyl The portion of the stem of a plant embryo or seedling between the cotyledons.

Imbibition To imbibe is to absorb or take in water or any liquid. Imbibition is the act of imbibing.

Incorporate To mix or blend herbicides in soil.

Interference Total adverse effect that plants exert on each other when growing in a common ecosystem; includes competition and allelopathy.

Invasive species An alien species that becomes established in natural or semi-natural ecosystems or habitats, is an agent of change, and threatens native biological diversity.

Invert emulsion An emulsion in which water is dispersed in oil; oil forms the continuous phase with water dispersed therein; usually a thick, mayonnaise-like mixture results.

Involucre A circle or collection of bracts surrounding a flower cluster, head, or a single flower.

Kairomone An allelochemical of favorable adaptive value to the organism receiving it.

K_d The ratio of sorbed to dissolved pesticide at equilibrium in a water/soil slurry.

K_{oc} Soil organic carbon sorption coefficient; K_d divided by the weight fraction of organic carbon in soil.

Label Directions for herbicide use created by the manufacturer and approved by federal or state regulatory agencies.

Lay-by Refers to the stage of crop development (or the time) when the last regular cultivation is done.

LD_{50} The dose (quantity) of a substance that causes 50% of test organisms to die; usually expressed in weight (mg) chemical per unit of body weight (kg).

Leaching Usually refers to movement of water through soil, which may move soluble plant foods or other chemicals.

Lodge (lodging) To beat down plants from action of rain and wind; often encouraged by high rates of nitrogen fertilizer.

Mechanism of action The precise biochemical or biophysical reaction or series of reactions that create an herbicide's final or ultimate effect; many herbicides have primary and secondary mechanisms of action.

Mesocotyl The elongated portion of the axis between the cotyledon and coleoptile of a grass seedling.

Miscible liquids Two or more liquids capable of being mixed, which will remain mixed under normal conditions.

Mode of action The sequence of events that occurs from an herbicide's first contact with a plant until its final effect (often plant death) is expressed.

Monocot Abbreviation of *monocotyledon* (see Dicot). One of two classes of angiosperms, usually characterized by having one seed leaf (cotyledon), parallel leaf venation, and root systems arising adventitiously that are usually diffuse and fibrous.

Mulch Material (grass, straw, plastic, plant residue) spread on soil to cover or protect soil.

Necrosis Localized death of tissue, usually characterized by browning and dessication.

Niche The area within a habitat occupied by an organism. It is also the set of functional relationships of an organism or a population to the environment it occupies. The term is used to describe a species' place in the community including when it is present, what place (space) it occupies, and what function(s) it fulfills in the community. The ecological concept of niche includes a species specialization—its special or unique function in the community.

Nonselective herbicide Herbicide used to kill plants generally without regard to species.

No-till, no-tillage Planting without prior soil disturbance.

Noxious weed Plant defined by law as being especially undesirable, troublesome, and difficult to control.

Perennial A plant that lives from year to year; in most cases, in cold climates, stems and foliage die, but roots persist (e.g., field bindweed, dandelion, Canada thistle, johnsongrass, leafy spurge).

Pesticide Any substance or mixture of substances intended for controlling insects, rodents, fungi, weeds, and other forms of plant or animal life considered to be pests.

Phenology Naturally occurring phenomena that recur periodically, such as flowering and time of seed germination.

Phloem Living plant tissue that transports metabolic compounds from site of synthesis to storage or site of use.

Phytotoxic Something that is poisonous or inhibitory to growth of plants (from Greek *phyton*, meaning "plant," and *toxikon*, meaning "poison").

Plagiotropic A term used primarily for roots, stems, or branches to describe growth at an oblique or horizontal angle.

Polyphagous Feeding on or using a variety of foods.

Postemergence (post-) After emergence of a specified weed or crop.

Preemergence (pre-) After a crop is planted but before it emerges.

Preplant Application of an herbicide (or anything) before planting.

Preplant incorporated (PPI) Herbicide applied and blended into soil prior to planting.

Radicle That part of the plant embryo that develops into the primary root.

Rate and dosage These are synonyms. *Rate* is preferred and usually refers to the amount of active ingredient applied to a unit area regardless of percentage of chemical in the carrier.

Registration The process of gaining approval to sell an herbicide or other pesticide from the US Environmental Protection Agency (US/EPA) as governed by the amended Federal Insecticide, Fungicide, and Rodenticide Act.

Residual Applied to an herbicide, the sense is to have a continued effect over a period of time.

Resistant The decreased response of a population to an herbicide. *See* Tolerance.

Rhizome An underground stem capable of sending out roots and leafy shoots.

Ribonucleic acid (RNA) A polymeric constituent of all living cells, which consists of a single strand of alternating phosphate and ribose units with the bases adenine, guanine, cytosine, and uracil bonded to the ribose. The structure and base sequence determine the proteins synthesized.

Runner A plagiotrophic shoot that may root when in contact with soil.

Safener A substance that reduces an herbicide's phytotoxicity.

Selectivity The property of differential tolerance; some plants are affected, others are not. It is an essential attribute of most herbicides.

Sequester To remove or set apart.

Sink A plant site with a high rate of metabolic activity where food resources are used.

Soil incorporation The mechanical mixing of herbicides in soil.

Soil injection Mechanical placement of an herbicide beneath the soil surface.

Soil persistence The length of time an herbicide remains in soil. It may refer to effective life (i.e., the time during which plants are killed) or to total soil residence time.

Soil sterilant An herbicide that prevents growth of all plants. The effects may be temporary (a few months) or long term (years).

Solution A homogeneous mixture of two or more substances.

Solution concentrate A liquid formulation that forms a solution when added to water.

Soluble powder A dry formulation that forms a solution when added to water.

Spike stage The early emergence stage of corn in which leaves are tightly rolled to form a spike, usually before corn is more than two inches tall.

Spot treatment Application of herbicide to localized or restricted areas as opposed to overall, broadcast, or complete coverage.

Spray drift Movement of airborne liquid spray particles.

Stolon An above-ground creeping stem that can root and develop new shoots (e.g., bermudagrass).

Stunting Retardation of growth and development.

Submersed plant An aquatic plant that grows with all or most vegetative tissue under water.

Surfactant Material added to pesticide formulations to impart spreading, wetting, dispersibility, or other properties that modify surface interactions.

Suspension A liquid or gas in which very fine solid particles are dispersed but not dissolved.

Sympatry Occurring in one area. *See* Allopatry.

Symplast A functionally integrated unit consisting of all living cells of a multicellular plant.

Synergism The action of two or more substances that creates a total effect greater than the sum of independent effects; achievement of an effect by two substances that neither is capable of achieving alone.

Systemic herbicide An herbicide that is translocated in plants to produce an effect throughout the entire plant system.

Teratogenic Something that produces birth defects.

Tolerance Amount of pesticide chemical allowed by law to be in or on the plant or animal product sold for human consumption (legal definition). Natural and normal variation that exists within a species and can evolve quickly. *See* Resistance.

Tolerant Capable of withstanding effects. *See* resistance.

Toxicity The potential to cause injury, illness, or undesirable effects.

Trade name A trademark or other designation of a commercial product.

Translocation Transfer of photosynthate or other materials such as herbicides from one plant part to another.

Tuber A much-enlarged portion of a subterranean branch (stolon) that has buds on the sides and at the tip.

Turion Scaly shoot developed from a bud on a subterranean or submerged rootstock.

Volatility A measure of the tendency to change state from liquid to gas.

Weed Any plant that is objectionable or interferes with the activities and welfare of man (definition accepted by the Weed Science Society of America).

Weed control (1) The process of limiting weed infestations so crops can be grown profitably or other operations can be conducted efficiently; (2) the process of reducing weed growth or weed infestation to an acceptable level.

Weed eradication Complete elimination of all live plants, plant parts, and weed seeds from an area.

Weed management A relatively new term in the lexicon of weed science that has not obtained an official definition (Vencill, 2002). A synthesis of definitions follows: rational deployment of appropriate technology to minimize weed effects, provide systematic management of weed problems, and optimize intended land use. (It is likely that the evolving definition will incorporate determination of an economic threshold.)

Weed prevention The process of stopping weeds from invading an area.

Wettable powder A powder that forms a suspension (not a true solution) in water.

Wetting agent A chemical that, when added to a spray solution, causes the solution to contact (wet) plant surfaces more thoroughly.

Winter annual A usually temperate-climate plant that starts germination in the fall, lives over winter, and completes its growth, including seed production, the following season (e.g., downy bromegrass); many summer annuals can behave as winter annuals if they germinate in the fall and live over the winter.

Xylem The nonliving plant tissue that conducts water and solutes from roots to shoots.

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