WEED-CROP COMPETITION

A REVIEW

Second Edition

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In order to penetrate ever further into their subjects, the host of specialists narrow their fields and dig down deeper and deeper till they can't see each other from hole to hole. But the treasures their toil brings to light they place on the ground above. A different kind of specialist should be sitting there, the only one still missing. He would not go down any hole, but would stay on top and piece all the different facts together.

—Thor Heyerdahl, *Aku-Aku: The Secret of Easter Island*

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Preface

The primary impetus for the first edition of this work twenty years ago came from my opinion, formed from limited international experience in the 1970s, that many weed scientists in developing countries did not receive and were not aware of current weed science literature (see Zimdahl 1980). They had limited or no access to journals commonly found in libraries of the developed world. Thus, they were denied use of printed resources that help develop an historical perspective. Often, they did not know what was known. An historical perspective combined with the stimulation of current research sharpens the focus of research programs and facilitates their justification to administrators and funding agencies. Lack of access to the literature can narrow one's perspective and usually impedes development of good weed science programs.

Because no comprehensive review of weed-crop competition had been published and because approval had been given for the project by the International Plant Protection Center at Oregon State University, there was additional motivation for the first edition.

The literature review for the present book began in mid-2001 in the library of the International Rice Research Institute (IRRI), Los Banos, Laguna, Philippines. The review was completed and writing began in late 2002. When the review began, I was a Fulbright Scholar in the Department of Agronomy of the University of the Philippines at Los Banos, and Dr. James Hill, chair of IRRI's Department of Crop, Soil, and Water Sciences, graciously offered a courtesy appointment and access to IRRI facilities. The Philippines, a place where weeds grow abundantly, was an appropriate location to begin to think again about what may be the central hypothesis of weed science: Weeds compete with crops and reduce crop yield and quality.

This hypothesis is rarely stated in scientific papers about weeds because it has dominated the thinking in weed science for so long that it is axiomatic. After all, if it were proven to be false and if it were discovered that crops tolerated weeds, the world would not need weed scientists. There would be no problems with weed-crop competition. However, the first edition of this book, published in 1980, showed that weed-crop competition is real and its effects had been studied in many ways, in many crops, for many years. The hypothesis that weeds negatively affect crop yield and quality has been tested and verified; it is accepted.

However, weed science, similar to most disciplines, continues to test its central hypothesis. Weed scientists have been productively engaged in what Kuhn (1970) calls normal science—"the activity in which most scientists inevitably spend almost all their time." It is, in Kuhn's view, "predicated on the assumption that the scientific community knows what the world is like." It is a "strenuous attempt to force nature into the conceptual boxes supplied by professional education." Thus, the weed science community has continued to test its central hypothesis about how weeds negatively affect crops. Weed scientists are moving, albeit slowly, from the normal science that repetitively asks what happens, although this review establishes that these experiments are still done, to the more difficult but more important and more scientifically demanding question of why does what is observed occur.

The first edition of this book was a report of what had been done by whom. It included articles directly related to weed-crop competition published prior to June 1978. This second edition is an attempt to summarize the literature about what is known about what happens and to explore current understanding of why. A goal is to urge a decrease of effort directed toward answering the first question and an increase of effort on the second. In spite of criticism of what has been done, I hasten to add that I have been continually impressed with the quality of the work and by the people who have done it. I have been most impressed by many of the papers and reviews mentioned here that are superlative work done by capable people whose scientific knowledge and skills often seem to extend beyond my analytical and review ability. I am humbled by what my colleagues have done.

Unless warranted, this second edition will not reconsider but will include some of the manuscripts used in the first edition. To this end, I begin this review at the end of the first edition and go forward. Older material is included for historical reasons and to make certain points. The book's focus is interference in the narrow sense of crop-weed competition. The abundant recent literature on weed biology and weed ecology is not included unless such studies directly address competition. There was no attempt to include any of the literature on allelopathy, which has been summarized by others (Inderjit et al. 1995, 1999; Putnam and Tang 1986; Rice 1974, 1979, 1983; Thompson 1985). It is my limitation, but in most cases, the review includes only literature published in English with emphasis on American and European journals of weed science. There are exceptions, but, in general, this review does not include papers published in the proceedings or research progress reports of U.S. regional (e.g., northeastern, north central, southern, or western) societies of weed science and by other regional weed conferences (e.g., Asian-Pacific Weed Science Society, Canadian Weed Science Society). This is the case because the review emphasizes papers that have passed peer review and been published in refereed journals. Second, many regional publications were not readily available to me. Finally, papers that emphasized herbicides or other weed management techniques have not been reviewed. Readers will note that much of what has been included seems repetitious. Roget's thesaurus helps, but not much, when one wants to say that someone or a paper showed, discovered, revealed, noted, or found. The ways to say what was discovered are limited, especially when so much of the work included is similar in design and result. I assure the reader that I recognized the risk and suffered while writing from repetition. The work assembled here is a resource, and I hope one result will be that a lot more work to explain what happens when weeds interfere with crop growth will not be done.

Authors resist and editors insist on uniformity and a limited set of notations and measurement systems. The current convention of using only metric units was tempting. However, readers who elected to consult a particular paper would need to convert back to the original units. Therefore, the units from original papers were used without conversion to metric. A short conversion table has been included as appendix table A.4.

All weeds are cited by the common or scientific name (if no common name has been accepted by the Weed Science Society of America). Equivalent scientific and common names, accepted by the Weed Science Society of America, are included in appendix table A.2, which lists them in alphabetical order by common name, and in appendix table A.3, which lists them in alphabetical order by scientific name. The scientific name of each crop is included in appendix table A.1.

Most papers selected for inclusion specifically discuss weed-crop competition. Others provide background information. Most literature concerning crop-crop interactions has been omitted as has that dealing with environmental conditions that stress crops (e.g., low water, high temperature) and increase their susceptibility to weed competition.

The second edition follows the general outline of the first edition. A chapter on modeling and a more detailed chapter on methods have been added.

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Robert L. Zimdahl

1

Introduction: An Historical Perspective

Two of the earliest references on the effects of weed competition appear in ancient writings of the Bible: "Cursed is the ground for thy sake; in sorrow shalt thou eat of it all the days of thy life; thorns also and thistles shall it bring forth to thee; and thou shalt eat the herb of the field" (Genesis 3:17–18). Another passage, the parable of the sower, notes that, "some fell among thorns; and the thorns sprang up, and choked them" (Matthew 13:7).

It is correct to suggest that competition among plants precedes recorded history and that it was recognized long before a defined term was assigned. Competition among plants in natural communities is common, but it is not a universal phenomenon (Goldberg 1990). However, in agricultural plant communities, weed-crop competition, with a few exceptions (e.g., living mulches, companion cropping), seems to be a natural, undesirable, ubiquitous, and inevitable phenomenon.

Competition is a predictable response of grouping living organisms into communities. Clements et al. (1929, p. 3) provided an early history of the literature, which they claimed was "not extensive." The book by Clements et al. (1929), although perhaps not extensive, provides an accurate historical perspective on the early development of the study of plant competition. Competition was recognized and reported by Petrus de Crescentiis in 1305 when he directed that trees in a forest community be cut first where they were too thick. The significance of competition in the plant kingdom was perhaps first perceived by Decandolle (1820) who described plant competition and stated that all species of a region and all plants of a given place are in a state of war with respect to each other. He derived a theory of antagonism between phanerogams, and a theory of crop rotation based on the idea that succeeding species should be those not inhibited by toxic substances left by preceding crops. One of the first studies of plant competition was by Sachs (1860), who attempted to relate soil mass to plant yield. Nageli in 1865 (cited in Clements et al. 1929) broadened the significance of competition in the plant community, pointing out that it furnished a solution to the problems involved with the presence of lime in soil.

Malthus (1798) was concerned primarily with growth of the human population and the consequent poverty and misery he saw in Liverpool, England. He proposed that the power of population was infinitely greater than the earth's ability to produce food. 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. Competition for food, if the Malthusian apocalypse comes true, still concerns many. Malthus said, "The cause to which I allude is the constant tendency in all animated life to increase beyond the nourishment prepared for it." The Malthusian hypothesis has three major points:

1. Population is necessarily limited by the means of subsistence.
2. Population infinitely increases when the means of subsistence increase unless it is controlled by powerful checks.
3. These checks that suppress the superior power of population and keep population and the means of subsistence in balance are resolvable by moral restraint, or population will be controlled by the four horsemen of the apocalypse: war, famine, pestilence, and vice.

Malthus's views are claimed by some to have been inspiration for Darwin's (1859) principle of natural selection. Darwin (1859) derived the concept of competition (a struggle for existence) in natural evolution and proposed it was ubiquitous and omnipresent. In reviewing Darwin's exposition of competition in the *Origin of the Species,* one can easily overlook the fact that he regarded competition as only one component of the struggle for existence, but possibly the most important one.

Nageli (cited in Clements et al. 1929) sought to give mathematical form to the suppression of plants by their competitors. He concluded that the number of species in an area was determined by the average life period and the average annual growth increment. In 1892, Macmillan (cited in Clements et al. 1929) considered the significance of competition between communities as well as within them. He was among the first to express the view that there are certain points of resemblance in the competition for food that takes place between similar individuals and causes the weaker to be more or less suppressed. Clements et al. (1929) stated,

> Competition is a question of the reaction of the plant upon the physical factors that encompass it and of the effect of these modified factors upon adjacent plants. In the exact sense, two plants do not compete as long as the water-content, the nutrients, the heat and light are in excess of the needs of both. The moment, however, that the roots of one enter the area from which the other draws its water supply, or the foliage of one begins to overshadow the leaves of the other, the reaction of the former modifies unfavorably the factors controlling the latter, and competition is at once initiated. (pp. 10–11)

Haldane (1932) noted, "Fitness depends in a quite complicated way on the environment. In order to test fitness in the Darwinian sense it would be necessary to grow the plants in competition." Thus, we must conclude that a complete analysis of plant competition must involve plants in a community and their communal relations, plus individual plant-growth patterns. The growth of plants in isolation can provide useful information but only when it is combined with community studies.

Brenchley (1917) studied several weeds in cultivated crops and observed that some were generally found in association with certain crops and others were common among all cultivated crops. She hypothesized that one of the foremost factors determining a particular weed species' abundance or scarcity was its ability to withstand competition. The aboveground struggle for light, she stated, was as important as the underground competition for nutrients and moisture. These three primary elements of plant competition—light, nutrients, and water—are mentioned repeatedly in the literature. Portions of this review will focus on each, but we must recognize that plants exist in environments where all elements of competition are active, and separation of the elements, while interesting, probably does not, and perhaps cannot, reflect the real world of inter- and intraspecific competition.

Plant competition has been studied from two major perspectives. Ecologists have studied competition to understand diversity and change in plant communities and patterns of succession in plant communities. The goal has been to develop principles for management of ecosystems. Agronomists, weed ecologists, and weed scientists (the difference between the last two categories is small) have been most interested in competition between weeds, the unwanted species, and crops. Studies have emphasized weed and crop density, relative time of weed and crop emergence, and the use of herbicides and other management techniques to minimize weed competition in crops. This review emphasizes the work of weed scientists but does not exclude complementary work by plant ecologists. The review intentionally excludes the many good studies on weed control.

Kropff and Walter (2000) noted that the "introduction of selective herbicides has been one of the main factors enabling intensification of agriculture in developed countries." During its first three decades, the journal *Weed Research* published mainly papers related to herbicides. As reported by Kropff and Walter (2000), most papers published now are on weed biology and ecology (32 in 1998 versus 17 in 1975) with fewer on herbicides (6 in 1998 versus 32 in 1975). The work reported in *Weed Science* has shown the same shift in emphasis (fig. 1.1). Thirty years ago (1973), 82 percent of the papers published in *Weed Science* dealt with some aspect of herbicides, and 18 percent dealt with some aspect of weed biology/ecology. Herbicide-related studies have steadily declined to only 37 percent of the papers in 2003, whereas 63 percent emphasize some aspect of weed biology/ecology. Figure 1.1 shows the steady decrease of herbicide papers and the steady increase of those on weed biology/ecology with the latter exceeding the former in 1999.

Kropff and Walter (2000) regard the shift in emphasis from herbicides to weed biology and ecology as desirable. They note Mortensen et al.'s (2000) report of significant application of weed biology research to solving practical weed management problems.

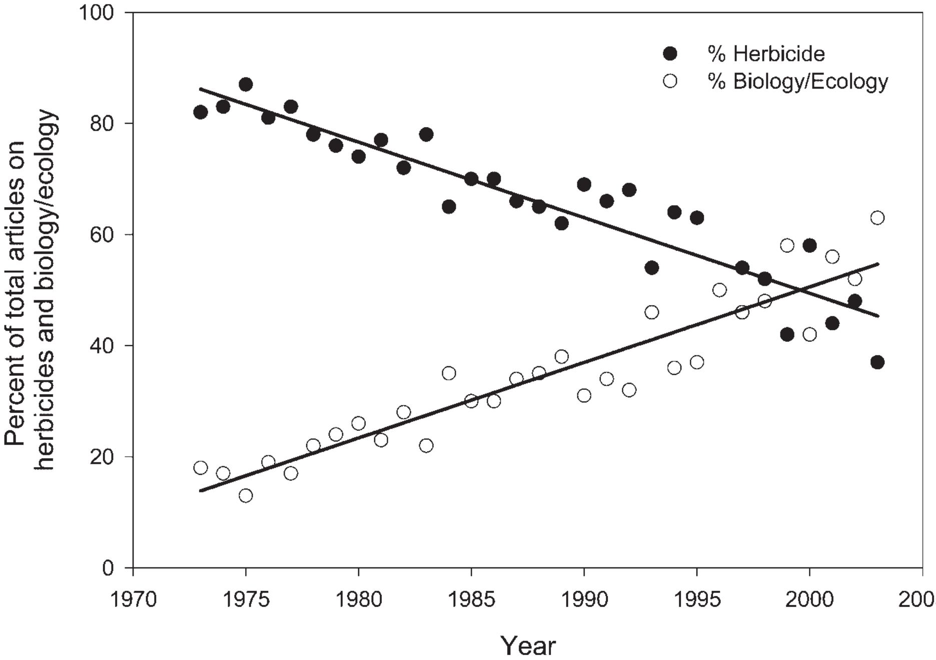

Figure 1.1. A 30-year account of papers published on herbicides and on weed biology and ecology in *Weed Science.* Herbicide articles included all articles that focused on herbicides in any way (e.g., physiology, mycoherbicides, herbicide resistance). Biology/ecology articles were selected only if they did not mention herbicides. Statistical and modeling papers were excluded.

Barbieri and Kropff (2002), two years later, reported a further shift in emphasis. They said that in weed biology "we are moving from prediction of the time of weed emergence to quantification of the process, taking particularly into account the variability of weather conditions." They suggest that there is an increasing number of people "studying the interactions between weeds and other biota." Barbieri and Kropff (2002) also suggest that crop-weed competition studies are increasingly applied to scenarios in which biological and cultural weed control methods play a major role. This review does not deny their observation but neither does it offer vigorous confirmation. Barbieri and Kropff (2002) propose that "if this trend toward system-thinking is real, it should be seen as a positive achievement for weed scientists." It is positive because it will produce research results that give farmers and consumers what they really want from weed science research. It is apparent that Barbieri and Kropff (2002) think that what farmers and consumers really want is improved accuracy and precision of weed-management recommendations and reduced chemical use. This is achievable, in their view, through integration of weed science with other disciplines (e.g., ecology and environmental science), and that integration in Barbieri and Kropff's (2002) view may be the beginning of the loss of identity of weed science as a stand-alone discipline.

It is not an objective of this book to engage in the legitimate debate about whether weed science has ever achieved standing as a discipline with its own university departments, curriculum, and degrees. However, perhaps weed scientists ought to or will be compelled by the direction of their science to begin to consider their future carefully and the benefits and losses of the desirable integration proposed by Barbieri and Kropff (2002).

To prepare this book, all issues of the world's three principal weed science journals: *Weed Science*, *Weed Technology,* and *Weed Research* from 1980 to mid-2002 were reviewed for articles that dealt with weed-crop competition. It is almost surely true that some important papers were missed. The error is mine and I apologize to those whose papers were missed and for the incomplete report that may be the result. Earlier volumes were reviewed for the first edition. It is interesting to note how many articles in each issue of each journal dealt specifically with weed-crop competition (table 1.1) and to compare those data with those in figure 1.1.

After this introduction and a brief historical perspective on plant competition, chapter 2 focuses on the definition of competition as it is used in the weed-crop literature, which recapitulates the material that appeared in the first edition of this book.

Chapters 3 and 4 cover the role of competition in the community and the influence of competition on individual plants. These chapters are brief not because they are unimportant but because these are not the areas that weed-science research has emphasized. The effects of competition in the crop-weed community have nearly always been measured by weed scientists as the detrimental effect of weeds on crops, and they have been expressed as a reduction of crop yield. This legitimate weed-science approach is contrasted with the ecological approach that emphasizes the mechanism(s) of competition in plant communities and the structure of communities. The chapters provide evidence for the desirable convergence of the two approaches.

Chapter 5, the largest part of this edition, reviews the many reports of the result of competition between several weeds in several crops. It provides abundant support for the hypothesis that increasing weed density decreases crop yield. Chapter 5 is arranged alphabetically by crop, and the literature for each crop is placed at the end of that crop's section rather than at the end of the whole chapter.

Table 1.1. Number of Articles on Weed-Crop Competition in Three Major Weed Science Journals, 1979 to 2002

	Journal		
Year	*Weed Research*	*Weed Science*	*Weed Technology*
1979	3	11	—
1980	4	18	—
1981	1	16	—
1982	2	16	—
1983	5	10	—
1984	7	31	—
1985	2	20	—
1986	3	31	—
1987	3	34	4
1988	5	26	6
1989	5	24	3
1990	4	17	7
1991	6	17	14
1992	8	28	8
1993	7	21	4
1994	8	18	9
1995	8	21	5
1996	7	36	4
1997	5	17	3
1998	8	11	1
1999	9	17	0
2000	5	6	7
2001	2	16	8
Mid-2002	8	9	5

Note: Weed Technology was first published in 1987.

Chapter 6 summarizes some of the literature in chapter 5 that describes the effect of competition duration. Chapter 5 emphasizes the effects of weed density (how many), whereas chapter 6 emphasizes the variation introduced by the duration (how long) of competition. Chapter 6 also reexamines the critical-period concept. There is an abundance of data that purport to define a critical period for weed management in several different crops, but the critical period seems peripheral to most weed management decisions. It is clear that the period varies with the place where the work was done, with the particular season, with each weed-crop combination, and with the relative time of emergence of the crop and weed(s). The data on the critical period for weed control are interesting but may be useful only where the work was done and not generalizable.

Chapter 7 attempts to separate, as the literature frequently does, the things (light, nutrients, water) that plants compete for, which plants that must integrate cannot separate.

Chapter 8 asks if all the work that has been done has made a difference. Has weed management improved because of all that has been done to establish that weeds reduce crop yield? The answer, sadly, seems to be that while the work is not useless, the evidence that it has made a major difference in weed management techniques is weak.

Chapter 9 explores the methods used to study weed-crop competition. These were mentioned in the first edition, but the importance of the experimental method to eventual interpretation of data was not emphasized in the first edition.

Chapter 10 is new because so little had been done on models before 1979. Now much has been done, and models and modeling are important to development of improved weed management methods.

Chapter 11 attempts to conclude the results of more than 650 research papers. There are three major conclusions. The first is that there is no question that what I have called the central hypothesis of weed science has been affirmed: Weeds compete with crops and reduce crop yield and quality. The work that has been done affirms this for numerous weeds in all of the important crops that have been studied. The second conclusion is that weed science will benefit from closer integration with plant ecology and greater emphasis on study and understanding of the coexistence of plants. The final conclusion is that modeling has become an important aspect of modern weed management systems and is likely to become more important.

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2
Definition of Plant Competition

> *Where there is so much of competition and uncertainty you must expect self interest will govern.*
>
> —Jeremy Collier, *Essays on Moral Subjects,* 1697

The *Oxford English Dictionary* defines competition as "the action of endeavouring to gain what another endeavours to gain at the same time; the striving of two or more for the same object; rivalry." To compete comes from the Latin word *competere*, which means to ask or sue for the same thing another does. Despite a precise etymology and concise definition, the meaning of the term competition is not precise in the plant science literature. Milne (1961) proposed that confusion resulted from (1) a misunderstanding of Darwin's original usage, (2) neglect of the etymology of the word, and (3) the mixing of competition with results. Milne, who worked with animals, found wide disagreement among definitions.

Bunting (1960) thought competition had different shades of meaning for the agronomist and the plant physiologist. In his view, physiologists think of competition as being for something, usually nutrients, water, or light. Agronomists and weed scientists, while agreeing, add that competition also exists between plants (Donald 1963) or parts of the same plant. The many definitions were reviewed by Milne (1961).

1. Mather (1961): "Competition implies the presence of one individual as an effective part of the other's environment and a similarity of need or activities so their impact on each other is prospectively detrimental."
2. Aspinall and Milthorpe (1959): "The interaction between plants and environment. Plants during growth modify the environment around them and the modified environment in turn influences the growth of the constituent plants."
3. Bleasdale (1960): "Two plants are in competition with each other when the growth of either one or both of them is reduced or their form modified as compared with their growth or form in isolation."
4. Milne (1961): "Competition is the endeavor of two (or more) animals to gain the measure each wants from the supply of a thing when that supply is not sufficient for both (or all)."
5. Birch (1955): "Competition occurs when a number of animals (of the same or of different species) utilize common resources the supply of which is short; or if the resources are not in short supply, competition occurs when the animals seeking that resource nevertheless harm one or the other in the process."
6. Clements et al. (1929): Competition involves the reaction of a plant to the physical factors that encompass it and of the effect of these modified factors upon adjacent plants. For Clements et al., competition is 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.

This definition makes competition different from the broader term *interference,* which includes competition, and allelopathy.

Harper (1960, 1961) decided that many definitions proved excessively cumbersome and, in his work, adopted and has argued for use of the inclusive term, *interference*, which has been advocated by Muller (1969). As mentioned in the preface, discussion of allelopathy has not been included in this review. Allelopathy is distinguished from competition because it depends on adding a chemical compound to the environment whereas competition involves the removal or reduction of an essential factor from the environment. Competition, as weed scientists understand it and use the term, is a struggle between a crop and a weed for a resource (e.g., light, water, or nutrients) that is in short supply

Grace and Tilman (1990) point out that definitions of competition range from "the narrow to the general, from operational to philosophical, and from phenomenological to mechanistic." The range of definitions, in their view, "has caused confusion and continues to cloud discussion of the substance of competition." The many definitions notwithstanding, weed scientists concerned with weed-crop competition discover, with pleasure, the two major points of plant competition outlined by Clements et al. (1929), followed by an inclusive definition. The principles are:

1. Competition is keenest when individuals are most similar and make the same demands on the habitat and adjust themselves less readily to their mutual interactions.
2. The closeness of competition between plants of different species varies directly with their likeness in vegetation or habitat form. Dissimilarity tends to eliminate competition and preserve the advantage of the superior form. These broad concepts seem to fit with the weed scientists' perception of weed-crop competition and are compatible with the work that has been done.

Donald (1963) combined the definitions of Milne (1961) for the animal world and Clements et al. (1929) for plants into a concise statement: "Competition occurs when each of two or more organisms seeks the measure it wants of any particular factor or thing and when the immediate supply of the factor or thing is below the combined demand of the organisms."

Connell (1990) defined competition as simply "a reciprocal negative interaction between two organisms." Connell (1990) points out that ecologists traditionally restrict the term to "instances involving only two broad categories of mechanisms: direct interference and indirect exploitation of shared resources." In the first case, two plants compete directly for a resource both require. In the second case, exploitative competition is an indirect action because of the requirement for a shared resource. Connell (1990) notes that if one wants to distinguish the types of competition (he cites four possibilities), knowledge of the mechanisms is required. He agrees with Tilman (1987) that few studies of competition by ecologists have demonstrated the mechanisms underlying the observed interactions, and therefore it is quite possible that many studies that purport to demonstrate competition may illustrate apparent, not real, competition. The lack of study of the mechanisms is certainly true for studies of weed-crop competition performed by weed scientists. However, as Radosevich and Roush (1990) point out (see chapter 9), while this is true, it should not be viewed as a devastating critique because the objectives of the studies performed by weed scientists have been distinctly different from the objectives of ecologists. Perhaps the simplest distinction between the worthy objectives of the two groups is that the former is interested in what happens and the latter in why.

One often reads of competition for space, and while this occurs in the animal kingdom, it is not usually the case with plants. Rivalry for space may occur with sugarbeet or carrot when two roots actually touch or become intertwined. Generally, in plant competition, the phrase implies competition for the resources space contains—nutrients, water, or light—rather than for the space itself.

Further evidence that the association of two or more plant species does not always result in competition can be found in the symbiotic association of legumes and grasses. Mather (1961) discussed this aspect of plant relationships and Donald (1963) provided another example: the germinating seeds of subterranean clover. The dormancy found in some varieties of this species for many weeks after harvesting may be broken by exposure to an atmosphere containing 0.5 percent carbon dioxide. If one seed in a dormant group germinates in a normal atmosphere, it will provide enough carbon dioxide to initiate germination of the rest. Work on living mulches and companion crops also points to the fact that not all plant combinations are competitive or harmful.

Donald (1963) also mentioned that competition cannot be assumed simply because a factor is in short supply. If all plants in a community are exposed to insufficiency while the environment of each is independent of its neighbors, there can be no competition. He used the example of poor oxygen supply delaying germination and growth of wheat seedlings in very wet, poorly structured soils. However, the circumstance is exceptional and competition soon occurs.

Plants cannot be considered to compete for heat because heat is not present in finite amounts, although heat can affect the process (see chapter 7). Competition for carbon dioxide may occur but probably only under extremely crowded conditions. Most of the factors for which there is competition are found as a pool from which supplies are drawn, according to Donald (1963). This concept can be easily visualized for water and nutrients but not for light. Light must be intercepted when available or it is lost forever. Thus, foliar height and breadth will determine a plant's effectiveness as a competitor for light. One can refer to Clements et al. (1929) to further elucidate the concept of a pool and its usage: "It is evident that practically all the advantages or weapons of competing species are epitomized in two words—amount and rate. Greater storage in seed or rootstock, more rapid and complete germination, earlier start, more rapid growth of roots and shoots, taller and more branching stems, deeper and more spreading roots, more tillers, larger leaves, and more numerous flowers are all of the essence of success." Thus, nothing succeeds like success.

Competitive ability has been proposed as a genetic character controlled by polygenes but not associated with morphological characters such as height, growing habit, and vigor of growth (Sakai 1961). The heritability of the trait, if it exists, appears to be very low and the outcome of competition surely must vary not only with intensity, but also with the environment in which it occurs.

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Weed-Crop Competition: A Review, Second Edition
Robert L. Zimdahl

3

Competition in the Community

The effects of competition in the crop-weed community have nearly always been measured by weed scientists as the effect of the weed or weeds on the crop, and the effect is commonly expressed as a reduction in crop yield. The importance of competition as a determinant of the structure of natural plant communities is well accepted and it has been evaluated in several ways (Connell 1990). In Connell's view, the first task is "to demonstrate unequivocally its occurrence in nature, yet this has often proved to be difficult." Goldberg (1990) concurs that competition is a common although not ubiquitous phenomenon.

Research for this book strongly suggests weed scientists regard competition as ubiquitous in agricultural plant communities. Demonstration of its occurrence has not been a problem for the weed-science community because it has been assumed to occur, unequivocally, albeit with the necessary semantic combination of competition and allelopathy under the general term *interference*. Both competitive and noncompetitive processes will (if both occur in a field) strongly influence plant growth in a multispecies community (Hall 1974). Connell (1990) states the evidence for competition (e.g., crop yield reduction) can often result from other types of plant interactions, which are frequently overlooked. These are illustrated in figure 3.1 (Connell 1990).

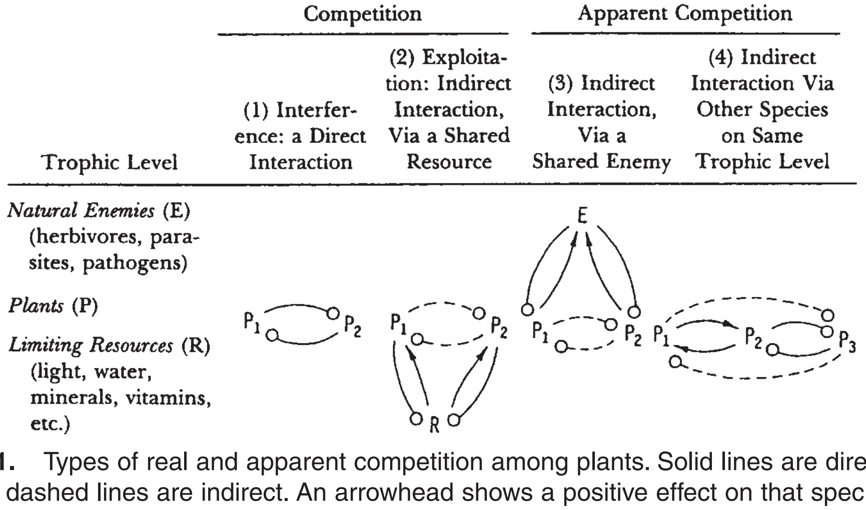

Figure 3.1. Types of real and apparent competition among plants. Solid lines are direct interactions, and dashed lines are indirect. An arrowhead shows a positive effect on that species, and a circle shows a negative effect. In case 4, apparent competition is between P1 and P3. (From Connell 1990; reprinted with permission)

PLANT COMMUNITIES

As weed scientists expand the search for mechanisms of competition and study the structure of crop-weed communities, the difference between direct and indirect competition and apparent competition will become more important. An example of the kind of work that weed science needs more of is the work on community assembly by Booth and Swanton (2002). *Community assembly*, a rare term in weed science, is a branch of ecology that examines how a community is assembled over time and what paths (trajectories) the members and the entire community follow over time.

The trajectories are determined by biotic (competition) and nonbiotic factors (environment). Booth and Swanton call these filters, each of which acts at multiple scales. Environmental filters act to remove or limit species that lack specific traits. Booth and Swanton present the basic ecological theory of community assembly and propose how it can be applied to weed-science research to predict how crop-weed communities change in response to what they call "imposed filters" such as tillage and crop rotation. Their work, if followed, may lead weed science toward fundamental theories of competition and away from continued emphasis on what happens. They acknowledge that a community assembly approach is the opposite of the current approach to weed management, which is "to look at weeds as a series of individual problems and to study the biology of each species in an attempt to identify weak links in their life cycle." Management techniques are then developed to address the identified weak links at specific sites under specific conditions.

Booth and Swanton (2002) recognize the utility of the approach but caution that it does little to "broaden understanding of why weeds occur where they do or how they interact in communities." The approach leads to solution of the weed problem addressed and creation of a new weed problem that the solution did not (could not) address. It is the kind of solution criticized by Berry (1981) as one that leads to a "ramifying series of new problems." Berry (1981) advocated, as Booth and Swanton (2002) do, solutions that cause a ramifying series of solutions. Understanding how communities are assembled and function should lead to a series of solutions.

The community, in which usually a single crop and one-to-many weed species exist, is important to weed management and the study of competition because it is the organizational level at which changes occur. Changes can occur within a species by mutation and ecotype development or by replacement of one species with another (Zimdahl 1999, pp. 130–131). There are at least four reasons why two or more species can coexist in a place. They can have one or more of the following characteristics:

1. Different nutritional requirements, as illustrated by legumes and grasses coexisting in pasture and hay fields.
2. Different causes of mortality, observed in pastures where animals selectively graze.
3. Different sensitivity to toxins, including allelochemicals and herbicides.
4. A different time demand for growth factors. Many plants require the same growth factors to succeed, but they do not demand them at the same time. This may be the most common reason for coexistence.

A more complete discussion of coexistence is presented by Grime (1979, pp. 157–177).

AGRICULTURAL COMMUNITIES

In agricultural fields, orderly, continuous, natural ecological succession does not occur, but change, due to human manipulation, does. Agricultural fields that are not in a permanent crop such as an orchard or have a semipermanent perennial crop (e.g., alfalfa, where disturbance is still frequent for harvest and the land is rotated to another crop perhaps as often as every three years) are regularly and intentionally disturbed and lack a natural (undisturbed) plant community. Environmental change is a driving force in natural plant succession but annual crop agriculture strives to modify and control the environment through tillage, fertilization, pest (weed, insect, and disease) control, and irrigation.

Because of regular disturbance and other cultural practices, the spatial and temporal variability of agricultural environments is reduced compared to natural plant communities (Radosevich and Roush 1990). Dominance of the planted crop species characterizes agricultural plant communities that also have a few (rarely only one) weed species that occur in cropped fields. Their removal (control) creates open niches into which another weedy species will move, but perhaps not immediately. Therefore, weed management, especially successful weed management, is a never-ending process (Zimdahl 1999). One could argue that the best weed management techniques may therefore be those that achieve less than 100 percent control and do not open niches that allow new introductions to succeed and necessitate further weed control.

LEVELS OF COMPETITION

The three primary processes that control the level of competition from a weed complex in a crop are described by Radosevich and Roush (1990) and have been recognized by many others. Time of emergence of the crop and weed often determine the outcome of interference. When the crop emerges prior to the weeds, it often wins the competitive battle; the reverse is also true. Firbank and Watkinson (1985) reported that emergence time and local crowding accounted for as much as 50 percent of the variation in performance of individual corn cockle plants. A second factor is growth ability and environment (Radosevich and Roush 1990). These are related because growth is surely affected by environment, but they can also be treated separately because growth of some species (e.g., green foxtail and field bindweed) will always be distinctly different, independent of the environment in which they are growing together.

Clearly, plant growth rate has a strong influence on competitive ability. Species that grow tall rapidly and gain greater ground cover (shading) or spread rapidly laterally will have a competitive advantage over those that do each thing but more slowly. Equally clearly, environments that favor rapid growth will favor the species with greater competitive ability. Finally, Radosevich and Roush (1990) mention the important but often neglected role(s) played by processes other than competition, such as herbivory, density-dependent mortality, predation, senescence, and allelopathy.

Aarssen (1989) stated that plant species coexist by avoiding competitive exclusion. He agreed with Sakai (1961) when he proposed that, at the species level, continuing selection results from genetically based differences in competitive abilities in local neighborhoods (fig. 3.2). Aarssen reported on multigeneration experiments with timothy and common groundsel to show that competitive ability may change as a consequence of selection. He explored the evolutionary consequences of such selection in a community of several species. The resulting hypothesis suggested that competitive exclusion is avoided at the population level because no population contains even one genotype that is competitively superior to all other genotypes in a coexisting population. Aarssen's (1989) hypothesis assumes that competitive ability is "intransitive" (not capable of transition to another species). If the intransitive characteristic extends across several species, then the most competitive genotypes are just as likely to belong to one species as to another. Aarssen (1989) concludes that the hypothesis of competitive combining ability helps to explain what he calls the "conflicting truism" that competition within plant communities is intense and should therefore have important evolutionary consequences, but that plant species coexist with apparently little differentiation that permits interaction avoidance.

Monoculture rarely occurs in natural environments because communal life is favored. Even what appears to the casual observer to be a monocultural plant community (e.g., a large field of corn) teems with other species (bacteria and fungi on or in plants, weeds, insects, soil microorganisms, etc.). Nature does not recognize the human categories of domesticated plant, or such things as inalienable rights. In natural environments, most living organisms are engaged in relentless competition for resources with peers as well as with many other organisms. That competition, which we know as part of the process of evolution, in a real sense, conserves past evolutionary achievements by protecting features that assured success.

In the ecological sense, competition and natural selection, as parts of the evolutionary process, generate and conserve what is valuable for survival; they create better fitness[1]. Plants do not escape the struggle for existence and the competitive process that creates better fitness. As pointed out above, competition, a part of evolution, is common but is not ubiquitous in all natural communities (Goldberg 1990). It is common and assumed to be ubiquitous in agricultural communities where its results have been studied by weed scientists and others interested in weed-crop competition. Goldberg's (1990) thought asks for separation of the effect of competition from the plant's response to competition. The effect could be on the abundance of one competitor and the response could be on the abundance of the other or on its yield. Weed-science research has tended to focus on the response, especially of the crop, with less attention to the effect that causes the response.

Brenchley (1917) emphasized the omnipresence of competition as a vital factor in the agricultural plant community when she said, "It is impossible to sow a crop without the certainty that other plants will appear." Pavlychenko and Harrington (1934) showed that competition exerts a powerful natural force in the agricultural plant community tending toward limitation or extinction of weaker competitors. They found that, within the community, each weed and each plant differed greatly in competitive ability and that all weeds suffered greatly from competition with crop plants.

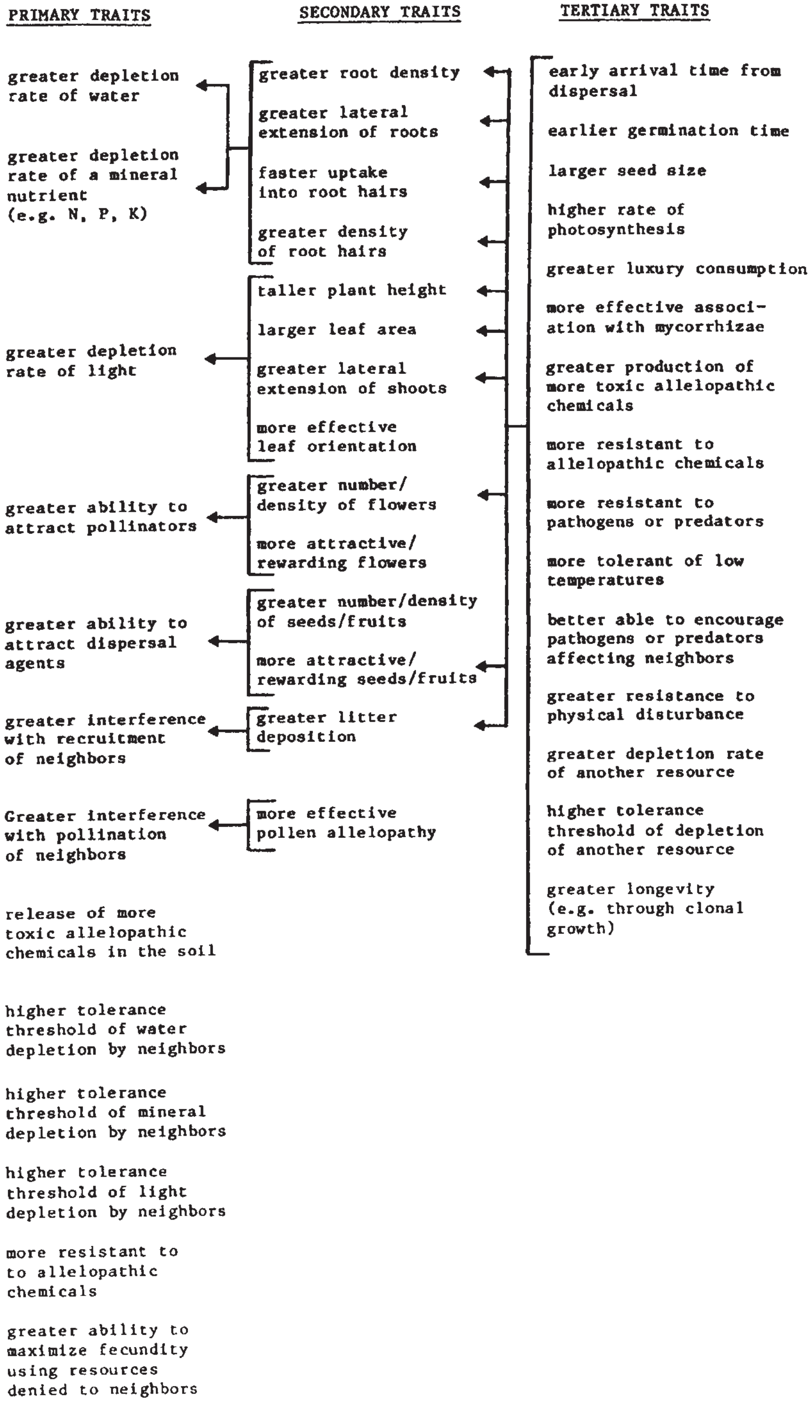

Figure 3.2. A proposed relationship among attributes of competitive ability in plants. Primary traits are those that have the most important role in determining the relative competitive ability of neighbors. Some primary traits are determined by secondary traits and some secondary traits are determined by tertiary traits. (From Aarssen 1989; reprinted with permission)

DENSITY

Donald (1963) began a discussion of density in the community with an examination of the relationship of density to total yield of dry matter, the biological yield of various crops (as distinct, for example, from the yield of grain). He pointed out that studies to determine optimum sowing rate rarely include a sufficiently wide range of densities to permit definition of the relationship of density and yield. The data from Donald's experiment (1951) on intraspecific competition among annual pasture plants indicate the relation of yield of dry matter to density at zero days (weight of seed embryo), 131 days, and 181 days in subterranean clover grown with adequate moisture and nutrients. At planting, there was a linear relation between density and yield. Competition for light developed in dense populations soon after germination and thereafter became operative in populations of lower and lower density. Competitive effects stopped growth at highest densities. Because of extreme growth rate reduction late in the season and concurrent high growth rate in sparse stands, sparse stands tended to approach the more dense stand in final yield. The final data showed that yield of dry matter is constant from moderate to high densities. The original linear relationship of density to yield of dry matter was replaced by a curve in which yield rose sharply with increasing density to a maximum, which was constant for all higher densities.

This work also stresses that the determination of optimum density for an early harvest is more difficult than at maturity. For an early harvest, the greater the density the greater the yield because the earlier harvest will come at a time when intercrop competition is less intense with consequent lower yield depression.

The early work of Aspinall and Milthorpe (1959) presents a similar relationship by analyzing competition between barley and pale smartweed where a constancy of final yield of dry matter per unit area at moderate to high densities was measured.

Mann and Barnes (1945, 1947, 1949, 1950, 1952), in several carefully conducted competition experiments, demonstrated that yield of crop and weeds tended to a maximum with a definite density of plants per volume of soil. However, effects between plants were inconsistent. Corn spurry and scentless chamomile limited the growth of barley and were, in turn, limited by barley. The same held true for clovers (Mann and Barnes 1952) and the grass redtop (Mann and Barnes 1949), in competition with barley. The effect of German velvetgrass (Mann and Barnes 1947) depended on which became established first in the community and barley seeding rate. If the weed established during the previous year, a thin stand of barley could reduce barley yield up to 100 percent. Competition of barley with common chickweed varied slightly in that the weed reduced the yield of barley, but the opposite relation was not true, primarily because of more rapid development of common chickweed (Mann and Barnes 1950). The work by Mann and Barnes is similar to many other studies that show the effect of weeds on a crop in terms of crop yield.

Topham and Lawson (1982) asked if crop interference changes the weed flora over time. Using diversity indices, they showed that despite increasing "substantial competitive pressure" from vining peas on dry matter accumulation by up to eight weeds, weed species composition did not change with time. Competition from peas suppressed weed growth and reduced the number of species identified on successive sampling dates. However, there was no selection pressure and species evenness was unchanged. In the view of Topham and Lawson (1982), the use of diversity indices is ecologically justified and will aid weed management decisions.

A comment by Salisbury (1942) summarizes: "Below a certain specific density the increased yield of the individual fails to compensate for the diminished population. On the other hand, above a certain density, the individual becomes so depauperate through competition, that the augmented population fails to compensate for the low yield of the individuals." Although Salisbury was speaking of an individual in a monoculture, his reasoning can be extrapolated to the community.

The literature on competition leads to the problem of determining if a given unit of soil will produce a fixed increment of growth and yield with the prevailing environment, or if the competitive influence in annual crops intervenes to reduce total yield in favor of the yield of one component of a population. The experiment by Aspinall and Milthorpe (1959) has been cited in this regard. Robinson and Dunham (1954) found that soybeans produce normal yields, and sometimes more, when forage companion crops were interseeded in soybean rows. As corn was intercropped with mung bean and the level of weed control was reduced, the relative advantage of intercropping increased so corn's productivity was 75 percent greater than in a monoculture (Bantilan et al. 1974). The response of weeds was correlated with light interception ability.

Mann and Barnes (1945) showed that with a constant amount of weediness from either of two weeds, an increasing density of barley plants diminished the injurious effects of the weeds. The combined weight of barley and weeds was rarely as great as barley alone in a weed-free plot. The research team stated that with a constant density of barley and a variable density of weeds, the total weight of the aboveground portion of barley and weeds was almost constant, independent of the number of weed plants of either species.

Moolani and Slife (1960) found that dry weight of weeds and corn combined was equal to the weight of weed-free corn. However, with soybeans, the crop plus weeds equaled one and one-half times the yield of the weed-free crop. In another experiment with corn and soybeans, Knake and Slife (1962) found that increases in dry matter of giant foxtail were proportional to decreases in dry matter of the crop. The combined yield did not vary significantly. Similar results were reported by Shadbolt and Holm (1948) working with vegetables.

Staniforth often mentioned total yield in his work with soybeans in Iowa, but the results were inconsistent. In two experiments (Staniforth 1958; Staniforth and Weber 1956), yield of soybeans alone was almost equal to soybeans plus weeds. In other work (Weber and Staniforth 1957), yield of soybeans and weeds was slightly higher than when soybeans were grown alone.

Allison et al. (1958) present a possible mechanistic explanation. In a discussion of the relationship between evapotranspiration losses and yield, they found a direct and high degree of correlation between evapotranspiration and the dry weight produced by aboveground parts. This was true regardless of crop rotation or fertility level.

COMMUNITY COMPOSITION

The weight of evidence presented here suggests that few generalizations can be made about the constancy of community composition or yield. Farmers and weed scientists have known for some time that weeds are not uniformly distributed across a field, that is, the community's composition is highly variable across a field. Weed management techniques have generally ignored this fact and managers have chosen control methods that have been applied uniformly to entire fields. The value of knowledge about patchiness and overall weed distribution will be to aid postemergence weed management decisions (Wiles et al. 1992). Other than the existence of patchiness, generalizations that are useful when making management decisions cannot be made with reference to species and environment, which vary among experiments. Natural environments favor life in a diverse community for plants. While pasture and hay crops are usually seeded as mixtures, most developed country agriculture relies on monoculture.

The question of possible yield advantages for mixed-culture communities persists. In this regard, without going into great detail, the work of Wes Jackson (1980, 1987; and Vitek and Jackson 1996) at the Land Institute (of Salina, Kansas) on high seed yielding, perennial polycultures is worth noting and learning from. Jackson emphasizes the model of the prairie, a place that sponsors its own fertility and pest management as a new, feasible, and proper paradigm for the practice of agriculture. Interested readers are referred to the Land Institute's Land Report, which is published three times annually.

Donald (1963) observed that native pasture communities commonly develop great complexity with several layers of each species. He asked, "Can such a community structure exploit the environment to a maximum?" If light-tolerant species will grow beneath the canopy and if roots with varying degrees of dispersal will better exploit available moisture and nutrients, the answer may be yes. Plants integrate all the variables in any environment. Therefore, an important agricultural and weed management question becomes: can two species fix more carbon when growing in association than when either species grows alone? Are there yield and weed management objectives that can be achieved through greater community diversity?

Clements et al. (1929) described competition for two factors: water and light. The beginning of competition is due to reaction, when the plants are so spaced that the reaction of one affects the response of the other by limiting it. The initial advantage thus gained is increased by cumulation, since even a slight increase in the amount of energy, as raw material, is followed by corresponding growth, and this by further gain in response and reaction. A larger, deeper, or more active root system enables one plant to secure an amount of the chresard (available water), and the immediate reaction is to reduce the amount obtainable to the other. The stem and leaves of the former grow in size and number, and thus require more water; the roots respond by augmenting the absorbing surface to supply the demand and automatically reduce the water content still further.

At the same time, the correlated growth of stems and leaves is producing a reaction on light by absorption, leaving less energy available for the leaves of the competitor beneath it, while increasing the amount of food for the further growth of absorbing roots, taller stems, and overshading leaves.

The view of Clements et al. (1929) strongly suggests that when two species grow together, one will be suppressed while the other will dominate. This has been the dominant view of weed science. Ahlgren and Aamodt (1939), in contradiction, suggested that when some common mesophytic plants are grown in pairs, the yield per plant of both species in the mixture may be less than the yield per plant in each of the corresponding pure cultures. They tested their hypothesis but did not substantiate it with a mixture of redtop and Kentucky bluegrass.

Several experiments (Aberg et al. 1943; Donald 1963; Erdmann and Harrison 1947; Roberts and Olsen 1942) with forage or grass species reveal extensive support for Donald's (1963) analysis of possible results when two species grow together. To summarize:

1. The yield of the mixture will usually be less than that of the higher-yielding pure culture.
2. The yield of the mixture will usually be greater than that of the lower-yielding pure culture.
3. The yield of the mixture may be greater or less than the mean yield of the two pure cultures.
4. There is no substantial evidence that two species can exploit the environment better than one.

In other work, Donald (1958) indicated that competition for two factors leads to multiple interactions between two groups of effects and thus greatly intensifies the effects of either factor operating alone. Aggressor species showed a negative interaction between the effect of two modes of competition (i.e., light and nutrient, or light and water). Yields dropped slightly due to competition for either factor alone, but when competition for both factors operated, yields approached levels obtained in the absence of competition. The aggressor competed more effectively when both means of competition were available to it. The effect of the two modes of competition on the suppressed species showed a positive interaction. Yield depression, under competition for both factors, greatly exceeded the sum of the effects of competition for the separate factors.

Studies of competition between associated species, other than forage crops, are rare, and perhaps justifiably so because other crops are rarely grown in the same way. Hanson et al. (1961) and Hinson and Hanson (1962) found that the advantage gained by one of a competing pair of soybean genotypes equaled the loss sustained by the other. They considered competition between soybean genotypes to be additive. Recent work with rice cultivars in China has shown that a mixture of two cultivars in a single field outyields either grown alone.

Stringfield (1959) observed that when two corn hybrids were grown in association, no marked advantage or disadvantage in productivity accrued to the mixture compared with the average of the contributing hybrids when grown separately. The results were constant whether the members of a given hybrid pair were alike or widely different. The increase in yield of one was balanced by a decrease in yield of the other. Two corn genotypes of different height were grown in association by Pendleton and Seif (1962). Alternate rows of a 106 inch tall and a 72 inch tall variety were planted. In direct contrast to Stringfield's (1959) results, the mixture yielded 7 bu A^{-1} less than the mean of the two pure cultures. The authors pointed out that considerable shading of the dwarf by the taller corn occurred, but there was only very ineffectual shading of the lower leaves of the taller by the dwarf.

Overall, the limited data available indicate relatively little gain from mixing species, but other advantages obtained in certain environments, economic situations, or crop rotations should not be dismissed. Harper and Gajic (1961) emphasized that knowledge of factors controlling population in the plant community also determines the extent of understanding of the reasons for one species succeeding at the expense of another. The same information helps explain why a diversity of plant species may cohabit in a relatively stable community without one becoming dominant while the population of the other declines. It is commonly accepted that two species scarcely ever occupy similar niches, but displace each other so each takes possession of certain resources, which gives it a competitive advantage. This view has been called the competitive exclusion principle.

The process of natural selection leads toward ecological differentiation of competing species and therefore promotes stability of ecosystems even though competition is an unavoidable consequence of communities. Two plants or two competing species can compete in at least two different ways. One species can rapidly deplete a resource required by both, or a species can continue to grow at depleted resource levels (Goldberg 1990). The interaction between the effect on (competition for) resources and the response to resource depletion must also be considered (Goldberg 1990). A given plant may respond in both ways dependent on the level of resources available. The responses could be positively or negatively correlated (Goldberg 1990). In some cases, plants that are able to survive at reduced resource levels compete not by taking possession of certain resources but by gaining a competitive advantage by being able to survive with reduced resources; by consuming less. It is similar to a social principle—those who do best in a time of declining resources may be those who can make do with the least rather than those who must consume the most.

The competitive ability of a species can be measured by how strongly it suppresses other individuals (the net competitive effect) or by how little it responds to the presence of others (the net competitive response) (Goldberg 1990). These different but related responses to competition can be measured by a plant's effect on resources (how much is used how quickly) or by its response to deficiency. In the first case, a plant competes by consuming more rapidly or in greater abundance than its neighbors. In the second case, the plant responds to deficiency or to greater consumption by a neighbor by increasing resource uptake, by decreasing resource loss, or by increasing the efficiency of use of resources already obtained, that is, reducing the requirement for additional resources (Goldberg 1990).

THEORIES OF COMPETITION

The difference in how plants deal with resources (compete or decline to compete directly) that is in the definition of competitive ability is well characterized by the theories of competition proposed by Grime (1977, 1987) and Tilman (1982, 1985, 1988) and discussed by Grace (1990). Grime (1977) thought competitive ability was directly related to traits that a plant possessed that permitted maximization of resource capture by individuals in a population. Consistent with the theory, Grime (1977) posited that species that are stress tolerant (low resource users) will dominate in nonsuccessional communities, even if resources have been used by other species (Goldberg 1990). In contrast, Tilman (1982) proposed that competitive ability was characterized by species whose population can deplete resources to a low level at some equilibrium state. Grime's theory is based on established and identifiable plant traits, whereas Tilman's theory is based on traits found in the population (Grace 1990). Grace (1990) suggests that the two theories are actually complementary when the differences in the definition of competition are considered. The differences then become subtle, although not unimportant, in Grace's (1990) view. "Grime defines competition as the capacity to capture resources whereas Tilman defines it as a negative relationship between the abundances of competing species that involves both capture and tolerance to low resource levels." Grace (1990) argues that Grime's definition is "not operational," which is to say it does not conform to accepted definitions of plant competition. Grace (1990) says the problem with Tilman's theory is that it is consistent with conventional definitions, but the operational definition is "such that competition is the only factor leading to dominance (regardless of disturbance rate or nonresource conditions)."

The debate over the proper definition and mechanism of competition in plant communities has not been resolved. The evidence from this review is that weed-science research has not been operationally affected by the debate. It will behoove the weed-science community to pay attention to the debate and make appropriate changes in research techniques and objectives. Changes or shifts over time of the weed species present in a disturbed (cropped) community are a secondary effect of weed management and may be independent of the means. Intensive cropping systems give rise to weed communities that are products of cropping patterns and weed management systems rather than a result of only "natural" competition and succession (Harwood et al. 1974). The fact that weed-crop competition takes place in such disturbed communities demands special techniques for study and analysis of results. It would be best if weed-science research techniques were developed and employed in full consideration of the work of plant ecologists in natural plant communities. That there is wisdom and value in ecological approaches to weed management is not a new plea and has been advocated by others (Liebman and Dyck 1993).

NOTE

1. I am indebted to my colleague Dr. Holmes Rolston, III, of the Colorado State University Department of Philosophy for this insight.

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Weed-Crop Competition: A Review, Second Edition
Robert L. Zimdahl

4

Influence of Competition on the Plant

Interference, the term favored by Harper (1961) to describe interactions among neighboring plants, strongly affects plant growth, development, and survival (Jolliffe 1988). Much of the weed science literature uses the word *competition* rather than the more inclusive term *interference* to describe the relationships among plants for required environmental resources. Competition is used as it was defined by Clements et al. (1929) and the weed science literature tends to regard it (often correctly) as the dominant interaction among plants in a community. Other sources of interference, such as allelopathy, which has been widely studied by weed scientists and others, and environmental modification of competitive interactions, which has been noted but has not been studied as carefully by weed scientists, are also important (Jolliffe 1988).

Sakai (1961) suggested that a plant's competitive ability is a genetic characteristic controlled by polygenes, whose action is influenced by environmental interactions. Competitive ability can be measured using vegetative growth rate or propagation rate, terms that are usually consistent with each other. However, to be most accurate, plant character variation due to competition must be observed as it is affected by intergenotypic competition (Sakai 1955). The environment varies in physical attributes to which plants respond; plants compete for some of these (water, nutrients, light), but not for others (e.g., time of planting and time of emergence) (Sagar 1968). The presence of neighbors of the same or different species may alter the environment to such a degree that a species that is unable to gain an early advantage also may be unable to exploit a competitive advantage later (Sagar 1968). For example, a high relative growth rate late in the growing season becomes valueless if a competitor has consumed the bulk of available soil nutrients.

DENSITY

Harper and Gajic (1961), studying the response of corn cockle to increasing density, theorized that plants could respond in two ways: (1) by increased mortality, and (2) by increased plasticity in size and individual reproductive capacity.

In either way, an individual annual plant can react to increasing density, and thereby its population becomes self-regulatory. Harper (1964) argued that the essential properties controlling the ecology of a species only can be detected by studying it in competition, and that its behavior in isolation may be irrelevant to understanding behavior in the community. To truly understand the individual in the population and the population, experimental designs must recognize and include the reaction of individuals to the presence of others. Other work has illustrated that density is a highly variable predictor. Lutman et al. (1996) asked if early postemergence assessments of crop and weed vigor could be a more reliable predictor of weed loss than weed density. They found that predictions based on the relative dry weight of six different crops and wild oats were more reliable. It is also interesting that Lutman et al. (1996) found that visual assessments of the potential effects of weeds were quite reliable.

COMPETITIVE ABILITY

Weber and Staniforth (1957) argued that differences in competitive efficiency of crops and weeds are well known. This review supports their observation and provides experimental results to verify it (see chapter 5). However, only a few clues and bits of evidence surface relating to why such things occur. While knowing that weeds of a certain species reduce crop yields a certain percentage is useful, the more difficult and interesting question of why this is true and why the effect varies among crops poses a continuing challenge to research work on plant interference.

The competitive ability of four annual weeds and barley was compared in greenhouse and field studies in the UK (Gustavsson 1986). Wild mustard was consistently more competitive than barley, which was consistently more competitive than field pennycress, pale smartweed, or scentless chamomile. Competitive ability was determined by using relative yields and relative total yield (determined by adding the yield of successive cuttings during the growing season). Gustavsson's (1986) stated purpose was to "open a discussion on" whether or not it is "worthwhile continuing comparisons of the growth of species with the method" of relative yield and relative total yield. The literature has been silent in response.

Studies that describe the outcome of competition do not help us understand if Grime (1979) was right when he proposed that competition was "the tendency of neighbouring plants to utilize the same quantum of light, ion of mineral nutrient, or molecule of water, or volume of space." Nor do they help us determine if Tilman (1987) was more correct when he proposed that competition was "the utilization of shared resources in short supply by two or more species." Competitive ability is then determined by a plant's minimum resource requirement, usually designated R*. Descriptive studies also cannot tell us if Grace (1990) was correct when he proposed that Grime (1979) and Tilman (1987) offered complementary not conflicting definitions. Grace (1990) suggested that if a habitat is fertile, a species' competitive ability is determined by its ability to capture the required resources. But if the habitat has low fertility, competitive ability is determined by a species' ability to tolerate low resource availability.

GENERAL PRINCIPLES

Gaudet and Keddy (1988) stated that "decades of study of interspecific competition in community ecology has yielded an overwhelming body of special cases but few general principles." The cause, in their view, is the persistent use of "the phenomenological, non-predictive approach." Progress toward general principles that allow prediction of competitive ability from easily observable plant traits requires a systematic screening of many species under standardized conditions.

Gaudet and Keddy (1988) used that approach with 44 wetland species to determine if competitive ability could be predicted from plant traits. Multiple linear regression showed a strong relationship between easily observable plant traits and competitive ability ($r^2 = 0.74$). Plant biomass explained 63 percent of the variation in competitive ability, and plant height, canopy diameter, canopy area, and leaf shape explained most of the residual variation. Their purpose was to encourage use of a predictive tool to study competition in natural communities and to encourage plant ecologists to avoid the phenomenological approach to study of competition.

The phenomenological approach has also characterized competition studies done by weed scientists. For example, Minotti and Sweet (1981) cited several phenomena as important determinants of the role of crop interference in limiting losses due to weeds: relative time of emergence and transplanting, the capacity of crop variety to interfere (its competitive ability), allelopathic characteristics, early establishment of a dense foliar canopy, row spacing and plant arrangement, and nutrient and water management. Each of these phenomena is important, but their combination has not yet provided a predictive tool. The literature suffers or is blessed by, depending on one's point of view, a large body of special cases but few general principles. There are literally hundreds of studies that demonstrate that weeds compete with crops (see chapter 5). There is an abundance of literature that demonstrates that a certain weed density present in a crop for a certain time will reduce crop yield by a certain amount. General principles that allow generalizations about weed-crop competition have not followed from all the preliminary work.

Clements et at. (1929) described plants' competitive equipment and provided valuable information on interplant competition. They cited four points, all centering on the determination of life form:

1. Duration or perennation—owing its effect on occupation and height
2. Rate of growth—most effectively expressed by expansion and density of the shoot and root systems
3. Rate and amount of germination—initial advantage
4. Vigor and hardiness—facilitate survival under stress

Hodgson and Blackman (1956), in a detailed analysis of the density response of field bean, concluded that a profound difference often occurs in the way plants with determinant and indeterminant growth respond to density. Species such as field bean, in which the flowering apices do not arise from the major vegetative apices, mainly respond to density by altering the number of parts formed. In contrast, common sunflower and similar species respond more by changes in size of parts. Blackman (1919) studied the compound interest law and plant growth and stated, what now seems so clear, that “in many crop plants the matter (of plant growth) is of course complicated by the effect of crowding on the individual plant.”

What are the complicating competitive factors inherent in the study of plant growth in competition? One reasonable explanation of the sum of the factors encountered by an individual plant was schematically outlined by Bleasdale (1960), who proposed that the competition encountered by an individual plant depends on the density, distribution, duration, and species of its competitors (fig. 4.1). Climatic and edaphic conditions modify the relationships.

Palmblad (1967, 1968) considered several factors on the left of Bleasdale’s (1960) scheme in an investigation of seven weeds. Friesen (1967) posed a series of questions focusing on the heart of weed-crop competition and enumerating the interactions suggested by Bleasdale (1960).

- What densities are necessary to reduce yields?
- Do similar densities have similar effects in all crops?

As affirmed in a brief study by Hume (1985), crop density is always important as is the more frequently measured and reported weed density. Hume (1985) demonstrated that wheat density varied by as much as 25 plants m^{-2} in adjacent quadrats in research and farmer field plots.

- Do similar densities have similar effects in all crops?
- At what stage(s) of development does competition occur?
- What is the influence of fertility and moisture?
- How important is a delay in sowing (or emergence) of the crop in determining the outcome of competition?
- How reproducible are the effects of weeds from field to field, area to area, and country to country?

To this list of questions can be added:

- How do different species (or populations) of weeds compare? (Sagar 1968)

There are some clues to answers to these kinds of questions. The emergence and development of natural infestations of wild oats was studied in 23 spring barley fields in one year and 9 in a second year, in the UK (Peters and Wilson 1983). Wild oats emerged up to the four-leaf stage of barley and 50 percent emergence took 22 days in one year and 36 in a second year. The majority of seed was shed by the early emerging plants in both years. In the first year, 79 percent of the wild oats emerged by barley’s two-leaf stage and 59 percent emerged by the two-leaf stage in the second

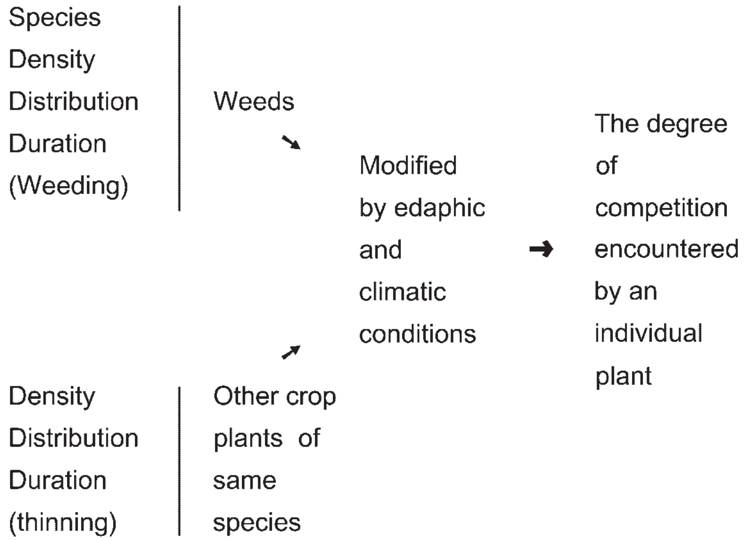

Figure 4.1. Schematic diagram depicting the competition encountered by an individual plant. (Adapted from Bleasdale 1960)

year, and these plants produced 97 and 80 percent of all seed shed, respectively (Peters and Wilson 1983). Wild oats that emerged before barley produced five times as much seed per plant as those that emerged between the crop's two- and three-leaf stage of growth. Early emerging plants were always the heaviest, had the most stems per plant, and caused the most yield loss.

Jennings and Aquino (1968a, b, c) studied the mechanism of competition among rice phenotypes. Competition was first observed when rice was 53 to 60 days old, which was 30 to 35 days after transplanting (1968c). Tall and dwarf cultivars differed genetically in ways that affected leaf number, leaf length, leaf angle, and plant height (1968b). Plant height had a pronounced effect on yield. Although short cultivars outyielded tall ones when grown in pure stands, the high-tillering, tall, leafy ones were vastly more competitive in mixtures (1968a). Tiller number, number of leaves, leaf length, leaf area index, height, and dry weight were greater in successful competitors, and the differences were observable before competition was apparent (1968c). Because of their greater height and leaf area, the better competitors received more light. Tall genotypes were more competitive under usual growth conditions and were relatively more competitive with added fertility and close spacing. Plant characteristics (mentioned above, Clements et al. 1929) that increased size and vegetative vigor during early growth stages conferred greater competitive ability.

Donald (1963) stated that plants show extreme plasticity, responding remarkably in size and form to environmental conditions. He emphasized that the presence of a neighbor constitutes one of the most potent external forces that may limit size and ultimate yield. Harper (1964) stated that, "The form, tolerances, and persistence of species may be profoundly modified by the proximity of neighbours of the same or other species. It follows that the characteristics of individual species shown by isolated individuals or pure populations may offer no significant guidance to their behavior in the presence of others."

COMPETITIVE SUCCESS

Characteristics leading to competitive success only can be exposed and demonstrated when species grow together. The concept of plant plasticity in response to competitive environments was advanced by Harper (1960). Because of plasticity, reducing seeding rates by half may not affect crop yield when remaining plants more nearly approach their biological potential (Harper 1960; Palmblad 1967). Donald (1963) said, "It is a surprising thought that man, in growing a successful, healthy field crop creates such intense competition that the individual plants are, in a very real sense, subnormal." He obtained maximum levels of dry matter production per pasture plant at lowest densities and observed a decreasing trend with increasing density (Donald 1954). Seeds per inflorescence and the weight per seed rose to a peak at intermediate densities, and then fell.

Donald's (1954) reasoning for these results centers on inter- and intraplant competition. With the least-dense planting, competition was absent during early growth stages when flower primordia originate. As growth proceeded, interplant competition became progressively stronger. During flowering and seed formation, the number of inflorescences was so great that competition occurred among them. Seed production efficiency decreased, leading to fewer seeds per inflorescence and reduced seed size, at the widest spacing. Therefore, at low densities intraplant competition prevails. In extremely dense stands, competition is already intense when floral primordia originate and both intra- and interplant competition function continually. However, in a moderately dense stand, interplant competition operates at the time of floral primordia initiation reducing the number of floral primordia formed. This reduced number more nearly matches the plant's capacity as interplant competition intensifies, while seeds per inflorescence and per unit area achieve a maximum. Thus, competition within plants and between plants combine to produce maximum seed yield per plant. Donald (1954) suggested that, at low density, competition within the plant may determine the maximum yield of any plant component.

However, Harper and Gajic (1961) indicated variability in seed set was greatest with corn cockle (1 to 24 capsules per plant) at low densities and least (almost all plants with a single capsule) at high densities. This work suggests that variation may be greatest at lower densities in contrast to Donald's (1954) findings and other work reported by him (1963).

Roots as vital, functional plant parts influence competitive relations, although far fewer experiments have been conducted. Clements (1907) mentioned that slight competition occurs between aerial parts of grasses with erect leaves; as a result, competitive interactions are primarily in the root zone.

Mann and Barnes (1945) thought that with nitrogen fertilizer in excess of the amount needed by the crop, any yield reduction of barley must be due to competition for root space. All possible variables, with the exception of light, were reportedly more than optimum in the experiment. However, the weeds, corn spurry and scentless chamomile, are shorter than barley; hence, light could have been limiting.

Pavlychenko and Harrington (1934, 1935) discussed weeds' competitive efficiency in cereal crops and proposed that root system development may be more important than early germination or the development of a large assimilation surface; root systems nearest the surface were most effective in competition. They found most weeds (20 days after emergence) had larger root systems and greater assimilation surfaces than any of the common cereals tested (Pavlychenko and Harrington 1935). In other work, specifically on root development as related to competition, they noted that the capacity of the root system developed by competitors influenced competition between some cereal grains and weeds (Pavlychenko and Harrington 1934). The research was conducted on the western Canadian plains where moisture is commonly the limiting external factor. Root system capacity immediately after germination and emergence was especially important.

Pavlychenko (1937), in a detailed examination of the root systems of weeds and crop plants, presented a picture of the competitive relations of roots. He traced total root development and carefully measured final development. For several days after actual germination and before emergence, plants develop in darkness with no photosynthetic organs. The roots are the main functional exterior organs during this period. The size of the plant increases 3 to 400 percent prior to emergence primarily due to root development. Competition, which begins as soon as roots attempt to occupy the same space, may occur early in development and affect development of aboveground parts. Pavlychenko (1937) found extensive root competition to be the rule. Single mature plants grown in the center of 10-foot squares produced total root lengths of:

Wild oat	3,456,005 inches
Wheat	2,802,821 inches
Rye	3,114,375 inches

When the same plants were grown in 6-inch rows with 18 to 20 plants per foot, a different ratio was obtained and root system lengths decreased 83 to 99 times.

Pavlychenko (1937) also grew cereal crops in 6-inch drill rows with weeds between the rows and compared crop root systems 40 days after emergence:

Table 4.1. Comparison of the Root Systems of Barley, Wheat, Wild Oat, and Wild Mustard

Type of competition	Ratio of root system length
Barley—wild oat	7.7 : 1.4
Barley—wild oat	6.2 : 2.4
Wheat—wild mustard	3.3 : 6.5

Source: Pavlychenko (1937).

Similar effects were noted in competing aerial plant parts.

Similarly, but in the wetter climate of the UK, established perennial ryegrass competed primarily below ground with invading annual bluegrass and red fescue (Snaydon and Howe 1986). With root competition and an absence of nitrogen fertilizer, increasing the density of ryegrass from 2.5 to 40 plants m^{-2} reduced the dry weight of invading weeds up to 70 times.

Further increases in ryegrass density had no effect. Red fescue was more affected by ryegrass competition than was annual bluegrass. Application of nitrogen fertilizer (400 kg N ha^{-1}) reduced the effects of root competition.

Black et al. (1969) proposed a biochemical basis for plant competition after examining data from many other studies and placing plants in an efficient or nonefficient group based on six criteria. From this grouping they proposed an hypothesis to explain the competitive success of several crops and weeds. The criteria were:

1. Response to light intensity
2. Response to increasing temperature
3. Response to atmospheric oxygen
4. Presence of photorespiration
5. Level of photosynthetic carbon dioxide compensation concentration
6. The pathway of photosynthetic carbon dioxide assimilation (C_3 versus C_4 CO_2 fixation)

After classifying over 50 crops and weeds, they made the logical and not unexpected conclusion that competition among plants depends on morphology, differential response to environmental parameters, ability to extract nutrients from water and from soil, and other factors. However, they proposed that competitive ability also depends on, and partially can be explained by, the net capacity to assimilate carbon dioxide and use the photosynthate, an ability intimately related to the six criteria. Plants that fix carbon dioxide at high rates probably secure an initial competitive advantage and are high-yielding crops or vigorous weeds. A second paper (Chen et al. 1970) affirmed the validity of the original hypothesis.

Dakheel et al. (1994) used growth chambers to study the effects of three temperature regimes and two moisture levels on growth, interference, and photosynthetic response of downy brome and medusahead. The optimum temperature for growth of both species was 24/11°C as opposed to 16/5 or 32/16. Moisture limitation reduced yield of both species at all three temperature regimes. Early resource allocation and high growth rates allowed downy brome to outperform medusahead at high nutrient levels (Dakheel et al. 1993). These advantages were reduced when nutrient levels were low; then the species were more nearly equally competitive. The two species commonly coexist on rangeland, and these studies showed that in mixtures, with limited or unlimited moisture, downy brome had a higher yield than medusahead in all three temperature regimes. Growth chamber studies by Nord et al. (1999) demonstrated that cool spring temperatures give wheat a competitive advantage over kochia and Russian thistle. Weaver et al. (1988) proposed that difference in relative times of emergence of crops and weeds can be used to suggest optimum planting times and to estimate potential crop yield losses from weed interference. The relative times of emergence of tomato and four weed species at five temperatures and five soil moisture levels were studied in a growth chamber. In general, total emergence decreased as soil moisture decreased but the species differed in the optimum temperature for emergence. The time to 50 percent emergence decreased with increasing temperature and slightly increased with decreasing soil moisture.

The role of water stress is illustrated in studies by Patterson (1986) who showed that growth reduction due to water stress was greater for soybean than for sicklepod. In competition, sicklepod reduced soybean growth more when both species were water stressed than it did when both had adequate water.

The first edition of this book did not discuss the relative competitive ability of herbicide resistant and susceptible weeds because the phenomenon of resistance, although known, was not widespread in the late 70s, and the spread of herbicide resistance was regarded by many as a minor problem. Now it is very important, and the continuing spread of resistance is regularly recorded (Heap 2003). In March 2003, there were 275 resistant weed biotypes and 165 resistant species (98 dicots and 67 monocots). Resistance was present in 59 countries (Heap 2003).

Weaver and Warwick (1982) reported that susceptible populations of redroot pigweed and Powell amaranth had greater competitive ability with respect to total biomass and seed production than resistant populations. Their work suggests that resistant populations of both species will persist primarily in areas where susceptible populations are present at very low densities or have been eliminated by regular herbicide application. The relative competitive ability of resistant and susceptible plants depends, partially, on the selective pressure exerted by continued use of the herbicide and on environmental factors.

Finally, although the thought is now more than 40 years old, Donald (1963) wrote an excellent and still valid appraisal of our understanding of competition among plants.

> 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, too, 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 a 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 fifty 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 utiliza-

> tion, more glume surface, or one of many factors affecting growth and photosynthesis. And, in particular, it has these desired characteristics when growing under the acute stress conditions of a commercial crop.[1]

NOTE

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Weed-Crop Competition: A Review, Second Edition
Robert L. Zimdahl

5

The Effect of Weed Density

The first edition of this book set forth the proposition that even a cursory review of a portion of the weed-crop competition literature would lead to the conclusion that increasing weed density decreases crop yield (Zimdahl 1980). This edition supports that hypothesis. The weed science literature focuses, as expected, on the effects of weeds on crops. The opposite effect is recognized in this chapter, but is not a major emphasis of the research reviewed. Mohler (2001) noted that "the density, arrangement, cultivar, and planting date of the crop that maximize the rate at which the crop occupies space early in the growing season usually minimize competitive pressure of weeds." Thus, the effect of crop and weed density is important but the latter is emphasized in the work reviewed for this chapter.

The first edition did not find many studies of weed-crop competition that employed mathematical analysis. Weed competition studies had been conducted in a wide range of crops by agronomists, horticulturists, and weed scientists who had not made significant use of mathematical models or mathematical description. Clearly, this is no longer true (see chapter 10).

Research has shown that, in most cases, the weed density–crop yield relationship is not linear. A few weeds usually do not affect yield in a way that can be detected easily; also, the maximum effect, total crop loss, obviously cannot be exceeded and usually occurs at less than the maximum possible weed density. Based on two assumptions, I proposed in 1980 that weed competition could be represented by a schematic sigmoidal relationship. The assumptions were: (1) A few (say five in a hectare) weeds might affect crop growth and final yield but the effect could not be measured with any precision, and (2) there is a high density of weeds beyond which no further crop yield loss can be measured.

A curvilinear relationship was reported by Roberts and Bond (1975), who described the effect of naturally occurring annual weeds at densities of 65 to 315 plants m^{-2} on yield of lettuce. Very low densities were not included. Roberts and Bond's (1975) study clearly shows that marketable lettuce yield sinks to zero at less than maximum weed density. It is now clear that the assumptions of the sigmoidal and curvilinear relationships are incorrect and that neither is capable of accurately describing the relationship between weed density and crop yield (Cousens et al. 1984; Cousens et al. 1985). The relationship is hyperbolic, which means, among other things, that it is best described by a hyperbolic curve that is usually referred to as a rectangular hyperbola. It also means that, even though the effect may not be measurable with precision, there is, in theory and actually, an effect of a few weeds (a low density) on crop yield and growth. Finally, the hyperbolic relationship means that the weeds' effect cannot exceed total (100 percent) crop loss.

Cousens et al. (1985) point out that the theory of the sigmoidial relationship (Zimdahl 1980) that no competition threshold exists was based on a faulty statistical assumption and not on sound biological principles or on economic rationality. Chapter 10 includes further discussion of this matter.

For all crops reported below, readers are referred to the first edition of this book for studies conducted prior to 1979. Because of the number of weed-crop competition studies in this chapter, they are arranged alphabetically by crop.

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ALFALFA—*MEDICAGO SATIVA* L.

Alfalfa in weed-free, 55-cm rows produced 820 kg ha^{-1} of seed in the year of planting. If a mixed annual population of 40 weeds in a m of row was present, seed yield was reduced to 45 kg ha^{-1} (Dawson and Rincker 1982). Competition from 55 weeds m^{-1} (a dense stand) of broadleaved weeds reduced yield to 80 kg ha^{-1}, whereas a light stand of 4 broadleaved weeds m^{-1} reduced yield from 820 to 310 kg ha^{-1}. Barnyardgrass with 75 culms m^{-1} of row (a heavy stand) reduced yield to 160 kg ha^{-1} (Dawson and Rincker 1982). One must conclude that seedling alfalfa is not a vigorous competitor. If wheat that emerged with alfalfa seeded in late August grew for 20 days, alfalfa yield was not affected. When wheat grew more than 30 days, yield decreased and uncontrolled wheat reduced first-cutting alfalfa yield more than 80 percent (Ott et al. 1990).

Similar to all crops, alfalfa yield is depressed most by annual weeds that emerge with alfalfa and remain uncontrolled until harvest (Fischer et al. 1988). Weeds did not affect alfalfa yield if they were removed before 36 days after alfalfa emergence, a figure in close agreement with the work of Ott et al. (1990). Yield decreased thereafter as the duration of competition lengthened. Interference was most damaging in early spring when winter annual weed growth was rapid. Weeds that emerged 65 or more days after alfalfa emergence did not affect alfalfa yield but often their presence at harvest reduced hay quality (Fischer et al. 1988).

In a study with four alfalfa seedling rates in the fall (4.5, 9, 13.5, and 22 kg ha^{-1}) and harvest at three times (early bud, early bloom, or late bloom), cheat (an annual grass) significantly reduced alfalfa production and forage quality (Pike and Stritzke 1984). Increasing alfalfa seeding rate only partially offset losses, and early harvest minimized but did not eliminate losses due to cheat.

Growth-chamber experiments and response surface analysis with a linearized hyperbolic equation suggested the effects of dandelion on alfalfa were more related to total species density than to the proportion of each species in a mixture (Rioux and Légère 1992). Duration of competition and alfalfa density (lucerne) accounted for the variation in shoot biomass of alfalfa grown with dandelion. Dandelion density explained most of the variation in alfalfa-root biomass.

Alfalfa dry matter yield was more influenced by intra- than by interspecific competition in studies with bladder campion (Wall and Morrison 1990). In contrast, the weed was more influenced by interspecific competition from alfalfa. Replacement diagrams and aggressivity indices demonstrated that alfalfa was the dominant and bladder campion the subordinate species. Over time the authors expected alfalfa would become the dominant species. Thus, if bladder campion is present, planting alfalfa is an effective weed management technique.

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BARLEY—*HORDEUM VULGARE* L.

Several papers report studies with both wheat and barley. In most of these, wheat is the dominant crop, and these studies are included in the section on wheat in this chapter.

Field experiments conducted in Canada with barley in competition with wild oats showed barley cultivars differed in their competitive ability. The specific cultivars are important to growers and scientists in the areas where the work was done, but here the general point of difference is emphasized. Barley's competitive ability (O'Donovan et al. 2000) always declined when spring emergence was delayed and always increased when seeding rate increased. Dhima et al. (2000) found, in Greece, that cultivars also differed in competitive ability against sterile oat and littleseed canarygrass. Sterile oat at a density of 120 m^{-2} was more competitive than 400 littleseed canary grass m^{-2}. Yield reduction among four barley cultivars varied from 8 to 67 percent for sterile oat, whereas littleseed canarygrass reduced yield only 1 to 55 percent at the same densities (Dhima et al. 2000). Torner et al. (1991) reported that Spanish barley cultivars also differed in their competitive ability with winter wild oat, even when the density of both species was taken into account. As the density of winter wild oat increased, barley yield declined exponentially. Yield declined 10 percent with winter wild oat densities of 20 to 80 panicles m^{-2} and yield losses were 50 percent when panicle density was greater than 300 m^{-2}. In contrast to the work of Dhima et al. (2000), Torner et al. (1991) found that, in general, barley yield was not affected by barley seeding rate, but the lowest seeding rate (100 kg ha^{-1}) resulted in the highest yield loss. Low barley seeding rates allowed greater weed-seed production and assured an infestation in future years. Growing season climate was an important determinant of competition between barley and winter wild oat. Ismail and Hassan (1988) working in Qatar showed that removing the natural weed population 15, 30, 45, or 60 days after planting produced barley yields similar to a weed-free check. No critical period or threshold density was observed.

Given the number of studies on barley (19 included), it is clear that wild oats have been regarded as the most important weed (12 studies of one of three species). In three experiments with barley planted at two rates (90 and 180 kg ha^{1}) and two row widths (10 and 20 cm), wild oats were more competitive than quackgrass at equivalent shoot populations (Cussans and Wilson 1975). Barley had a greater influence on competition than plant arrangement (density). The difference between the two weeds was attributed to their patterns of growth. Wild oats grew much like barley, whereas quackgrass grew slowly at first but was able to continue vegetative growth later than barley or wild oats (Cussans and Wilson 1975). Peters and Wilson (1983) studied emergence and development of wild oats in 23 spring barley fields in one year and 9 in a second year in the UK. Emergence continued up to the crop's 4-leaf stage. In one year, the mean number of days from planting to 50 percent emergence was 22, and it was 36 in the second year of the study. The majority of seeds shed to create future infestations came from early emerging wild oats. In one year, 79 percent of the wild oats had emerged by the crop's 2-leaf stage and in the second year the value was 59 percent. These plants contributed 97 and 89 percent of the seed shed. Peters and Wilson (1983) were able to establish that wild oats emerging at an early stage of barley caused a greater yield loss than the same density of later-emerging wild oats. Wild oats that emerged before the crop produced five times as many seeds per plant as those that emerged between the crop's 2- and 3-leaf stage. Early emerging wild oats always caused the greatest yield reduction but the pattern of emergence varied between years. Most wild oats had emerged by the crop's 2-leaf stage and these produced more than 89 percent of all seed shed.

Wilson and Peters (1982) in 51 experiments carried out over 2 years, showed that wild oat infestations of spring barley ranging from 8 to 662 seedlings m^{-2} resulted in yield reductions of 0 to 72 percent. There was a poor relationship between barley yield loss and spring wild oat population. Yield reductions of 0.5 T ha^{-1} were found from wild oat densities less than 50 seedlings m^{-2}, however yield losses were up to 1.5 T ha^{-1} when wild oat density was greater than 200 plants m^{-2}. Between 50 and 200 seedlings m^{-2}, effects were variable. Yield reductions were poorly correlated with the number of seedlings, wild oat panicles, or wild oat seed produced, but there was a good correlation between barley yield loss and the dry weight of wild oats present at barley harvest. Wilson and Peters (1982) did not find any system of yield loss prediction that could be used with confidence.

Evans et al. (1991) used addition series field experiments to determine the relative aggressiveness of spring barley and wild oat. Barley was more aggressive than wild oat, and barley biomass was more affected by intraspecific competition whereas wild oat biomass was more affected by interspecific competition. Increasing wild oat density had a negative, "asymptotic-like" competition effect on barley grain yield at all barley densities.

Dunan and Zimdahl (1991) used a replacement series experiment in the field and growth analysis and confirmed the results of Evans et al. (1991) by showing that barley was always the stronger competitor. Barley's interspecific competition with wild oat was 7.3 times greater than its interspecific competition on a dry weight basis. When leaf area (see Chapter 9 on methods) was used as the yield variable, barley's intraspecific competition was only 2.4 times greater than interspecific competition owing to barley's higher leaf area. Barley had a greater leaf area, root and shoot biomass, absolute growth rate, and shoot-root ratio than wild oat. But wild oat always had a higher leaf area ratio. The relative growth rates (RGR) and net assimilation rates (NAR) did not differ.

Morishita and Thill (1988a) found the critical duration of wild oat interference began at about barley's two-node stage and continued to maturity when final densities were 160 and 170 plants m^{-2}, respectively. Wild oat reduced barley's biomass, number of tillers, tiller heads per unit area, and tiller grain yield but not the number or grain yield of barley's main stems. Wild oat also did not affect the soil's matric potential or barley's total plant or the soil's nitrogen content. Wild oat's presence reduced total water and turgor pressure in barley's boot stage and that may affect tiller formation and explain the results reported. In a separate study, Morishita and Thill (1988b), using additive culture, showed that barley and wild oat tiller head production was decreased by the presence of either species but plant height was not affected. In mixed culture, wild oat's biomass was reduced more at early growth stages (two to three tillers) than barley's was. They had similar total plant nitrogen content throughout the season. Consistent with other studies, Morishita and Thill (1988b) showed that barley and wild oats in monoculture had similar growth and development. In mixed culture, barley was more competitive than wild oat. In further work, Morishita et al. (1991) showed that intraspecific interference affected barley growth more than interspecific interference from wild oat. In fact, interspecific interference from barley reduced wild oat growth more than intraspecific interference among wild oat plants. Nevertheless, wild oats are vigorous competitors and emerge above the barley canopy near barley anthesis.

Peters (1984) studied the growth and competition of wild oats that emerged at different times and the time competition began in natural populations of spring barley. In one experiment, wild oats that emerged at the 0- to 0.5-, 0.5- to 2.5-, or the 2.5- to 4-leaf stage of barley achieved densities of 54, 46, and 15 m^{-2}. If these densities competed all season, seed production was 82, 17, and 1 percent of all seed shed, respectively, and the yield loss was 16 percent at the highest density but there was no yield loss from the lower densities. Consistent with other studies reported above, when wild oats were removed up to barley's 2.5-leaf stage, later emerging wild oats did not compensate by making extra growth. In one study, barley and wild oat density were 416 and 414 m^{-2} and in another study in which densities were 295 and 294 m^{-2}, grain yield losses were significant only if wild oats remained until barley had 2.5 to 4.5 or 4.5 to 6.5 leaves, respectively. If a top dressing of nitrogen was added when the crop had 3 to 4 leaves, no yield loss occurred unless wild oats remained to barley's 6-leaf stage (Peters 1984). In a second study, Peters (1985) compared the effects of heavy (greater than 18 mg) and light (less than 11 mg) wild oat seed on barley yield when barley was planted in 25-mm rows. In wild oat grown from heavy seeds sown 75 mm deep with an equal number of barley seed, barley produced 47 percent more panicles, 54 percent more seed, and 56 percent more dry weight per plant than plants grown from light seed. When both were sown 25 mm deep, the differences were smaller (21, 28, and 34 percent, respectively). When barley and wild oat were planted 25 mm deep at equal densities, the dry weight of barley (compared to monoculture) was reduced from 10.4 g to 7.7 g for heavy seed and was 5.8 g for light seed. When planting depth was 25 mm for barley and 75 mm for wild oat, the weight of a barley plant was reduced from 9.5 to 7.2 g by wild oat grown from heavy or light seed. The reduction in number of grains was mainly due to a reduction in the number of fertile heads (Peters 1985).

Gonzalez-Ponce (1998) reported on barley's ability to compete with rigid ryegrass in a replacement series study in the greenhouse. The growth, seed production, and nitrogen uptake of both species had a positive response to nitrogen fertilization. However, nitrogen fertilization did not alter the competitive relationship between the species. Similar to the relationship between barley and wild oat, barley was the more effective competitor, primarily because of its earlier tillering and greater nitrate absorption.

Conn and Thomas (1987), working in Alaska, showed that common lambsquarters' density explained 75 percent of the variability in barley yield over 2 years. The maximum yield loss attributed to common lambsquarters was 23 percent in one year and 36 percent in the second year of the field study. Elberse and de Kruyf (1979) studied competition between common lambsquarters and barley with different dates of emergence in a careful study in the Netherlands. When common lambsquarters was planted 7 days before barley, it did not compete with barley. If the weed was planted 21 or 31 days before barley, barley could not compete effectively with the weed. Elberse and de Kruyf (1979) concluded that light was the most important factor in competition between these two species. They also concluded that common lambsquarters will not be a detrimental weed in barley when it emerges 15 days or less before barley. The authors properly caution that this work was done in a controlled climate chamber with optimum conditions for barley growth. The conclusions therefore may not have application to the field where conditions for barley growth in the spring are not as favorable and growing conditions usually favor common lambsquarters over barley.

O'Sullivan et al.(1982) developed an index of competition to measure the interference between barley and Canada thistle as a tool to provide an economic justification for controlling Canada thistle in oilseed crops and barley. The model was most reliable when square root transformed weed count data were used with percent yield loss.

When 30 tartary buckwheat plants m^{-2} were present at barley emergence, barley yield decreased 16 percent. Yield loss was best represented by a linear equation

$$Y = 0.63 + 2.75 \sqrt{x}$$

where Y = percent yield loss and x = plant density (de St. Remy et al. 1985).

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CORN = MAIZE—*ZEA MAYS* L.

The crop Americans call corn, most of the world calls maize. The world grows a little less than 140 million ha, far less than wheat or rice, but because the average yield is greater than 4,200 kg ha^{-1} , the total production (590.8 metric tons) is greater than wheat and only slightly less than rice (United Nations 2000). Corn is probably the most important crop in the United States in terms of the number of acres and annual value. The United States produces almost one-half of the world's corn and most is used for animal feed.

Begna et al. (2001) found that over two sites and 3 years the decrease in corn biomass production due to transplanted and naturally occurring weeds was greater with narrow corn row spacing than it was from high plant population density. The combination of narrow rows and high population densities increased corn canopy light interception 3 to 5 percent. Weed biomass production was five to eight times lower under the corn canopy than when the weeds were grown in monoculture. Weed biomass production was reduced more by early-maturing corn hybrids than by late-maturing hybrids with large leaves. Begna et al. (2001) proposed that hybrid selection and plant spacing could be used in an integrated weed management program. Lindquist and Mortensen (1998) compared the response of two old and two new corn hybrids. Each hybrid was grown in monoculture and in mixture with velveleaf at 1, 4, 16, or 40 plants m^{-2}. The maximum corn yield loss was 32 percent lower for the two old hybrids. Velvetleaf capsule production was reduced 62 percent at low velvetleaf densities with old hybrids compared to modern hybrids. In one year, the yield loss of one modern hybrid was 74 percent lower than the other three hybrids at low velvetleaf densities, whereas the maximum yield loss of one old hybrid was 44 percent lower at high density. Lindquist and Mortensen (1998) found that hybrids with greater weed tolerance and velvetleaf suppressive ability had a greater leaf area index, and light reception area, which suggests that optimizing a corn hybrid's leaf area index and photosynthetic photon flux receptivity may be useful in developing integrated weed management systems for corn.

Tillage and row spacing effects were investigated by Teasdale (1995). Weed control was poor and yield was reduced when no herbicides were applied regardless of row spacing (38 versus 76 cm) or corn population (standard versus 2x). The corn leaf canopy in the high population in 38-cm rows reduced light transmittance 1 week earlier than in the 76-cm rows with a lower plant population. Less herbicide (25 percent of recommended rate) provided acceptable weed control and grain yields similar to the standard treatment with narrow rows and high population density but weed control was reduced in 76-cm rows with the low herbicide rate. Murphy et al. (1996) showed that increasing corn stand density from 7 to 12 plants m^{-2} or decreasing corn row width from 75 to 50 cm significantly increased corn's leaf area index and reduced the photosynthetic photon flux available to weeds growing below the corn canopy. Narrow rows and high corn density reduced the biomass of late-emerging weeds. Corn yield increased 10 to 15 percent with narrow rows. However, the gains were not without cost. Intraspecific corn competition in higher density planting reduced early corn growth and offset gains in yield from reduced weed competition. In comparison to plots where late-emerging weeds grew without control, interrow cultivation did not decrease biomass of late-emerging weeds and did not increase corn yield.

Only one study (Ford and Mt. Pleasant 1994) examined the effects of hybrids on competition. The six medium-season hybrids differed in leaf angle, leaf width, leaf number, leaf area index, height, total dry matter, and grain and stover yield. The lowest yielding hybrids produced 87 to 91 percent of the highest yielding hybrid. In spite of the observed differences in hybrids, Ford and Mt. Pleasant (1994) concluded that aboveground plant characteristics did not correlate with weed numbers, weed cover, or weed biomass. Their work found a significant interaction between hybrid and weed control for grain yields in one year, which suggested, but did not prove, that some hybrids were more competitive when weed density was high.

For the first edition, no reports of velvetleaf competition were found, whereas seven are reported herein (Zimdahl 1980). Coffman and Frank (1991) reported on a 5-year conservation tillage study in Maryland that showed that weed flora had shifted from dominance by giant foxtail to smooth pigweed in subsequent years. Annual weeds continue to dominate corn studies but they have changed over the years. One suspects the change has not been due to the fact that the weeds studied prior to 1979 have disappeared or that they have been successfully controlled. The change in the dominant weed flora and the increasing importance of weeds such as velvetleaf has been due to the response of weeds to the cultural methods (including control) that have been used.

Such shifts are illustrated by the work of Wilson (1993) who evaluated the effect of tillage and herbicides on weed density and corn grain yield over 4 years in Nebraska. Ridge-tillage favored development of kochia and reduced density of wild proso millet and common lambsquarters. Tandem disking increased longspine sandbur and redroot pigweed density, whereas moldboard plowing favored common sunflower. Cultivation of the crop reduced weed density 86 percent, but the remaining weeds reduced corn yield 40 percent compared to a hand-weeded control. Wilson (1993) advocated recognition of the effects of land preparation on weed population and the integration of cultivation and herbicides in weed management strategies.

The effects of conventional tillage and no-tillage on the outcome of early weed competition in corn was studied in Nigeria by Ayeni et al. (1984a). There were more different weedy species with no-tillage, but total weed weight was only 52 percent of the weed weight in conventionally tilled plots 6 weeks after corn planting. Cropping pattern had no effect on plot weediness. With minimum or no weed interference, corn yield was better after conventional than after no-tillage but worse if weeds were allowed to grow well into the season.

In work in Colorado (VanGessel 1995), weed densities of 0, 33, 50, or 100 percent of the indigenous population affected corn yield but the weed's distribution in the field did not. Each additional weed reduced corn yield 8.5 kg ha^{-1} in one year and 2.3 kg ha^{-1} in the second year of the study. Weed density 5 to 8 weeks after planting provided a better estimate of the eventual effect of weeds on yield than did weed density immediately before corn harvest. Bussler et al. (1995) used aboveground plant volume to quantify interference of common cocklebur and velvetleaf with corn. They found that the ratio of aboveground plant volume to the total neighborhood volume was the independent variable that accounted for the most variation in target plant seed production. Although the method must be verified in different soil, fertility, and water environments, plant volume (Bussler et al. 1995) could be used to predict individual plant seed production in two separate two-species (common cocklebur or velvetleaf versus corn) interactions.

Dieleman et al. (1999) found an interaction between initial weed seedling density and postemergence herbicide or mechanical weed control for corn and soybeans in competition with velvetleaf (a range of 0 to 500 seeds m^{-2}) or common sunflower (a range of 250 to 2,500 seeds m^{-2}). There was a positive linear relationship between initial weed seedling density and the density of surviving seedlings. Weed management outcomes for a range of management intensities were dependent on initial seedling density. As initial density increased, the absolute number of survivors increased but the proportion of survivors appeared to remain constant over the density ranges included. Their results emphasize the need, in any crop, to know the weed density when assessing the efficacy of any weed management system.

Ayeni et al. (1984a,b,c) studied weed interference in corn and cowpea and a corn-cowpea intercrop in Nigeria. They found that weed interference effects on crops under no-tillage depended on cropping season (year), cropping pattern, and crop species (Ayeni et al. 1984c). Except for the corn-cowpea intercrop that showed significant yield reduction when exposed to 4 weeks of weed interference early in the season, all cropping patterns required more than 4 weeks of weed interference before yield reduction could be measured. Weed interference was more detrimental to yield in monocultures in the early season than was true in the intercrop. Late in the growing season, all cropping patterns were equally sensitive to weed interference. In the first 6 weeks of growth, cropping pattern had no effect on weed growth. Weeds did not affect crop growth until 5 to 6 weeks after crop planting (Ayeni et al. 1984b). Total crop dry weight was not affected by cropping pattern. Three weeks after crop planting, weeds from weedy, cropped plots had taken up two to four times as many nutrients (N, P, K, Ca, and Mg) as weed-free crops. Remison (1979), also working in Nigeria, found no significant interaction between weeding and nitrogen at any site. After corn had been grown for several years, weed competition lowered corn yield as much as 50 percent, but two hand-weedings 3 and 7 weeks after planting were as efficacious as more intensive weeding.

In recent years, several studies have been done to determine the effect of competition on growth and seed production of some weeds. Longspine sandbur has become a problem in corn in the Great Plains. If it emerges in late May, with or soon after corn, seedlings produce 1,120 burs per plant. Seedlings emerging 4 weeks later produce 84 percent fewer burs (Anderson 1997). If longspine sandbur is controlled before 4 weeks of interference occur, there is no loss of corn grain yield (Anderson 1997). Burcucumber seed production was studied by Esbenshade et al. (2001). Burcucumber grown without competition from corn produced 716 g dry matter and 4,500 seeds per plant. Biomass was greatest for plants established in May but seed production was greatest for those established in mid-June. When burcucumber established in corn, it produced 96 percent less dry matter and seed than plants grown without competition, but seed was still produced.

The importance of velvetleaf in corn is emphasized by the work of Scholes et al. (1995) who found that when velvetleaf was grown in corn at densities of 0, 1.3, 4, 12, or 24 plants m^{-2}, the weed's leaf area index and total plant biomass were correlated with velvetleaf density and both were negatively correlated with corn biomass. The maximum yield loss was 37.2 percent with a loss of 4.4 percent per unit of velvetleaf density.

Cardina et al. (1995) found that corn yield loss and velvetleaf seed production were higher in a warm-wet year than in a dry-cold year. Corn yield loss was generally greater with no-tillage than in conventional tillage and from early rather than late-maturing velvetleaf. The maximum velvetleaf seed production ranged from 18,000 seeds m^{-2} for early emerging weeds in no-till to only 100 seeds m^{-2} for late-emerging weeds. Corn reduced velvetleaf's seed rain by 50 percent (Zanin and Sattin 1988). Seed rain reached a maximum at 20 to 30 plants m^{-2} in corn, and 30 to 35 plants m^{-2} in monoculture. When only 4 to 5 velvetleaf m^{-2} competed with corn, the weed produced eight thousand to ten thousand seeds, indicative of the weed's great seed production potential. Zanin and Sattin (1988) also calculated the economic threshold to be between 0.3 and 2.4 weeds m^{-2} for velvetleaf in corn based on studies that included weed densities from 0 to 80 m^{-2}.

Defelice et al. (1988) found that monocultural velvetleaf had a greater dry weight, leaf area index, and height than when it grew with corn. Velvetleaf planted 5 weeks after corn was lower in all indices than that planted with corn. There was no effect of tillage system on velvetleaf plant characteristics. Interference from corn and delayed planting reduced velvetleaf population at the end of the season.

Work by Frantik (1994) showed that competition from all weeds is not equal. *Chenopodium suecicum* J. Murr. and redroot pigweed were competitively equivalent to 1.1 and 0.26 corn plants, respectively, whereas 1 corn plant was equal to 5.5 weed plants as measured by effects on biomass. Redroot pigweed was a more effective competitor with corn and with *C. suecicum* than the reverse. Corn reduced the competitive effectiveness of redroot pigweed against *C. suecicum*. Corn yield loss increased as the proportion of *C. suecicum* in the mixture increased. *C. suecicum* that was seeded before corn and not removed until 32 days after corn emergence significantly reduced corn yield (Frantik 1994).

Several papers report specific effects of specific weeds on corn yield reduction. More than 13 species have been studied and the papers are summarized below and in table 5.1.

Natural stands of hemp dogbane reduced corn yield not at all or up to 10 percent (Schultz and Burnside 1979). Jimsonweed decreased corn yield 14 to 63 percent when corn density was 8.3 plants m^{-2} and jimsonweed density was 8.3 or 16.7 plants m^{-2}, in Spain (Cavero et al. 1999). Yield reduction, as one would expect, increased as the time between crop and weed emergence decreased. Corn's leaf area developed faster and it was able to successfully compete for light with jimsonweed, although the weed's competitive effects on corn (reduced crop growth rate, lower grain number per ear, and reduced grain weight) could be observed late in the growing season. When giant ragweed and corn emerged concurrently, densities of 1.7, 6.9, and 13.8 weeds 10 m^{-2} gave a predicted loss rate of 13.6 percent for the first weed 10 m^{-2} in the linear response range at low densities and a maximum loss of 90 percent at high weed densities (Harrison et al. 2001). Corn yield loss response was linear when giant ragweed emerged 4 weeks after corn and it was equivalent to a yield loss rate of 1 percent per unit increase in weed density. Giant ragweed's seed production decreased significantly with delayed emergence. For common milkweed, corn yield loss ranged from 2 to 10 percent with milkweed densities between 11,000 and 45,200 plants ha^{-1}. (Cramer and Burnside 1982).

When Palmer amaranth was grown with irrigated corn at densities of 0, 0.5, 1, 2, 4, or 8 plants m^{-1} of row and the weed emerged with corn, corn yield declined 11 to 91 percent as Palmer amaranth density increased from 0.5 to 8 plants m^{-1} (Massinga et al. 2001). However, when the weed emerged later than

Table 5.1. Effect of Several Weeds on Corn Yield

Weed Species	Density	Yield reduction	Source
Barnyardgrass	100 m^{-2}	18%	Kropff et al. 1984
	200 m^{-2} concurrent emergence	26–35%	Bosnic et al. 1997
	Emergence when corn had 4 leaves	6%	
Common milkweed	11,000 to 2 to 45,200 plants m^{-2}	10%	Cramer and Burnside 1982
Giant ragweed	1.7, 6.9, or 13.8 plants m^{-2}	13.6% 90%	Harrison et al. 2001
Giant foxtail	10 m^{-1}	13–14%	Fausey et al. 1997
Green foxtail	0, 29, 56, or 89 m^{-2}	20–56% but nonsignificant	Sibuga and Bandeen 1980
	129 m^{-2}	5.8–17.6%	
Hemp dogbane	Natural	0–10%	Schultz 1979
Itchgrass	2, 4, up to 14 wk	125 kg ha^{-1} for each week of presence	Strahan et al. 2000
	Season-long	33%	
Jimsonweed	8.3 or 16.7	14–63% plants m^{-2}	Cavero et al. 1999
Quackgrass	65 to 390 shoots m^{-2}	12–16%	Young et al. 1984
	745 shoots m^{-2}	37%	
Palmer amaranth	0.5 to 8 m^{2}	11–74%	Massinga et al. 2002
Redroot pigweed	0.5 m^{-1} with concurrent planting or 4 m^{-1} with planting at corn's 3–5 leaf stage	5%	Knezevic et al. 1994
Wild proso millet	10 m^{-2}	13–22%	Wilson and Westra 1991
Yellow nutsedge	100 shoots m^{-2}	8%/100 shoots	Stoller et al. 1979
	300 tubers m^{-2}	17%	
	700 tubers m^{-2}	41%	

corn, yield loss occurred only when the weed emerged at corn's 4- and 6-leaf stages. Palmer amaranth's seed production per plant decreased with greater density, but seed per unit area increased from 140,000 to 514,000 seeds m^{-1} at 0.5 and 8 plants m^{-1}, respectively (Massinga et al. 2001). When Palmer amaranth grew with irrigated corn at densities of 0, 0.5, 1, 2, 4, or 8 plants m^{-1} of row, corn grain yield and forage quality of weeds harvested with corn both declined with increasing Palmer amaranth density (Massinga and Currie 2002). Forage yield declined 1 to 44 percent of the weed-free yield with Palmer amaranth densities of 0.5 to 8 plants m^{-1} of row, whereas grain yield declined 11 to 74 percent at the same weed densities. Thus, Palmer amaranth interference in corn may not affect forage quality much, but corn yields decline significantly (Massinga 2002). Redroot pigweed performed similarly at the same densities (Knezevic et al. 1994). When redroot pigweed and corn were planted concurrently, 0.5 weeds m^{-1} of row reduced corn yield 5 percent, which was the same reduction obtained from 4 weeds when they were planted at corn's 3- to 5-leaf stage of growth. Redroot pigweed that emerged after corn had 7 leaves did not decrease corn's yield. Therefore, Knezevic et al. (1994) concluded that the time of the weed's emergence was more important than its density.

Sibuga and Bandeen (1980) studied full-season interference from common lambsquarters and green foxtail. Nonsignificant yield reductions were obtained from green foxtail densities of 20 and 56 plants m^{-2}. Increased green foxtail densities of 89 and 129 plants m^{-2} reduced corn yield 5.6 to 17.6 percent over 2 years. Common lambsquarters density less than 109 m^{-2} did not affect corn yield over 2 years. Densities greater than 172 m^{-2} reduced yield 12 to 38 percent one year and 6 to 58 percent in a second year. The effects of the two weeds were similar. They differed primarily in the ability of common lambsquarters to reduce corn ear and seed size (Sibuga and Bandeen 1980).

Beckett et al. (1988) compared corn yield reduction caused by season-long interference from shattercane, common lambsquarters, common cocklebur, and giant foxtail at densities of 0.4 to 13.1 plants or clumps m^{-1} of row. Corn seed yield decreased linearly with increasing density of 2 to 3 clumps of shattercane or 5 to 8 clumps of giant foxtail. There was a 22 percent yield loss from 6.6 shattercane clumps m^{-1} of row, a 27 percent loss from 4.7 common cocklebur m^{-1} of row in one year and a 10 percent loss from 6.6 common cocklebur m^{-1} in 2 of 3 years. Common lambsquarters reduced yield in only one year, and the maximum loss was 12 percent from 4.9 m^{-1} of row. There was an 18 percent loss in corn yield from 13.1 giant foxtail clumps m^{-1} of row (Beckett et al. 1988).

There is no reason to argue that broadleaved species are more detrimental or more ubiquitous than annual grass weeds in corn. Because the studies have been done in so many different places in different years, it is not possible to say what type of weed is more detrimental. Several studies have reported on interference from grass weeds.

Fausey et al. (1997) studied giant foxtail interference in corn at densities of 0, 10, 20, 30, 60, 84, or 98 m^{-1}. Corn yield was reduced 13 percent in one year and 14 percent in a second year from 10 giant foxtail m^{-1} of row. Corn dry matter at maturity was reduced by nearly one-quarter from the same densities. Ten weeds in a meter of row produced 15,700 seeds, and their germination was not affected by plant density (Fausey et al. 1997).

Barnyardgrass has been a common weed in several crops for decades. A natural stand of barnyardgrass with an average density of 100 weeds m^{-2} reduced corn yield to just 18 percent of the weed-free control in the Netherlands. The yield reduction varied a great deal between years primarily due to differences in the relative emergence time of the crop and the weed and the resultant competition for light (Kropff et al. 1984). Bosnic and Swanton (1997) also reported the importance of relative time of emergence. When barnyardgrass and corn were planted at the same time and when barnyardgrass was planted at the 1- to 2- or 3- to 4-leaf stage of corn growth, yield losses were quite different. Barnyardgrass at a density of 200 plants m^{-2} and planted with corn reduced yield 26 to 35 percent but less than 6 percent if it emerged after corn had four leaves. Barnyardgrass that emerged up to corn's 3-leaf stage produced an average of 34,600 seeds m^{-2} whereas barnyardgrass that emerged after corn had four leaves produced only 1,200 to 2,800 seeds m^{-2}.

Mickelson and Harvey (1999) determined the effects of density and time of emergence on woolly cupgrass growth and seed production in corn. Compared to woolly cupgrass grown at 3 plants m^{-2} that emerged with corn, total aboveground mature biomass was reduced 54, 97, and 99 percent when woolly cupgrass emerged at the V2, V5, or V10 stages of corn growth in one year and by 70, 87, and 99 in a second year. Woolly cupgrass aboveground vegetative biomass production per mature plant was linearly related to seed production per plant, which decreased nonlinearly as density decreased and time of emergence was delayed (Mickelson and Harvey 1999). Seed production was 12,700 per plant in one year and 57,100 in the other. The work suggests that late-emerging woolly cupgrass is not of great importance to long-term management of the weed.

Wild proso millet is an important weed across the semiarid Great Plains of the United States, where corn may be grown in rotation with winter wheat and proso millet (mainly for bird seed). In corn, wild proso millet seedlings begin to emerge in May in Colorado within 2 weeks of corn emergence. Early emerging seeds produced the most seeds (2,800 per plant), whereas seedlings that emerged 4 weeks later produced 88 percent fewer seeds (Anderson 2000). If the weed was controlled by late June, there was no loss of corn grain yield (Anderson 2000).

Itchgrass did not compete at all with corn or was allowed to compete for 2, 4, 6, 8, 10, 12, or 14 (all season) weeks. Season long (14-week) interference reduced corn height 18 percent and yield 33 percent over 2 years. Each week of interference reduced corn yield 125 kg ha^{-1}. Itchgrass competition for more than 2 weeks after corn emergence always reduced corn yield (Strahan et al. 2000). Wild proso millet is a more ubiquitous weed across the U.S. central Great Plains, and although it is not as large a plant as itchgrass, it is as effective a competitor. Wilson and Westra (1991) found yield reductions of 13 to 22 percent from 10 wild proso millet plants m^{-2}. If weed removal was delayed for 2 weeks after corn planting, yield could be reduced as much as 10 percent. If removal was delayed up to 6 weeks after planting, corn yield was reduced 16 to 28 percent (Wilson and Westra 1991).

Quackgrass is a vigorous competitor with corn and reduced yield 12 to 16 percent with 65 to 390 shoots m^{-2}. Yield reduction was 37 percent with 745 shoots m^{-2} (Young et al. 1984). Young et al. (1984) demonstrated that when light and nutrients were not limiting, an adequate supply of soil water can eliminate the detrimental effects of quackgrass on corn. When soil water was limiting, irrigation increased the yield of quackgrass-free corn and of quackgrass-infested corn. The presence of quackgrass did not affect corn's nutrient status (Young et al. 1984).

Stoller et al. (1979) showed that corn yield was reduced 8 percent for every 100 yellow nutsedge shoots m^{-2}. Early competition was the most detrimental and use of preplant herbicides always reduced yield loss. Without control, corn yield declined 17 percent with 300 yellow nutsedge tubers m^{-2} and 41 percent with 1,700 tubers m^{-2}. The persistence of the tubers is emphasized by their finding that at least 2 years of effective control were required to reduce tuber numbers to 20 percent of the original number and 3 years to gain an additional 5 percent reduction. Ghafar and Watson (1983a) recommended the use of crop density to manage yellow nutsedge. When corn density increased from 33,300 to 133,200 plants ha^{-1}, yellow nutsedge's aboveground biomass, tuber numbers, tuber weight, and height all declined at the end of the growing season, primarily due to increased light competition from the more dense corn stand. Manipulation of the corn planting date to assure that it emerged prior to yellow nutsedge is a key to effective yellow nutsedge management (Ghafar and Watson 1983b).

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COTTON—*GOSSYPIUM HIRSUTUM L.*

Cotton began to replace wool as people's most important fiber in the nineteenth century. China has been the world's major producer and the United States has been a close second. Cotton in Europe, Asia, and Africa probably originated in what is now Pakistan (Hobhouse 1985, p. 142). Cotton may have been endemic in the New World but how it got to the United States remains a mystery. One bale of U. S. cotton was exported to Liverpool in 1784. It was not accepted and rotted on the pier because it had not entered on a British ship. From that bad beginning, the cotton trade grew to 4 million bales, and the history of the growth of that part of U.S. agriculture includes the whole history of Southern slavery and the Civil War (Hobhouse 1985, p. 142).

The interference of more than 30 different weed species has been studied in cotton. A general survey in California (Kempen 1984) reported that several annual and perennial weeds reduced cotton lint production by 0.5 bale A^{-1} or more. More than 50 percent of Kern County, CA, cotton fields were weed free at harvest. In weedy fields, the dominant species varied between clay and sandy soils with some causing severe, some moderate, and some only light losses.

Planting date had little influence on weed interference in cotton in Arkansas. Losses increased 30 to 50 percent when weed density increased from 1.7 to 6.7 m^{-1} of row (Klingaman and Oliver 1994). Miller et al. (1983) found no yield advantage for 51- or 102-cm rows in California. Barnyardgrass density increased after cotton layby regardless of row width, so that at harvest the number of weeds was equal for the two row widths. Similarly, cotton yields were not affected consistently by interrow cultivation in a four-state, 3-year study (Colvin et al. 1992). When all frequencies were considered, cultivation initiated 1 or 2 weeks after cotton emergence and continued for two, four, or six times increased yield at only three of nine locations over all years. For two locations, cotton yields were increased by only two cultivations.

Byrd and Coble (1991b) compared the amount of cotton yield loss caused by eight annual weeds, each at a density of one weed in each 3 m of row. Yields were reduced between 1 and 7 percent. Sicklepod did not cause any yield loss, while redroot pigweed, common cocklebur, and common ragweed decreased yield 7, 6, and 5 percent, respectively. In a second year, yield losses from individual weeds ranged from 3 to 27 percent. Common cocklebur, jimsonweed, and common ragweed reduced cotton yield 28, 15, or 12 percent, respectively. Spurred anoda and common cocklebur exerted an influence 160 and 136 cm from the cotton row, whereas sicklepod had an influence of only 46 cm. The primary, but not startling, conclusion one can draw from this work is that the influence of a weed or an aggregate of weeds is highly variable but all have some effect. No general principles or generalizations can be derived except what I have earlier (see preface) called the central hypothesis of *Weed Science*: Weeds compete with crops and reduce crop yield and quality.

Many studies in support of this hypothesis have been reported in the last several years. Studies on 30 different weeds are summarized below but no additional general principles can be derived from these papers. Keeley and Thullen spent a great deal of time and effort in a quest to analyze the competitiveness of all weeds important in cotton in California. Their work on several weed species will be cited frequently below in studies with similar design and objectives.

Barnyardgrass—*Echinochloa crus-galli*

Barnyardgrass that competed for 6, 9, 12 or 25 weeks after cotton emergence reduced cotton yield 21, 59, 90, or 97 percent. A weed-free period of 9 weeks after emergence was required to prevent cotton yield reduction. If cotton was kept weed free for 3 or 6 weeks after emergence, it yielded 13 and 87 percent as much as cotton that was weed free for the whole season (Keeley and Thullen 1991a). The importance of regular control is illustrated by the fact that barnyardgrass produced 80 to 90 percent fewer seeds in plots kept weed free for the first 6 weeks after emergence. Weeds that emerged after 9 to 12 weeks of weed control did not grow more than 10 cm tall due to shading by cotton and did not produce seed. Keeley and Thullen (1991a) proposed that barnyardgrass is as competitive as weeds known to be particularly aggressive such as johnsongrass.

Bermudagrass—*Cynodon dactylon*

In short-term competition experiments done in the greenhouse, growth of cotton planted 3 weeks after bermudagrass was severely reduced to about 15 percent of the control 10 weeks after planting. Cotton growth was not affected when it was planted before the weeds (Horowitz 1973). The effect was attributed to the weed's rapid growth and possible allelopathic effects. Similar results were reported for purple nutsedge and johnsongrass (Horowitz 1973). Losses of 16 or 26 percent of the weed-free yield were reported by Keeley and Thullen (1991b) when bermudagrass competed with cotton for 12 or 25 weeks. If cotton was hand-weeded for 8 to 12 weeks after emergence, yield was not affected and was 9 percent greater than cotton hand-weeded for only 4 weeks after emergence. The future weed problem from bermudagrass was affected because bermudagrass did not produce seed, and rhizome production was negligible when weed competition did not exceed 8 weeks after emergence and weed-free periods exceeded 4 weeks (Keeley and Thullen (1991b).

In no-till cotton, 3,600 kg ha^{-1} of bermudagrass reduced cotton height as early as 5 weeks after planting, and seed cotton yield was reduced 25 percent (Vencill et al. 1992). When bermudagrass was present, soil water content was decreased significantly up to 15 cm deep. Soil water was not significantly affected 30 to 60 cm deep. In a subsequent study by Vencill et al. (1993), cotton height and yield were significantly reduced by bermudagrass and the effects were magnified by increasing weed density. Soil volumetric water content decreased in the upper 30 cm of soil with increasing bermudagrass density. The critical period for bermudagrass competition was 4 to 7 weeks after planting (Vencill et al. 1993).

Black Nightshade—*Solanum nigrum*

Black nightshade that competed with cotton for the full season reduced yield 60 to 100 percent. If cotton was cultivated about 3 weeks after emergence and kept free of black nightshade for the rest of the season, yield was not reduced. The largest yield reduction (82 to 100 percent) occurred in a year when 0.5 to 0.7 inches of rain fell within 10 days after cotton planting (Keeley and Thullen 1989a). The importance of regular control of black nightshade is emphasized by the fact that fields had to be kept free of black nightshade seed production for more than 5 years if populations were to be reduced to a level that did not affect cotton yield.

Buffalobur—*Solanum rostratum*

The dry weight of buffalobur increased by 0.06 to 0.3 kg per plot for each added weed in 10 m of row (Rushing et al. 1985a). The threshold density for cotton yield loss varied from 2 buffalobur in each 10 m of row, 8 in each 10 m of row, to 32 in each 10 m of row at three different sites. Cotton lint yield decreased 6 to 18 kg ha^{-1} for each added buffalobur in 10 m of row.

Coffee Senna—*Cassia occidentalis*

With season-long competition, each coffee senna plant in 7.5 m of row reduced cotton yield 9 to 117 kg ha^{-1} (Higgins et al. 1986). Each additional week of competition from 40 coffee senna m^{-1} of row reduced cotton yield 118 kg ha^{-1} and reduced cotton stem height 1.25 cm. If cotton was kept weed free for 8 or more weeks after emergence, coffee senna did not grow successfully.

Common Cocklebur—*Xanthium strumarium*

The dry weight of common cocklebur increased with increasing density up to 16 plants in 15 m of row, whereas seed cotton yield decreased as weed density increased up to 16 in 15 m of row (Snipes et al. 1982). Cotton yield losses ranged from 72 to 115 kg ha^{-1} for hand-harvested cotton and 57 to 90 kg ha^{-1} for machine-harvested cotton for each common cocklebur present in 15 m of row. Cotton stem diameter and height also decreased with increasing weed competition and both were good indicators of common cocklebur competition. Common cocklebur reduced cotton yield when competition was longer than 4 weeks after emergence in 2 years and 2 weeks after emergence in a third year (Snipes et al. 1987). Cotton yield was not affected when it was free of common cocklebur competition for 8 to 10 weeks.

When cotton was grown less than 60 cm from a common cocklebur plant, it was shorter, had less leaf area, and had lower leaf, stem, boll, and biomass dry weight than cotton grown more than 60 cm from a common cocklebur (Byrd and Coble 1991a). Differences in leaf area and biomass were greater 13 weeks after planting, and 15 weeks after planting, cotton leaf area and biomass were reduced 11 and 15 percent. When one common cocklebur grew in 2.1 m of row for 27 weeks after planting, cotton yield was reduced 31 percent. Even weed plants 99 cm from the cotton row reduced cotton yield. Cotton also competes and common cocklebur grown alone produced 67 percent more biomass than did cotton grown alone (Byrd and Coble 1991a).

Devil's-claw—*Proboscidea louisianica*

Random densities of 5.5 +- 1.1 devil's-claw plants m^{-2} reduce cotton lint yield 41 kg ha^{-1} or about 5 percent for each week the weed was present. Interference of 4, 8, or 12 weeds in each 10 m of row decreased cotton yield by 22, 49, or 56 kg ha^{-1}, respectively, for each week of interference (Riffle et al. 1989). Devil's-claw has a deep taproot similar to cotton and probably competes primarily for water and nutrients (Mercer et al. 1987). As devil's-claw density doubled from 1 to 32 plants 10 m^{-1} of cotton row, cotton yield decreased between 84 and 146 kg ha$^{-1.}$ Maximum yield losses ranged from 59 to 74 percent over three sites (Mercer et al. 1987). In support of the hypothesis that devil's-claw competes primarily for water, Riffle et al. (1990) demonstrated greater water depletion early in the cotton-growing season, which was the time of the weed's most rapid growth. When cotton was grown alone, the greatest water demand was late in the season during peak bloom and early boll formation. The vigor of devil's-claw competition and the interaction with water are illustrated by the finding that in one year, yield was reduced 96 percent, whereas it was reduced only 46 percent in a second year with higher rainfall.

Hemp Sesbania—*Sesbania exaltata*

Hemp sesbania has been studied more as a competitor in soybeans and rice than in cotton. Densities of 1, 2, 5, or 10 plants in 13.3 m of row reduced cotton yield 19, 25, 45, or 53 percent, respectively (Bryson 1987). Cotton plant density, seedling vigor, and the number of white blooms per hectare did not differ among hemp sesbania densities 75 days after planting. The weed's height was equal to or greater than cotton's 55 to 65 days after planting, which suggests that light competition may play a role. Light penetration 1 m above the cotton canopy was 36 percent less than in weed-free plots when hemp sesbania density was equal to or greater than 5 per hectare. However, light was only reduced at the soil surface at the maximum density studied (10 plants in 13.3 m of row) (Bryson 1987). Although early season vigor and growth of cotton seedlings up to 28 days after planting was not affected by as many as 3 hemp sesbania in 1 m of row (32,000 ha^{-1}), white cotton blooms and cotton yield were reduced when hemp sesbania was not removed by 70 days after planting (Bryson 1990).

Hogpotato—*Hoffmanseggia glauca*

Hogpotato is a native perennial, semiprostrate plant in the southwestern United States, and it rarely grows more than 30 cm tall. As many as 105 +- 21 hogpotato m^{-2} reduced cotton height after full-season competition by 14 to 44 percent. The weed's dry weight was reduced 54 percent by full-season competition from cotton whose lint yield was reduced 31 to 98 percent after full-season competition (Castner et al. 1989). Interference during the first 7 weeks of cotton growth reduced lint yield 40 percent, but if the weed emerged after 7 weeks of crop growth, it had no affect on cotton yield. As is the case with the deep-rooted perennial devil's-claw, competition for water is important. Hogpotato uses soil water mainly from below 120 cm, while cotton uses water in the upper 75 cm of soil.

Ivyleaf Morningglory—*Ipomoea hederacea*

Ivyleaf morningglory planted in California from April through August began to emerge about 1 week after planting. When the weed's density was one plant in 2 m of row and it was present from early April or May for the entire season, the competition was so severe that the entire cotton crop was lost (Keeley et al. 1986). June planting reduced cotton yield only 11 percent and later plantings had no effect. The April through July plantings began flowering within 7 weeks of planting, and viable seed was collected as soon as 9 weeks after planting. In an Oklahoma study (Wood et al. 1999), cotton yield reductions from 1 weed 10 m^{-1} of row ranged from 31 to 36 kg ha^{-1} at one location and from 35 to 36 kg ha^{-1} at a second location. Lint yield reduction for each weed in 10 m of row ranged from 3.8 to nearly 7 percent at the two locations. The weed did not affect harvest efficiency at either location.

Jimsonweed—*Datura stramonium*

Variation in rainfall between geographic regions affected jimsonweed competition in cotton but not in soybeans. Jimsonweed's competitive ability was reduced in dry years, but it was always more competitive in the less-competitive cotton than in soybeans (Oliver et al. 1991).

Johnsongrass—*Sorghum halepense*

When johnsongrass competed for the full season, a minimum density of 2 plants in 9.8 m of row was required to reduce cotton yield, and yield decline increased rapidly as density increased (Bridges and Chandler 1987). The yield loss was 4, 14, 40, 65, or 70 percent for johnsongrass densities of 2, 4, 8, 16, or 32 plants 9.8 m^{-1} of cotton row. Cotton yield loss was proportional to its yield potential at the median densities of 4 and 8 plants m^{-1} of row, but not above or below those densities. Rhizome johnsongrass was a more vigorous competitor than plants from seed. Three to 4 weeks of competition from rhizome johnsongrass decreased cotton yield, but 6 weeks were required before significant yield reductions were obtained from seedling johnsongrass competition (Bridges and Chandler 1987). If cotton was maintained weed free for 4 weeks after emergence, yield loss in one year was prevented, but it was not in the second year of the study. When cotton cultivars that were 66, 122, or 168 cm tall at maturity competed with 4 or 6 johnsongrass plants 6 m^{-1} of row with cotton planted in rows 1 m apart, there was no effect of cultivar on competition (Bridges and Chandler 1988). Yield of all cultivars declined as johnsongrass density increased. In the absence of johnsongrass, the yield of the cultivars did not differ.

In California a weed-free period of 9 weeks after emergence was required to prevent cotton yield loss (Keeley and Thullen 1989b). Competition for 6, 9, 12, or 25 weeks after emergence reduced cotton yield 20, 60, 80, or 90 percent. When johnsongrass was removed 3 weeks after emergence and the plots were kept weed free for the rest of the season, cotton yield was not reduced. Cotton in plots that were kept weed free for 3 or 6 weeks (after which weeds were allowed to grow) lost 19 or 11 percent of the weed-free yield.

The effect on picker versus stripper harvest efficiency of johnsongrass densities of 3, 4, 5, 8, or 15 plants 15 m^{-1} of row was evaluated in Oklahoma. With three or fewer plants in one year and four or fewer in a second year, harvest efficiencies were 4.9 to 7.6 percent higher for stripper than for picker harvest. With four or more in one year and five or more in the second, differences in harvest efficiency between the two machine methods were not significant (Wood et al. 2002). For both years, cotton lint yield was reduced nearly the same amount (3.5 to 5.5 percent) for the two methods for each johnsongrass plant in 15 m of row.

Noogoora Bur and Fierce Thornapple—*Xanthium occidentale* and *Datura ferox*

Cotton lint yield was reduced 36 and 12 percent and the maximum distance of influence was 1.7 m for noogoora bur and fierce thornapple. Noogoora bur was the more vigorous competitor. Its threshold was one weed in 195 m of cotton row and for fierce thornapple it was one weed in 73 m of row (Charles et al. 1998).

Polygonum spp.

The interference of three members of the polygonaceae [ladysthumb (Askew and Wilcut 2002a), pale smartweed (Askew and Wilcut 2002b), and Pennsylvania smartweed (Askew and Wilcut 2002c)] has been studied in North Carolina. Each remained shorter than cotton for 70 to 80 days after cotton planting. Each grew taller than cotton by harvest and produced significant dry biomass by cotton harvest. However, cotton significantly reduced the biomass of each weed by about four times. The hyperbolic function accurately described the relationship between each weed's density and cotton yield loss. In general, cotton yield loss decreased in the range of 0.7 to 1.3 kg ha^{-1} for each gram increase in weed dry biomass m^{-1} of crop row.

Pigweeds—*Amaranthus* spp.

The interference of four pigweed species has been studied in cotton. Four field experiments were done in Oklahoma to determine the effect of full-season competition of Palmer amaranth (Rowland et al. 1999). For densities up to 12 weeds 10 m^{-1} of row, each increase of 1 weed reduced lint yield 58 to 112 kg ha^{-1} (roughly 6 to 11 percent) depending on location and year. Lint yield versus end-of-season weed volume per unit area was linear for almost all locations and years. For each m^3 increase in weed volume, cotton lint yield decreased 1.5 to 2.3 percent. Lint yield versus end-of-season weed biomass fit a linear model. Lint yield decreased 5 to 9 percent for each additional kg of Palmer amaranth biomass in a plot. No consistent effects on fiber properties were found (Rowland et al. 1999). Smith et al. (2000) found that Palmer amaranth affected lint and seed yield only when weed density was 3,260 ha^{-1} (the highest density studied). Mechanical harvest efficiency was affected by the highest and lower weed densities even though most weed material was discarded in the field. Palmer amaranth did not affect seed moisture content, ginning time, fiber quality, or the percentage of cleaned lint (Smith et al. 2000). When Palmer amaranth density ranged from 0 to 10 plants in 9.1 m of row, cotton canopy volume was decreased 45 percent 10 weeks after emergence and biomass declined 50 percent 8 weeks after emergence (Morgan et al. 2001). Similar to the work of Rowland et al. (1999), cotton yield decreased linearly from 13 to 54 percent with 1 to 10 Palmer amaranth 9.1 m^{-1} of row. There was no effect on cotton lint properties.

Smooth pigweed affected cotton by reducing plant water status early in the season and by shading late in the season (Stuart et al. 1984). With a smooth pigweed density of 2.5 m^{-2}, cotton's leaf water potential (0.53 MPa) and turgor pressure (0.21 Mpa) reductions were significant. Late in the season, photosynthetic photon flux to the cotton canopy at noon was reduced as much as 90 percent. Smooth pigweed was able to maintain a higher water potential and turgor pressure than cotton. The weed was able to extract water from lower in the soil profile, and it had higher diffusive resistance and a lower transpiration loss.

One redroot pigweed 15 kg ha^{-1} of row reduced cotton yield 21 to 38 kg ha^{-1} in a study with densities up to 32 weeds in 15 m of row (Buchanan et al. 1980). Sicklepod was regarded as slightly more competitive than redroot pigweed.

Full-season interference from 64 tumble pigweed in 10 m of cotton row reduced lint yield 8 to 11 kg ha^{-1} for each added weed in 10 m of row. The dry weight of tumble pigweed increased 0.15 to 0.4 kg per plot for each added weed in 10 m of row (Rushing et al. 1985b). The threshold density for lint yield reduction ranged from 4 to 16 tumble pigweeds 10 m^{-1} of row. Cotton height was reduced, but only when the weed density was 32 or 64 10 m^{-1}.

Purple and Yellow Nutsedge—*Cyperus rotundus* and *C. esculentus*

Keeley (1987) wrote a complete review (93 citations) of interference reactions of purple and yellow nutsedge in eight agronomic and nine horticultural crops. His review demonstrated that both weeds reduce crop yield and both are effective competitors. The article's conclusion is similar to the plea herein, a lot is known about what happens when specific weeds compete with crops. Good descriptions of what happens are readily available. Keeley (1987) says "perhaps" (a weak word) it is time to move on to determine "why, when, and under what conditions specific crop-nutsedge interactions occur." His plea was, one assumes, heard but not heeded by many. Keeley et al. (1979) also showed that cropping systems affect yellow nutsedge populations. Two years of alfalfa or double cropping barley (with appropriate herbicides) followed by corn that preceded cotton, reduced yellow nutsedge tubers by 96 percent. Two years of chemical fallow (with glyphosate) following barley and preceding cotton removed 98 percent of yellow nutsedge tubers. Continuous cotton treated with MSMA was also effective (91 percent reduction) in reducing nutsedge tubers over 3 years.

Yellow nutsedge and johnsongrass had higher height, biomass, leaf area, growth rate, and photosynthetic efficiency than cotton or purple nutsedge (Holt and Orcutt 1991). Cotton had greater leafiness and canopy closure than the weeds over 10 weeks but the weeds dominated because they had better overall resource use and production efficiency. Linear correlation analysis indicated that most growth variables were significantly correlated with aggressivity; a synonym for competitiveness. Of the 12 growth variables studied, 4—leaf growth rate, height, relative growth rate, and the growth rate of the initial propagule (seedling or rhizome bud)—were best correlated with agressivity. The ability to capture light and establish a rapidly growing seedling early was the best predictor of competitive success (Holt and Orcutt 1991).

The vigor of competition from yellow nutsedge is illustrated well in work by Keeley and Thullen (1983) who showed that hoeing cotton from 4 to 12 weeks after emergence reduced the population of yellow nutsedge present at harvest by 67 to 87 percent. Over six locations, a yellow-nutsedge-free period of 4 to 12 weeks was required to avoid cotton yield reduction. All levels of nutsedge control (from 2 to 12 weeks after emergence) reduced the number of nutsedge shoots at harvest and cotton yield loss.

Purple nutsedge has a greater leaf area and dry weight than three other weeds (large crabgrass, prickly sida, and velvetleaf) that commonly infest cotton. Among these weeds, purple nutsedge was the most and prickly sida the least competitive (Elmore et al. 1983) in competition with cotton and with each other.

Sicklepod—*Cassia obtusifolia*

Full-season competition of 4, 12, or 32 sicklepod 15 m^{-1} of row with 5, 10, or 20 cotton plants m^{-1} of row using conventional cultural practices showed no effect of cotton density on competitive effects of sicklepod. Cotton yield was inversely related to the weed's density (Street et al. 1981). When sicklepod was combined with redroot pigweed and smooth pigweed in all possible combinations of 1, 2, 4, 8, and 16 weeds of each species in 7.5 m of row, seed cotton yield declined as a quadratic function of increasing weed density (Street et al. 1985). Sicklepod was more competitive than either pigweed species. With one pigweed in 7.5 m of row, cotton yield decreased 26 kg $ha^{-1.}$ With one sicklepod in 7.5

m of row, yield declined 85 kg ha^{-1}. When the weeds were present together with two plants in 7.5 m of row, yield decreased 110 kg ha^{-1}. At low weed density (less than 4 in 7.5 m^{-1} of row), the competitive effect of sicklepod and either pigweed was additive. At higher densities, competition was not additive because of intraspecific competition among the weeds (Street et al. 1985). Buchanan et al. (1980) found that one sicklepod 15 m^{-1} of row reduced cotton yield 34 to 43 kg ha^{-1}.

Silverleaf Nightshade—*Solanum elaeagnifolium*

This perennial weed with sharp spines is a vigorous competitor. It is assumed that competition in cotton is primarily for water because irrigated cotton competes much better than dryland cotton (Green et al. 1987). Cotton height decreased with 4 or more silverleaf nightshade in 10 m of row. There is no evidence of intraspecific competition and the predicted cotton yield loss is 1.5 percent per weed in 10 m of row. The weed also interfered with mechanical harvest when density was 16 or 32 10 m^{-1}. When cotton was grown with silverleaf nightshade, water loss was greater in the lower parts of the soil profile early in the season than when cotton was grown alone (Green et al. 1988). The weed's effect on cotton yield, height, and boll size was directly correlated with the amount of soil water available. There was a negative, linear relationship between cotton lint yield and weed biomass. Each 1 kg of weed biomass 10 m^{-1} of row of established stands of silverleaf nightshade decreased cotton yield 9 percent for 1-year-old weeds and 21 percent for 2-year-old weeds. Each stem of the weed in 10 m of row reduced cotton yield about 0.3 percent (Smith et al. 1990).

Spotted Spurge—*Euphorbia maculata*

Spotted spurge densities of 5, 10, or 50 plants m^{-1} of row reduced cotton yield 47, 57, or 85 percent, respectively, after season-long competition. As the weed's density increased, cotton's height, leaf area, dry weight, and boll number all decreased (Bararpour et al. 1994).

Spurred Anoda—*Anoda cristata*

Three cotton cultivars varied in their response to spurred anoda competition, but yield of all was reduced as much as 38 percent by season-long competition. Cotton yield and the weed's effects varied due to highly variable weather during the 3 years of the study (Chandler and Meredith 1983). Early-season competition reduced the yield of the early maturing cultivar most. The competitive effect of spurred anoda and velvetleaf (see velvetleaf studies below) increased with time of competition (Patterson and Highsmith 1989). Growth reduction in cotton was associated with reduced leaf area duration and the effect was more severe in a dry year. Drought, when imposed, did not affect the relative competitive ability of the two weeds or cotton. Intraspecific competition was more severe on cotton than intraspecific competition.

Tropic Croton—*Croton glandulosus*

Cotton height decreased with increasing weed density 10 weeks after planting, but weed height was not affected. Cotton lint yield decreased linearly at 2 kg ha^{-1} with each gram increase in tropic croton density m^{-1} of crop row (Askew and Wilcut 2001). Tropic croton was less competitive with cotton than other weeds studied by Askew and Wilcut (2002a, b, c) but was regarded as an important threat.

Velvetleaf—*Abutilon theophrasti*

Velvetleaf is a good competitor when soil water is adequate because it transpires a lot of water. Light interacts with water because solar radiation is the driver of plant water use (Salisbury and Chandler 1993). In this greenhouse study, velvetleaf used significantly more water than cotton when water and light were abundant. Transpiration of both species decreased in dry soil. Velvetleaf reduced transpiration losses via leaf abcission, but cotton leaves did not abcise. Both species transpired less when shaded, and shading reduced competitive stress in dry soil.

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OILSEED CROPS

Flax—*Linum usitatissimum*

Greenhouse studies suggested that dog mustard was less competitive than wheat but similar to flax. Competition from both crops reduced the leaf area, shoot dry weight, height, and seed production of the weed compared to its growth on summer fallow land. Wall (1997) concluded that dog mustard was not a vigorous competitor with wheat or flax.

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Rapeseed = Canola—*Brassica napus* L.

The average annual loss in rapeseed yield due to infestation with perennial sowthistle was estimated to be 9.4 million kg in Saskatchewan and 6.1 million kg in Manitoba (Peschken et al. 1983). The weed was present in 39 percent of the rapeseed fields surveyed but because it existed in patches, it actually infested only about 7 percent of the hectares surveyed.

Wild mustard and common lambsquarters interfered with rapeseed growth early in the season and caused significant reductions in dry weight by June each year. When weed density varied from 20 to 80 plants m^{-2}, wild mustard reduced rapeseed grain yield 19 to 77 percent, whereas common lambsquarters reduced yield only 20 to 25 percent (Blackshaw et al. 1987). Both weeds produced abundant seed and, if not controlled, added large quantities of seed to the soil seedbank. As few as 4 wild radish m^{-2} that emerged with canola reduced canola yield 9 to 11 percent and 64 wild radish m^{-2} reduced yield 77 to 91 percent (Blackshaw et al. 2002). Wild radish interference was influenced greatly by its time of emergence relative to canola. If it emerged 10 weeks after canola, it had no measurable effect but still produced seed in most years. Its effect decreased as the time increased.

Rapeseed was less competitive than rye, wheat, or barley in competition with quackgrass in studies in Denmark (Melander 1994) but more competitive than peas. Yield losses for rapeseed were about 35 percent from densities of 100 quackgrass shoots m^{-2} in spring. Prevailing climate conditions did not affect yield-density relationships in rye, peas, or barley but had significant effects on rapeseed and wheat. Melander (1994) points out that this was probably due to the stimulation of quackgrass growth and inhibition of rapeseed growth by the cool rainy weather in the spring of one year. Volunteer barley severely reduced canola yield, but the financial losses were partially offset if a grower was able to harvest barley as a crop (O'Donovan et al. 1988). Barley was at least 1.5 times more competitive in canola than wild oat.

Oilseed rape fruit weight was reduced by 200 wild proso millet plants m^{-2}, fruit number and shoot weight were inhibited by 400 plants m^{-2}, and 600 weeds reduced height and delayed flowering (Miller and Callihan 1995). The number and weight of oilseed rape fruits was reduced one-third after 8 weeks of interference compared to 4 weeks of wild proso millet interference. With 600 weeds m^{-2}, shoot weight was reduced 74 percent, fruit number 85 percent, and fruit weight 82 percent after 12 weeks of interference.

Yield losses caused by common chickweed were often high but differed greatly among ten experiments in the UK (Lutman et al. 2000). For example, a 5 percent yield loss could be caused by 1.4 to 328 weeds m^{-2}. Predictions based on relative dry weight of weeds and crop (weed dry weight/crop + weed dry weight) in December (oilseed rape is a winter crop in the UK) were somewhat less variable than those based only on weed density. In this case, a 5 percent yield loss was caused by 1.4 to 10.6 percent range of relative dry weight. Variations in yield loss were caused by variation in oilseed rape and common chickweed competitiveness related to weather differences between sites and years and the 8 to 10 months between planting and harvest. Lutman et al. (2000) reported that despite the variations, "there were indications that the greater the crop dry weight was in December, the lower the final crop yield loss." Weed competition was not affected by crop density between 44 and 113 plants m^{-2} apparently due to the "compensatory ability of the lowest density."

Canola yield is not affected significantly by usual canola planting density. When tartary buckwheat was the competing weed, canola planted at 200 plants m^{-2} was able to reduce the weed's effect compared to densities of 50 to 100 plants m^{-2} (O'Donovan 1994). This planting density may not be economically feasible if other control methods are cheaper. However, with 100 tartary buckwheat plants m^{-2}, canola yield was estimated to be 115 g m^{-2} if canola density was 50 plants m^{-2}, but yield increased to 157 g m^{-2} when canola density was 200 m^{-2} (O'Donovan 1994). In other work, O'Donovan (1991) showed that there was little interspecific competition from quackgrass until its density was greater than 200 shoots m^{-2}. However, 50 to 100 quackgrass shoots m^{-2} reduced canola yield 18 to 32 percent, a significant loss. In most cases the hyperbolic model described the data well (O'Donovan 1991, O'Donovan et al. 1989). In O'Donovan et al. (1989), a population of only 1 wheat plant m^{-2} reduced canola yield 1 percent.

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Safflower—*Carthamus tinctorius* L.

When safflower was planted in 11- and 22-cm rows at densities of 10 to 192 plants m^{-2}, its yield and biomass peaked at a density between 70 to 84 m^{-2}. Decreasing row spacing slightly improved safflower competition with green foxtail but increasing crop density had a greater effect (Blackshaw 1993). Safflower competing with 500 green foxtail m^{-2} increased biomass and seed production up to 100 plants m^{-2} in one year and up to 156 in a second year. At these densities, weedy safflower yielded less than weed-free safflower, but its yield was three to four times more than at lower densities. Safflower is an effective competitor with green foxtail. High safflower density reduced green foxtail biomass up to 72 percent and seed yield up to 85 percent. The competition arose from the dense foliar canopy developed by safflower early in the season and its effective shading of the shorter weed.

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Sunflower—*Helianthus annuus* L.

Only four competition studies have been done in sunflower since 1980, and all but one have been done in Europe. The high competitive ability of sunflower was verified by studies in Italy of sunflower in competition with common lambsquarters, wild mustard, and greater ammi (Onofrio and Tei 1994). Consistent with many other studies, the hyperbolic model best described the relationship between yield and weed density. The three broadleaf weeds had competitive indices between $I = 1.08$ and 1.75, which supports the high competitive ability of sunflower. The economic threshold was 4 to 6 plants m^{-2} for all three broadleaf weeds when control was by hoeing. It was 6 wild mustard when a postemergence herbicide was used.

Six studies were conducted in southern Spain to derive competitive models and define the economic threshold for corn caraway competition in sunflower (Carranza et al. 1995). Losses ranged from 19 to 56 percent of the weed-free yield. Consistent with several other studies, correlation between percent sunflower loss and weed density were better than those with dry weight. When weeds emerged before mid-March, they were about 1.5 times more competitive than those that emerged later. The economic threshold to offset the cost of a shallow tillage that may have achieved 70 percent control ranged from 2.5 weeds m^{-2} for low-yielding sunflower (1,200 kg ha^{-1}) to less than 1 weed m^{-2} for high-yielding sunflower (2,800 kg ha^{-1}) (Carranza et al. 1995).

Season-long competition by kochia densities of 0.3, 1, 3, or 6 plants m^{-1} of row decreased sunflower achene yield 7, 10, 20, or 27 percent, respectively. Just 21 weeks of competition after sunflower emergence decreased yield 6 percent (Durgan et al. 1990).

One of the very few studies of competition of a parasitic weed with any crop was done in Spain with nodding broomrape and sunflower (Castejon-Muñoz et al. 1993). Nodding broomrape attached to sunflowers with 6 to 7 leaves and continued to grow and attach throughout sunflower's vegetative and flowering stages. Extensive, but subterranean, nodding broomrape shoot development was observed mainly at sunflower's early heading stage and sunflower's growth was reduced. Early planting increased sunflower yield and reduced nodding broomrape's detrimental effects.

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Peanut = Groundnut—*Arachis hypogaea* L.

Florida beggarweed has been studied more than other weeds in peanut. Buchanan and Hauser (1980) studied the effect of Florida beggarweed and sicklepod grown with peanut in three row widths with the same in-row planting rate for all row widths. Peanut yield increased and weed growth decreased with decreasing row width but row width had no effect on peanut quality. Peanut yield decreased with increasing time of weed competition. Peanut yield, without weed interference, in 20.3 cm rows was 6 to 20 percent higher than in 81.2 cm rows. Similarly, peanut yield with weed interference in 20.3 cm rows was 8 to 25 percent higher over 3 years than in 81.3 cm rows. In a later study, Hauser et al. (1982) showed that Florida beggarweed was more detrimental to peanut yield than sicklepod when competition lasted all season. Peanut yield decreased 15.8 to 30.2 kg ha^{-1} for each Florida beggarweed m^{-2} whereas for each sicklepod m^{-2} yield decreased 6.1 to 22.3 kg ha^{-1}. Each kg of Florida beggarweed decreased peanut yield 0.15 to 0.74 kg ha^{-1}, and each kg of sicklepod decreased peanut yield 0.08 to 0.23 kg ha^{-1}. Peanut yield correlated best with weed dry weight rather than weed population. Florida beggarweed is a good competitor because it grows above the peanut canopy by 52 days after planting (DAP), and by 73 days after planting photosynthetic active radiation (PAR) reaching peanuts was reduced 45 percent (Barbour and Bridges 1995). Sicklepod grew above peanut 42 DAP and reduced PAR 41 percent at 79 DAP. Wild poinsettia grew above peanut 44 DAP and reduced PAR 39 percent at 85 DAP (Bridges et al. 1992). By these criteria, the three weeds ought to be equally competitive with peanut, and in the Barbour and Bridges (1995) study they were. The distance of influence for the three weeds was Florida beggarweed—162 cm, sicklepod—150 cm, and wild poinsettia—190 cm. Yield losses within the distance were 26, 27, and 22 percent, respectively.

The effects of crop and weed management systems on weed populations in a corn-corn-peanut rotation demonstrated that rotation and weed control were both important (Johnson et al. 1992). Florida beggarweed and yellow nutsedge were the dominant weeds in corn when a high-input (intensive) weed management system was used. If no herbicides were used, Florida pusley dominated, illustrating how weed management simultaneously solves and creates weed problems. The weed management system in peanut became more difficult because the dominant weeds in corn were controlled successively and the dominant weed in peanut was the more difficult to control yellow nutsedge.

The importance of prompt control of sicklepod populations in a peanut-cotton-corn rotation was emphasized in work by Johnson et al. (1994). Each year of sicklepod presence at an initial density of 2 sicklepod 9.1 m^{-1} of row resulted in exponential increase in sicklepod seedlings in subsequent years. Of the three crops, corn was the most effective competitor with sicklepod and the weed produced the fewest seed. When sicklepod was present at what Johnson et al. (1994) defined as a subeconomic threshold density of 2 sicklepod 9.1 m^{-1} of row that was established in the first year of the study, a 7, 21, and 20 percent increase in sicklepod population in the next 3 years resulted.

Common ragweed height was not affected by its density or by peanut canopy diameter. The weed grew taller than peanut throughout the growing season, indicating competition for light was primary (Clewis et al. 2001). The rectangular hyperbola described the relationship in which common ragweed's aboveground biomass per plant decreased as its density increased, but the weed's total biomass per meter of crop row increased with weed density. Clewis et al. (2001) concluded that common ragweed is a very competitive weed in peanut and will cause serious losses if not controlled.

Common cocklebur has been identified as a major weed in many crops in the southern United States. With common cocklebur densities of 2, 4, 8, 16, or 32 weeds 8 m^{-1} of row, yields were reduced 32, 48, 65, or 88 percent after full-season interference in one year and 18, 30, 46, 62, or 75 percent in a second year, respectively (Royal et al. 1997). The reduced effect in the second year was due to that year having above-normal rainfall, which either reduced the weed's competitive ability or enhanced the crop's.

Predicted yield losses due to wild poinsettia in peanut were 4, 8, 12, 15, 26, 40, or 54 percent for season-long interference of densities of 1, 2, 4, 8, 16, or 32 wild poinsettia 9 m^{-1} of row in Georgia. Losses from the same densities in Florida were approximately the same (9, 14, 22, 30, 37, or 41 percent; Bridges et al. 1992).

After full-season interference from 8, 16, 32, or 64 bristly starbur plants 7.5 m^{-1} of row, peanut yield was reduced 14, 26, 43, or 50 percent. If peanuts were kept weed free for 6 weeks after emergence, the seed yield was reduced not more than 3 percent (Walker et al. 1989). When peanut density was 72 plants 7.5 m^{-1} of row, bristly starbur interference for 2 weeks after emergence reduced seed yield an average of 4 percent. Yield was reduced 54 percent after 13 weeks of interference. With a bristly starbur density of 35 plants 7.5 m^{-1} of row, peanut reduced the weed's dry weight about 32 percent after 13 weeks of interference.

Horsenettle presence for 6 to 8 weeks after emergence did not reduce yield of Spanish runner peanuts, and weed-free maintenance for 2 weeks after emergence increased yield (Hackett et al. 1987). Linear regression predicted a peanut yield increase of 69 kg ha^{-1} for each week of weed maintenance after emergence or a 40 kg ha^{-1} yield decrease for each week of weed interference but only in one year. The work seems to indicate that horsenettle may not be a major problem. In one year, 32 weeds in 10 m of row, the highest density in the study (35,200 in an acre), reduced yield, but in a second year, the same density had no effect on yield.

The interference of two grasses has been reported. Full-season interference of a natural infestation of broadleaf signalgrass at 8, 16, or 1,050 plants 10 m^{-1} of row reduced peanut seed yield 14, 28 or 69 percent. Slightly less than 4 weeds 10 m^{-1} of row reduced yield significantly. If broadleaf signalgrass was present for 6 weeks or less after emergence, yield was not affected, but 8 weeks of interference or longer reduced yield (Chamblee et al. 1982). Peanut is a weaker competitor because full-season interference by broadleaf signalgrass reduced peanut forage yield 64 percent, whereas peanut interference for the full-season reduced the weed's yield only 10 percent.

One study reported the interaction between tobacco thrips (*Frankliniella fusca* Hinds) control with aldicarb [2-methyl-2-(methylthio)propionaldehyde-*O*-(methyl-carbamoyl)oxime] and large crabgrass interference in peanut (Murdock et al. 1986). Thrip control did not affect large crabgrass dry weight or peanut yield without herbicidal weed control. There was greater early-season peanut canopy development when thrips were controlled, but there was no increase in peanut yield due to thrip control.

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POTATO—*SOLANUM TUBEROSUM* L.

A natural stand of grasses including barnyardgrass could compete with the potato cultivar Superior for 6 to 8 weeks before yield was depressed. On the other hand, a 2 to 4 week weed-free period was sufficient to assure no loss of potato yield (Vitolo and Ilnicki 1985). Raby and Binning (1985) affirmed that potato cultivars differ in their competitive ability.

A mixture of annual weeds that emerged 1 week after potatoes and competed for the full season, reduced yield an average of 54 percent compared to only 16 percent loss when weeds emerged 3 weeks after potatoes (Nelson and Thoreson 1981). With full-season competition, each additional 10 percent of total weed biomass reduced tuber yield 12 percent. The reduction in tuber yield was calculated as follows:

percent reduction in tuber yield from weeds = 47.5 + 1.23 (percent of total biomass as weeds) + 0.0045 $(\text{days})^2$

In the equation, days represent the number of days between planting and harvest (Nelson and Thoreson 1981).

Potato yield decreased with increasing quackgrass density and duration of competition. Quackgrass had a greater influence on marketable tuber yield than on total yield (Baziramakenga and Leroux 1994). The duration of the critical period for weed control varied with quackgrass density and year. If a 5 percent yield loss was deemed acceptable, the critical period began 15 days after potato emergence at a low level of quackgrass interference (35 to 38 g m^{-2}) to approximately 3 days after emergence at a medium infestation level of 87 to 95 m^{-2}. With a high level of infestation (135 to 158 g m^{-2}), the critical period began prior to potato emergence, so one must conclude there was no critical period because weed control was required from crop emergence on. Weed control was not required 23 to 68 days after emergence depending on quackgrass density and year. Because the onset of interference varied less than the end, early control of quackgrass is required (Baziramaenga and Leroux 1994). In further studies of quackgrass interference in potato, Baziramakenga and Leroux (1998) determined that the dry weight of quackgrass was the best determinant of potato yield loss. A yield loss of 10 percent was caused by 25 quackgrass shoots m^{-2}, which was equivalent to 20 g of total dry biomass. The economic threshold for quackgrass in potatoes varied between 0.04 and 2 shoots m^{-2} or 0.0165 and 1.5 g of total dry biomass.

Potato cultivars Atlantic and Russet Burbank and barnyardgrass were more competitive than redroot pigweed when the measure was relative competitive ability (VanGessel and Renner 1990b). In additive design field studies, 4 redroot pigweed plants or 4 barnyardgrass plants in each m of row did not reduce the yield of Atlantic potatoes when the weeds were planted between crop rows following hilling 6 to 7 weeks after planting. However, a single plant of either weed in a m of row reduced tuber yield 19 to 33 percent when the weeds were seeded in the potato row when potatoes were planted. Aboveground potato biomass was not a consistent predictor of total tuber yield. The variability of aboveground biomass was not due to increases in weed weight or density. For Russet Burbank and Atlantic potatoes, a single hilling was not adequate in either of two years for full-season weed control (VanGessel and Renner 1990a). Early hilling tended to increase the biomass of C_4 compared to C_3 weeds on mineral and muck soil, but it provided adequate weed control in only one year on mineral soil. Weeds reduced aboveground potato biomass on both soils, but this was not indicative of tuber yield. Russet Burbank potato yield was reduced by weeds more than Atlantic on mineral soil when conventional cultural practices (two hillings) were used; the opposite was true on muck soil (VanGessel and Renner 1990a).

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RICE—*ORYZA SATIVA* L.

If the number of people who depend on a crop for a major portion of their daily food is the most appropriate measure of importance, then rice is the world's most important crop. The International Rice Research Institute has claimed that a third of the world's people rely on rice for 50 percent of their daily caloric intake. The world grows 153.8 million ha of rice annually. The average worldwide yield is 3,885 kg ha^{-1}, which gives a worldwide production of 598.8 million metric tons, a total production greater than that of either corn (590.8 million metric tons) or wheat (576.3 million metric tons) (United Nations 2000). Rice is the only major grain crop that is grown almost exclusively for human food. It is also the only major grain crop that is grown in standing water (although it does not have to be—upland rice is common in South America) and that is eaten with little additional processing (it is dehulled) after harvest.

It may be related to the crop's importance or simply to the interests of the scientists, but compared to other crops, the work on rice reported here has more emphasis on exploration of why rather than on what happens in crop-weed competition. In a series of studies, Jennings and Aquino (1968a, b, c) defined varietal traits that made some cultivars more competitive than others. High-tillering, leafy tropical indica rices were more competitive when mixed with small, erect, sturdy plant types even though pure stands of the latter always outyielded the former (1968a, b). Competition was first observed when plants were 53 to 60 days old, which was 30 to 35 days after transplanting. Tall and dwarf cultivars differed genetically in ways that affected tillering, leaf number, leaf length and angle, and height. Tall genotypes were more competitive under normal growth conditions and became relatively more so in response to fertility and close spacing (1968b). The number of tillers, leaf number, leaf length, leaf area index, height, and dry weight were always greater in successful competitors before competition was observed (1968c). Leaf length was a critical factor because it determined the angle or degree of erectness and the amount of light the leaf could receive. Jennings and Aquino (1968c) concluded that any plant trait that increased size and vigor during early growth conferred competitive ability.

Thirty years later, Ni et al. (2000) described nearly the same traits that conferred competitive ability: initial biomass, plant growth rate, leaf area index, and biomass at tillering. Biomass at tillering was the best predictor of competitiveness against weeds in this study, which included newer (different) varieties than those studied by Jennings and Aquino (1968a, b, c). The importance of high tillering capacity to breeding efforts to maximize the ability of rice cultivars to compete with weeds was again emphasized by Estorinos et al. (2002).

A study of the competitiveness of cultivars of upland rice under low-input conditions in the Ivory Coast showed that cultivar competitiveness was correlated with root growth at early growth stages and with shoot and root growth at later growth stages (Fofana and Rauber 2000).

Work by Lindquist and Kropff (1996) emphasized the importance of early leaf area expansion to competitive ability because of the central role of light capture. Their ecophysiological approach predicted that the leaf area index 70 to 75 days after planting was a good indicator of leaf area expansion rate. The model showed that if the early leaf area expansion rate could be increased, barnyardgrass seed production decreased. Therefore, competitive rice cultivars could reduce the need for other weed management techniques. Detailed study of three rice cultivars showed that the cultivar that accumulated more biomass had a higher leaf area index, a higher specific leaf area, and, especially in early growth stages, partitioned more biomass to leaves was the most competitive with weeds (Johnson et al. 1998).

In contrast to the preceding studies but not in any essential disagreement, Pantone et al. (1992) used path analysis to show that the number of panicles per plant and florets per panicle were the yield components that determined the responses of fecundity and grain yield to competition. The effects of density on percent filled florets and grain weight varied and were relatively small, suggesting that these things were determined primarily by density-independent factors.

Ahmed and Hogue (1981), in Bangladesh, defined cultivar height as an important characteristic. Yield reduction from weeds increased with decreasing plant height. It is a logical assumption that this is related to competition for light as described by Caton et al. (2001) who used a rice:weed model to analyze the effects of the leaf area density (LAD) of weeds, leaf angles, and maximum height on growth and competition of weeds with rice. Short weeds and weeds with conical LADs were weakly competitive regardless of other traits. For other weeds, interference with rice was positively correlated with maximum height, LAD, and leaves that were planophile (oriented parallel to the ground). Ampong-Nyarko et al. (1992) examined the response of upland rice and three C_4 weeds (junglerice, goosegrass, and itchgrass) to low light intensities (150, 250, and 400 µmol $m^{-2}s^{-1}$ of photosynthetically active radiation). All three weeds had higher net CO_2 exchange rates than rice at all light intensities. The response to CO_2 exchange rates was greatest when plants were young and gradually decreased as plants matured. Itchgrass is an important weed in the tropics and has superior growth and carbon assimilation compared to rice under low and high light intensity. The other two weeds were more susceptible to the negative effects of shading.

Further evidence of the important role of light in rice-weed competition is provided by the work of Gibson et al. (2002). Late watergrass seeded with water-seeded rice was not affected by rice. When the weed was seeded after rice, shading by the crop increased and competition was effective. Gibson et al. (2002) proposed that management strategies that delay germination and growth of late watergrass and other *Echinochola* species "might confer a competitive advantage to rice and reduce the need for herbicide applications." However, the grass is a good competitor that can reduce the yield of rice by 18 percent after only 30 days of competition. In an earlier study (Gibson et al. 1999), root competition was identified as the primary mechanism determining competition between water-seeded rice and late crabgrass. Gibson et al. (1999) suggested that researchers should not rely solely "on correlations between shoot traits and competitive ability as evidence that competition is primarily for light." Shading by rice had little effect on late watergrass when it and rice were seeded at the same time.

Ampong-Nyarko and DeDatta (1993a) studied the response of four weeds (spiny amaranth, goosegrass, itchgrass, and purple nutsedge) and rice to nitrogen. The nitrogen response of two rice cultivars and itchgrass reached a plateau between 69 and 103 mg N kg^{-1} of air-dried soil, whereas the other weeds continued to respond to increasing amounts of nitrogen. At the higher nitrogen rates, nitrogen uptake by weeds was higher than that of rice. If nitrogen was applied at rates that were suboptimal for rice production, the competitive ability of rice was reduced in the presence of each of the four weeds. Ampong-Nyarko and DeDatta (1993a) studied the interaction of light and nitrogen when rice competed with itchgrass and junglerice in the field. Nitrogen availability increased the canopy light absorption coefficient and reduced the sunlit leaf area index of rice. When rice was grown in a growth chamber with low photosynthetically active radiation (PAR), it had higher shoot nitrogen concentration than when it was grown at higher PAR. Rice's photosynthetic rate was highly correlated with leaf N content per unit leaf area. Without nitrogen application, there was no difference in rice's dry matter yield at 150 versus 400 µmol $m^{-2}s^{-1}$. The limited response of rice to nitrogen applied to shaded plants and acclimation of rice to reduced light could be "significant factors in light and N interaction in rice-weed competition." In further work, Ampong-Nyarko and DeDatta (1993b) suggested that timing of nitrogen application could be employed for weed management, although there is no evidence that it has been.

In field studies in Greece (Eleftherohorinos 2002), interference between red rice and two rice cultivars began 3 weeks after emergence and was not affected by increasing nitrogen fertility from 100 to 150 kg ha^{-1}. One cultivar (Thaibonnet) was affected more than the other and its yield was reduced 58 percent by 40 red rice plants m^{-2} and the other (Ariette) was reduced only 46 percent. Red rice grew taller than both cultivars 10 weeks after planting and light competition may have been important.

Smith was one of the most productive of the weed scientists who worked on rice. In 1988, Smith identified the weeds that were most damaging to rice yield in Arkansas and ranked them. Of the grasses, red rice reduced rice yield the most followed by barnyardgrass, bearded sprangletop, and broadleaf signalgrass. Among the broadleaf/aquatic weeds, hemp sesbania reduced rice yield the most followed by northern jointvetch, ducksalad, spreading dayflower, and eclipta. He also reported that barnyardgrass, broadleaf signalgrass, and ducksalad interfered with rice the most during the early season, and eclipta, hemp sesbania, northern jointvetch, red rice, and spreading dayflower were more detrimental from midseason to late season.

Pantone and Baker (1991) used reciprocal yield analysis to study red rice interference. Over 4 years, 1 red rice plant reduced rice yield as much as 4 rice plants of the same cultivar. Rice yield losses from red rice interference were 13, 37, 48, or 92 percent from densities of 4, 16, 25, or 300 red rice plants m^{-2}.

Season-long densities of 1, 2, 5, 10, 20, or 40 red rice m^{-2} demonstrated that interference occurred with as few as 2 red rice m^{-2} (Kwon et al. 1991b). Ten red rice m^{-2} reduced total milled and head rice of the semidwarf cultivar Lemont but did not affect the short-statured cultivar Newbonnet. The difference was due to the shading effect of red rice on the semidwarf cultivar. When 20 red rice m^{-2} were grown for 120 days after rice emergence, the straw weight of Lemont was reduced 58 percent and the taller Newbonnet was reduced 34 percent. Grain yields were reduced 86 percent in Lemont and 52 percent in Newbonnet. These effects were attributed to the difference in shoot morphology of the two cultivars and to the vigor of red rice competition (Kwon et al. 1991a).

Red rice at a density of 5, 108, or 215 plants m^{-2} reduced rice yield 22, 77, or 82 percent, respectively, when cultivated rice density was 195 plants m^{-2} (Diarra et al. 1985). Only five red rice m^{-2} reduced rice grains per panicle by 8 to 18 percent, and 108 or 215 reduced grains per panicle 56 or 70 percent. A medium grain cultivar (Mars) that matured in 138 days in Arkansas competed better than Lebonnet, a long-grain cultivar that matured in 126 days.

Ferrero (1996) used a day-degree predictive model for growth of roundleaf mudplantain in competition with rice. The weed was allowed to emerge at 7-day intervals for 49 days after rice emergence. Consistent with results from other studies on rice and other crops, the weeds that emerged first were the most damaging to yield. The results of the day-degree model were consistent in that the weeds that accumulated (emerged earliest) the greatest number of day degrees (403) caused the greatest loss (95 percent).

Echinochloa spp. were much more competitive in direct-seeded than in transplanted rice (Hill et al. 1989). Three *Echinochloa* spp. m^{-2} reduced direct-seeded rice yield 20 percent, but 6.6 weeds were required to give the same yield reduction in transplanted rice. In terms of competitiveness, 25 transplanted rice plants m^{-2} were equal to 300 m^{-2} in direct-seeded rice. The regression model developed by Hill et al. (1989) showed that total plant stand and the dependent variable, relative yield, were more useful measures of competitive effects than the more commonly employed weed density and crop yield.

The importance of early competition as a determinant of the effect of barnyardgrass on rice is emphasized in the work of Kleinig and Noble (1968). Barnyardgrass grows rapidly and tillers abundantly (earlier than rice) early in the season when light is abundant. The addition of phosphate fertilizer stimulates the weed's tillering and final tiller number is influenced by nitrogen supply.

Barnyardgrass reduced the yield of a semidwarf (Lemont) cultivar more than that of a short-stature cultivar (Newbonnet) (Stauber et al. 1991). Season-long interference of 20 barnyardgrass plants m^{-2} reduce yield of the semidwarf cultivar 301 kg ha^{-1} and of the short-statured cultivar 257 kg ha^{-1}. The importance of proximity is illustrated by the fact that when barnyardgrass was 25 to 50 or 50 to 100 cm away from rice plants, there was no effect on rice yield. When a barnyardgrass plant group (4 plants in 140 cm^{2}) was within 25 cm of rice plants, rice yield was reduced up to 21 percent. Perera et al. (1992) studied barnyardgrass interference in rice in Sri Lanka and provided an explanation for the quantitative effects observed by others. They used rice grown in bags sunk in a rice paddy so that roots could intermingle with weed roots in one bag, or be separated from other roots. Thus, they were able to calculate the relative importance of shoot and root competition among three rice cultivars with different shoot morphology. Independent of shoot morphology, root was always more important than shoot competition. Perera et al. (1992) concluded that inhibition of rice root growth led to a reduced capacity to take up nutrients from soil and was the most important factor in the interference between barnyardgrass and rice.

Red rice (Diarra et al. 1985) and bearded sprangletop (Smith 1983) are more vigorous competitors than broadleaf signalgrass. A density of 180 broadleaf signalgrass m^{-2} reduced rice dry yield a maximum of 48 percent 95 days after rice emergence for the cultivar Bond. For Mars, a more competitive cultivar (Pantone and Baker 1991), the maximum yield reduction after season-long interference was only 21 percent (McGregor et al. 1988a). Each broadleaf signalgrass reduced rice yield by 18 kg ha^{-1} in 2 years of study in Arkansas (McGregor et al. 1988b). However, the results over 2 years were quite different. In one year, 50, 100, or 150 weeds m^{-2} reduced rice dry weight 6 weeks after emergence, but in the second year, only the highest density (150 weeds m^{-2}) reduced rice dry weight. McGregor et al. (1988b) suggested the difference between the years was related to the presence in the second year of barnyardgrass and red rice as additional competitors. The difference was not related to weather.

Yields of direct-seeded paddy rice at optimum stands of 215 to 270 plants m^{-2} were reduced 9, 18, 20, or 36 percent by bearded sprangletop densities of 11, 22, 54, or 108 plants m^{-2} (Smith 1983). There was a linear decrease of 21 kg ha^{-1} for each bearded sprangletop m^{-2}. Weed densities of 54 and 108 m^{-2} reduced whole milled rice kernel yield and the highest density (108 m^{-2}) reduced rice seed germination. In a second study, Carey et al. (1994) showed that durations of 63, 70, or 130 days after rice emergence led to yield losses of 11, 21, or 50 percent for the semidwarf cultivar Lemont, and of 11, 13, or 37 percent for the conventional cultivar Newbonnet, the better competitor because of its height. Competitive durations of 21 to 56 days after emergence did not affect yield of either cultivar.

With the same crop density as the previous study (Smith 1983), drill-seeded paddy rice yields were reduced 18 percent by 22 spreading dayflower m^{-2} competition for 125 to 140 days (full season) (Smith 1984). Competition durations up to 80 days did not affect rice yield.

When rice was planted in a greenhouse with 400 seeds m^{-2} and redstem was planted at 50 or 100 seeds m^{-2}, redstem was taller than rice 45 days after planting (Caton et al. 1997). By midseason (57 days after planting), redstem had no observable effects on any plant variable. By final harvest (110 to 118 days after planting), redstem at both densities reduced rice tiller density, panicle density, shoot biomass, and grain weight. The weed's effects were only observed (measurable) after it had grown above the crop canopy. Thus, the competitive effects were due to shading and light competition. Season-long competition reduced rice yield 31 and 39 percent at the two densities. Caton et al. (1997) classified redstem as the most competitive dicot weed they had studied.

Ransom and Oelke (1982) studied the interference of common water plantain in wild rice (*Zizania palustris*). Wild rice cultivars did not differ in their response to interference and no density of water plantain grown from seed with up to 82 m^{-2} reduced rice yield. However, water plantain established from rootstocks significantly reduced rice yield at densities as low as 3 plants m^{-2}. A density of 43 plants m^{-2} established from rootstocks reduced wild rice yield 91 percent. If the water plantain was removed by 7 weeks after planting, there was no effect on yield but interference for 9 weeks or longer reduced yield. The yield component most affected was panicles per plant.

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SORGHUM—*SORGHUM BICOLOR* (L.) MOENCH

Barnyardgrass, large crabgrass, and Texas panicum were evaluated in the field over 3 years to determine the effect of interference duration and weed density on sorghum yield (Smith et al. 1990). Linear regression predicted a yield loss of 3.6 percent for each week of weed interference regardless of year or the weed species. When grain sorghum was grown in 61-cm rows, it was not affected much by full-season interference from any of the three grass weeds. If rows were 91 cm, the effects of interference increased as weed density increased.

Cramer and Burnside (1982) showed that sorghum yield was reduced 4 to 29 percent with 11,000 to 45,200 common milkweed plants ha^{-1}. Common milkweed has a greater effect on sorghum than on corn or soybean yield. Hemp dogbane, another perennial weed, reduced sorghum yield 37 to 41 percent, a greater effect than was demonstrated in corn and soybeans (Schultz and Burnside 1979).

Weerakoon and Lovett (1986) also found that sorghum has limited competitive ability in work with lanceleaf sage in Australia. The weed was more competitive with a summer crop of sorghum than in winter wheat.

Redroot pigweed at densities of 0.5, 1, 2, 4, or 12 plants m^{-1} of row in a 25-cm band over the crop row was planted with sorghum or when sorghum was in the 3- to 4-leaf stage (Knezevic et al. 1997). The rectangular hyperbola model, based solely on weed density, was not well suited to estimate sorghum yield across locations. A quadratic polynomial equation, because it was able to account for time of weed emergence relative to crop growth stage, was more appropriate. Knezevic et al. (1997) determined that the time of weed emergence relative to sorghum's leaf growth stage was critical to estimating the weed's effect on final sorghum yield. Significant sorghum yield losses occurred only when redroot pigweed emerged before sorghum had 5.5 leaves.

In an experiment with implications relative to climate change, weed competition, and crop growth, Ziska (2001) showed in climate-controlled greenhouse studies that single-leaf photosynthetic rates declined for sorghum and common cocklebur in competition. Elevated CO_2 reduced the percentage decline of common cocklebur and increased it in sorghum 35 days after planting, relative to ambient CO_2 level. When both plants were grown in monoculture, elevated CO_2 significantly stimulated leaf photosynthetic rate, leaf area, and aboveground dry weight of common cocklebur more than that of sorghum. Therefore, Ziska (2001) concluded that as atmospheric CO_2 continues to increase, vegetative growth, competition, and potential yield of several economically important C_4 crops could be reduced when they compete with C_3 weeds such as common cocklebur.

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SOYBEAN—*GLYCINE MAX* (L.) MERR.

Soybeans, one of the world's major crops, are very important to U.S. agriculture. The soybean, native to China, is a crop that has grown to prominence in my lifetime. The United States grows more than 50 percent of the world's soybeans, about one-third of which are exported. In 1925 the total U.S. crop was about 5 million bushels. It grew rapidly to 90 million bushels in 1939, almost 300 million in 1950, 700 million in 1963, and more than a billion bushels in 1980. In 1994, U.S. farmers grew 2.5 billion bushels (United Nations 2000).

It is also a crop that demands careful weed control. Herbicides are used for weed management in most fields where soybeans are grown. Total use in 1997 was 84.5 million pounds or 13.3 percent of the U.S. herbicide market. Sixty-eight percent of the U.S. crop acreage was planted with genetically modified seed in 2001 (http://web.lexis-nexis.com/statuniv/att), all of which received at least one herbicide application.

The number of studies of weed-crop interference in soybeans exceeds those for any other crop by at least a factor of 2. Stoller et al. (1987) summarized the extant work on soybean-weed interference in a complete review that is a good starting point for those who wish to study soybean-weed interference.

The majority of studies reports the effect of known densities of a specific weed on the yield of soybeans. Nearly 30 different weeds have been studied but the most work has been done on common cocklebur, sicklepod, velvetleaf, and pitted morningglory. A few studies have emphasized other factors in the interference equation, and these will be reviewed before turning to those that deal with the effects of specific weeds.

Stoller et al. (1987) reviewed a few papers that dealt with differences in the competitive ability of soybean cultivars, including early work by Burnside (1979) who showed that Amsoy 71 was more competitive than Beeson with early- and late-emerging weeds. Van Acker et al. (1993) suggested, as others have, that development of cultivars with early branching and the use of narrower rows would be successful weed management techniques. Shaw et al. (1997) showed that one (Hutcheson) of three Group V soybean cultivars was consistently more competitive in Mississippi. Buehring et al. (2002), also in Mississippi, found that the same cultivar (Hutcheson) was the only one of three tested that contributed to sicklepod control and increased soybean yield but only in narrow (19 cm) as opposed to 38 cm rows. However, it was only under optimum growing conditions that narrow rows improved soybean yield. A glyphosate-resistant cultivar grown in medium population (455,735 plants ha^{-1}) and narrow (19 cm) rows with two glyphosate applications gave similar sicklepod control and a 24 percent greater yield than soybeans grown in 76 cm rows.

Shilling et al. (1995) demonstrated, in field studies, that sicklepod was tallest when grown with the tallest cultivars (Centennial or Biloxi) and shortest when grown with a dwarf isoline of the cultivar Tracy M. Depending on the cultivar, soybean competition reduced early-season sicklepod density 30 to 50 percent. Centennial, a tall cultivar from maturity Group VI, and Tracy M, a short cultivar from maturity Group VI, reduced early-season sicklepod biomass 30 percent. Sharkey and Biloxi (maturity Group VII) reduced sicklepod biomass 40 percent. Late in the season, sicklepod biomass reduction ranged from 18 percent for Tracy M to 55 percent for Biloxi and was directly related to cultivar height.

It is well accepted that soybean cultivars differ in their competitive ability. Exactly why one is more competitive than another remains unknown. According to Rose et al. (1984), the factors that determine a soybean cultivar's competitive ability (and one assumes the competitive ability of most crop plants) include: rate of emergence (compared to competing weeds), seedling vigor (growth rate), rapidity of canopy closure, and allelopathic attributes.

James et al. (1988) evaluated 12 soybean cultivars in competition with sicklepod and found no correlation of soybean cultivar maturity group or date of introduction as a commonly used cultivar with sicklepod interference. James et al. (1988) recommended development of cultivars with improved tolerance to sicklepod infestation. Monks and Oliver (1988) did not find any cultivar advantage in competition with several common southern weeds.

Bussan et al. (1997), on the other hand, found that the yield and ranking of 16 soybean cultivars varied with the weed with which they competed. Grass weeds reduced yield the most and small-seeded broadleaved weeds reduced yield the least. Some cultivars yielded well and still allowed a high weed biomass. In their work (Bussan et al. 1997), there was no relationship between weed competitiveness and soybean canopy area, height, and plant volume 30 to 45 days after planting. Jordan (1992) used and recommended path analysis to study differential interference between cultivars and weeds. He used a semidwarf determinate and an indeterminate cultivar. When the two cultivars grew with common cocklebur, there was an early period in interference, 40 to 62 days after planting, and a later period, 63 to 145 days after planting. Late interference measures were independent of early measures. The semidwarf cultivar had early interference effects on cocklebur that were 5.3 and 9.5 times greater than the other indeterminate cultivar, which had a greater interference effect in the late period.

It is also well accepted that narrow rows increase soybean's competitive ability, reduce weed competition, and may increase yield. Costa et al. (1980) found that 27 cm rows versus more conventional (in 1980) 76 cm rows, produced an average seed yield 21 percent higher over all years, populations, and cultivars. The review by Stoller et al. (1987) stated that when soybeans emerged before velvetleaf, competition was always reduced to soybean's benefit. Early planting of soybeans favored soybeans over velvetleaf primarily due to velvetleaf's photoperiod sensitivity. Stoller et al. (1987) citing Murphy and Gosset (1981) also claimed that planting date did not affect the period of weed-free maintenance required early in the season to prevent yield loss. Parker et al. (1981) found little yield response to changes in row width when soybeans were planted on time. Planting later than June lowered yield especially in wider rows. In contrast, Klingaman and Oliver (1994a) found that the percent soybean yield loss increased as planting date was delayed after early May. Soybean yield losses from 1.7 weeds m^{-1} of row were 10, 18, and 20 percent for early-May, mid-May, and early-June plantings. Yelverton and Coble (1991) also showed that as row spacing increased weed density increased and the density and effect of weeds coincided closely with the amount of light that penetrated to the soil surface.

Shaw et al. (1991) found that a series of herbicide treatments all controlled sicklepod better late in the growing season when soybeans were planted in 25 cm as opposed to 97 cm rows. Bendixen (1988) confirmed that better johnsongrass control was achieved with four of six herbicides when they were used in 25 cm as opposed to 76 cm rows. Walker et al. (1984) found no effect of row spacing on soybean height or seed size, but the number of pods per plant was higher in 80 than in 40 cm rows. Soybeans planted in 20 cm rows outyielded those 40 cm and 80 cm rows if sicklepod was not controlled. The work of Walker et al. (1984) was similar to that of McWhorter and Sciumbato (1988), who showed that the height and weight of sicklepod were less when soybeans were planted in 25 cm as opposed to 102 cm rows. Sicklepod interference for the entire season reduced soybean yield regardless of the soybean row spacing and the average soybean yield increased with 51 cm rows compared to 102 cm rows regardless of the length of sicklepod competition.

Jackson et al. (1985) found that the time of weed removal from soybeans was as important as the extent of removal. Interference up to 4 weeks after soybean emergence did not reduce soybean yield as long as moisture was adequate. With a drought or very high weed density, yield was reduced with 4 weeks of interference and there was no difference in the competitive effect of annual grasses and annual broadleaved weeds. Drought also played a role in work by Mortensen and Coble (1989). Well-watered and drought-stressed common cocklebur reduced soybean yield 29 and 12 percent, respectively. Drought-stressed common cocklebur interfered with soybeans over a shorter distance, and the magnitude of the effect at any distance was reduced. Drought (water stress) was more harmful to common cocklebur than to soybeans. Common cocklebur's canopy diameter, stem diameter, node number, and height were all reduced as they were in soybeans but the magnitude of the effect was greater in common cocklebur. Soybean's yield potential was reduced by drought stress and that reduction also reduced the effect of weed interference. For example, in well-watered soybeans, the canopy closed about 12 weeks after emergence. In drought-stressed soybeans, the canopy never closed and this reduced light interference between soybeans and common cocklebur. Mortensen and Coble (1989) concluded that reciprocal interference between soybeans and common cocklebur is not stable across soil-moisture conditions, and that was significant for modeling of the interactions.

Patterson et al. (1988) studied the effect of small (2.7 m^2) versus large (11 m^2) plots on results with row spacings of 15, 30, 45, and 90 cm when soybeans competed with sicklepod or common cocklebur. The biomass and seed yield of both weeds in small and large plots increased as soybean row spacing increased. Soybean biomass was not affected by row spacing if weeds were absent. Patterson et al. (1988) suggested that soybean biomass from small plots may be substituted for seed yield from large plots as a measure of sicklepod or common cocklebur interference, if both plots have the same row spacing.

A few reports have emphasized the effect of environment (e.g., water, light, and temperature) on interference in soybeans. No reports on nutrient competition in soybeans were found. Too often the differences between years in repeated studies are said to be due to environmental differences and, in fact, they are. But the explanation stops there and the underlying physiology or mechanism is not explored as it should be.

Scott and Geddes (1979) showed that, on a given day, the differences in water potential between soybeans and common cocklebur were small. They found greater diffusive resistance values in soybeans and the diffusive resistance was always greater when either species was in competition. Patterson (1986) showed that growth reduction related to water stress was greater for soybeans than for sicklepod. With adequate water, competition from sicklepod reduced leaf area duration (LAD) of soybeans while competition from soybeans reduced LAD and sicklepod's net assimilation rate (NAR). In competition studies, sicklepod reduced soybean dry weight more under drought than with adequate water. In greenhouse studies, Patterson and Flint (1983) found net photosynthetic rate, net assimilation rate, and water use efficiency on a whole plant or single leaf basis were greatest in the C_4 plant smooth pigweed than in soybeans, common cocklebur, jimsonweed, prickly sida, spurred anoda, or velvetleaf. Total dry matter production 29 days after planting under similar conditions was greatest in common cocklebur and least in jimsonweed. Munger et al. (1987) found that at leaf water potentials less than -2.5 MP_a, stomatal conductance, net photosynthetic rate, and transpiration rate were always greater in velvetleaf than in soybeans. Velvetleaf's photosynthetic rate increased linearly up to 1.5 cm s^{-1}, but there was no further increase above 1.5. As water stress became greater, stomatal conductance, photosynthetic rate, and transpiration of velvetleaf declined more rapidly than they did in soybeans (Munger et al. 1987). Thus, one might conclude that with poor moisture, soybeans should be a more-effective competitor with late-emerging velvetleaf.

In a study of the role of water in interference between common cocklebur, entireleaf morningglory, and soybeans, Mosier and Oliver (1995b) showed that interference from soybeans and entireleaf morningglory or from soybeans alone reduced the leaf area index and growth rate of common cocklebur more than entireleaf morningglory alone, and the effects were always greater without irrigation. Irrigated cocklebur produced 687 burs per plant whereas nonirrigated plants produced only 359. Irrigated entireleaf morningglory reduced cocklebur bur production 42 percent, but without irrigation bur production was reduced only 28 percent. A mixture of soybeans and common cocklebur reduced entireleaf morningglory seed production 84 to 90 percent.

Entireleaf morningglory is an important weed in soybeans in the southern United States, but it was not competitive in any treatment combination either year of this study (Mosier and Oliver 1995b) because of its low leaf area index and, therefore, its inability to compete effectively for light and water. In a separate report, Mosier and Oliver (1995a) showed that both weeds were effective competitors in soybean. The total leaf area index, the leaf area index within the soybean canopy, and soybean's growth rate and seed yield were decreased more by common cocklebur than by entireleaf morningglory. The essential role of water in interference is illustrated by data that showed that interference from entireleaf morningglory, common cocklebur, or both reduced soybean yield 21, 57, or 64 percent with irrigation and 12, 60, or 76 percent without irrigation. Soybeans extracted water from greater soil depths when it grew with weeds than when it grew in monoculture. Mosier and Oliver (1995a) concluded that soybean's high water use efficiency (WUE) without irrigation suggests that soybeans use water more efficiently when soil water is limiting than when it is abundant.

Geddes et al. (1979) explained some of the competitive effects of cocklebur for water. Roots of common cocklebur explored a greater volume of soil than did those of soybeans. The total amount of water used by a pure stand of soybeans and a mixed stand of soybeans and common cocklebur was greater than that used by a pure stand of common cocklebur. Twelve weeks after emergence, the percent reduction in dry matter and leaf area due to interspecific competition were greater in common cocklebur than soybeans and they were greater in a dry than in a wet year. There was no difference in water use efficiency (WUE) between the species in a wet year and for up to 10 weeks after emergence in a dry year (Geddes et al. 1979).

Cool early season temperature slowed growth of hemp sesbania but did not affect soybean growth and yield. There was negligible competition between soybeans and hemp sesbania densities of 3 or 6 plants m^{-2} (King and Purcell 1997). In one year, hemp sesbania grew above the soybean canopy and decreased soybean's light interception 29 to 68 percent and eventual yield 30 to 48 percent. King and Purcell (1997) concluded that competition for light was the primary cause of soybean yield loss from hemp sesbania competition. Both plants increased their dry weight when day/night temperatures were 30 and 20°C compared to 25 and 15°C. Hemp sesbania growth was more stimulated by warmer temperatures than soybean growth. Stoller and Myers (1989b) emphasized the importance of light competition in their study of interference between soybeans and four weeds. All five species adjusted to reduced irradiance by decreasing the rate of light-saturated photosynthesis, photosynthetic leaf respiration rates, root shoot ratios, and leaf density while increasing their leaf area ratio. As irradiance was reduced, plant support tissues (roots, stems, and petioles) and leaf ratios did not change for common lambsquarters or velvetleaf. All increased for soybeans, eastern black nightshade, and tumble pigweed. This indicates a superior adaptation of the latter two weeds for efficient light harvesting with reduced light. Of the five species studied, eastern black nightshade had the lowest respiration rate, the highest leaf area ratio, and the lowest support tissue to leaf area ratio and was optimally adapted for superior competition under reduced light (i.e., under the soybean canopy).

When the lower leaves of greenhouse-grown common cocklebur and velvetleaf were shaded to only 5 percent of full light for 12 days, there was an increase in upper (unshaded) leaf area beginning 3 (velvetleaf) and 6 (common cocklebur) days after shading began (Regnier and Harrison 1993). Total plant dry weight of velvetleaf 12 days after shading began was unaffected by shading, but it was reduced 10 percent in common cocklebur. Regnier and Harrison (1993) showed that common cocklebur has greater shade tolerance than velvetleaf and that both species have the ability to compensate for shading of lower leaves by altering upper shoot growth.

Murphy and Gosset (1981) found shading increased until 11 weeks after planting and then declined (there was more light at the soil surface) 14 weeks after planting because of soybean leaf loss. Light at the soil surface, 3 and 5 weeks after planting averaged 55 and 40 percent of available light, respectively. Murphy and Gosset (1981) found that less shading was required to prevent weed establishment than the 90 percent previously reported by Knake (1972) for control of giant foxtail.

Flint and Patterson (1983) studied temperature's effects on growth of soybeans, common cocklebur, and smooth pigweed. For all three species, height, dry weight, and leaf area increased significantly when temperatures ranged from 26/17, 29/20, to 32/23°C. The net assimilation rate of all three species peaked when temperatures were 29/20°C. Dry weight and leaf area were reduced by interference. Rising temperature reduced the effects of interference on growth of smooth pigweed (a C_4 plant) but not of the other species. Common cocklebur and soybeans were roughly equal competitors at all temperatures, and both were superior to smooth pigweed, which competed less well in any mixture at any temperature, but especially at low temperatures (Flint and Patterson 1983). Thus, Flint and Patterson (1983) concluded that common cocklebur is more likely than smooth pigweed to compete effectively in early-seeded soybeans, especially if they emerge together.

One report (Black et al. 1996) showed an effect of soybean infestation by *Rhizoctonia solani* in one year. Independent of infestation by common cocklebur, hemp sesbania, or johnsongrass, soybean yields decreased up to 18 percent. There was no significant interaction between *R. solani* infestation and weed density in either year of the study.

A few studies have combined the effects of herbicides with other aspects of competition. Adcock et al. (1990) reported that increasing herbicide rates resulted in higher soybean:weed fresh weight ratios and higher herbicide response coefficients. The specific ratio was affected by the weed and herbicide combination, which is to say that the effect was not constant over all herbicides or herbicide combinations. Mulugeta and Boerboom (2000) reported that weed control efficacy and crop yield were influenced more by glyphosate application time than by the rate applied. The critical time of weed removal, the time beyond which weed competition reduced soybean yield more than 3 percent compared to a weed-free check, was at the low rate (0.42 kg ha^{-1}) and soybean's V2 growth stage with 18 cm rows in reduced tillage plots and at V2 in 76 cm rows and with reduced tillage for both years of the study. The critical time of weed removal (with glyphosate in this study) for 18 cm and 76 cm rows in no-tillage soybeans was at the V4 stage of soybean growth. The study (Mulugeta and Boerboom 2000) showed that the critical time of weed removal varied between reduced- and no-tillage and between years. A single glyphosate application can prevent yield loss in narrow-row glyphosate-resistant soybeans when growing conditions are favorable, but application timing is more critical with wide rows because the critical period for weed removal occurs early in the growing season. A second herbicide application may be needed for later-emerging weeds in widely spaced soybeans. Krausz et al. (2001) demonstrated what is often assumed but rarely shown: herbicides almost always act as stressors on the crop while they relieve stress from weed competition. One labeled herbicide combination reduced soybean height 6 percent 21 days after application but did not increase time to maturity, population density, or yield.

Banks et al. (1986) demonstrated that soybean yields were similar in no-till and conventionally tilled plots if sicklepod was absent. If sicklepod was present, soybean yields were higher in no-till plots and increasing sicklepod density caused lower soil water content in tilled and no-till plots.

Norsworthy and Oliver (2002a) demonstrated that glyphosate increased soil moisture availability for dryland soybeans and as soybean population increased from 247,000 to 729,000 plants ha^{-1} pitted morningglory and hemp sesbania control increased from 60 to 91 percent. Three sequential glyphosate applications reduced pitted morningglory seed production from 247,000 ha^{-1} to 9,000 and eliminated hemp sesbania seed production. The work (Norsworthy and Oliver 2002a) illustrates the importance of consideration of crop planting density and soil moisture in any management plan.

If the number of papers dealing with a weed is a good indicator of the weed's importance, then sicklepod and common cocklebur have to be the most important weeds in soybeans in the last 20 or so years.

Soybeans that were kept free of sicklepod for 4 weeks after emergence produced yields equal to season-long control over 3 years (Walker et al. 1984; Rushing and Oliver 1998). In contrast, McWhorter and Sciumbato (1988) found that sicklepod competition for 4 weeks decreased soybean yield in 2 of 3 years. A reason for sicklepod's competitiveness in soybeans is that whereas soybeans grew only slightly between 35 and 84 days after emergence, sicklepod continued to grow until it was 30 to 45 cm taller than soybeans (Bozsa et al. 1989). This is explained at least partially by the fact that sicklepod's growth responded to distance from the soybean row and time of emergence relative to the crop (Smith and Jordan 1993). In a separate greenhouse study, Bozsa and Oliver (1990) showed that soybeans were 1.5 to 2 times taller than common cocklebur and were more competitive aboveground during the first few weeks of growth. Common cocklebur had 20 to 50 percent more small roots, which have a greater uptake of water and nutrients per unit of surface area than larger roots, and it was more competitive below ground during early growth (Bozsa and Oliver 1990). Thus, by 4 weeks after emergence, common cocklebur's greater capacity for root competition significantly reduced soybean's growth.

These observations are at least partially explained by the fact that common cocklebur has a longer vegetative growth period than soybeans and was twice as tall at maturity (Bozsa and Oliver 1993). Shoot and root dry weight and seed yield of soybeans were reduced by whole-plant (shoot and root) interference from common cocklebur, but common cocklebur growth was not affected by soybean's presence. Only common cocklebur shoot interference reduces soybean seed production 48 percent, which was equal to that caused by whole-plant interference (Bozsa and Oliver 1993). Regnier et al. (1989) had shown previously that decreases in soybean yield were due to shoot interference. Yield always decreased more when root interference also occurred, but the shoot effects and competition for light dominated as a cause of common cocklebur's effects on soybeans.

Regnier and Stoller (1989) demonstrated that common cocklebur had more leaves within the soybean canopy than jimsonweed or velvetleaf. By the end of the growing season, common cocklebur's leaf area was evenly distributed above and below the soybean canopy while nearly all the leaf area of the other two weeds was above the soybean canopy. Regnier and Stoller (1989) proposed that common cocklebur had greater shade tolerance than the other two weeds. Growth from the lower axillary buds of jimsonweed and velvetleaf was strongly inhibited by soybeans but was not for common cocklebur. The latter had more axillary growth along lower stems than soybeans, which makes it a more aggressive competitor even though common cocklebur and soybeans were similar in height and seemed to compete for the same aboveground niche. Lower branching and shade tolerance make common cocklebur a more effective competitor (Regnier and Stoller 1989).

Sicklepod's height, the number of main stem nodes, the number of branches, and its shoot dry weight all decreased 12 weeks after emergence when the plants were close to the soybean row (Bozsa et al. 1989). Plants that emerged 7 days after soybeans were shorter. Nearly all sicklepod plants were taller than soybeans, but if they were close to the soybean row, their dry weight was reduced up to 60 percent. Similarly, sicklepods that were 10 to 30 cm apart in the soybean row reduced soybean yield 25 to 35 percent more than when they were 90 cm apart (Bozsa et al. 1989).

However, these results contrast with those of Berti and Sattin (1996) who found that the position of common cocklebur or barnyardgrass relative to the soybean row was of little importance relative to weed density as a determinant of yield loss. Relative cover was the most important factor. Both common cocklebur and barnyardgrass can grow taller than soybeans. Berti and Sattin (1996) concluded that for weeds that grow taller than the crop, the main competitive factor is shading caused by the taller plant.

Interference of one common cocklebur in 1.8, 0.9, or 0.3 m of row for 8 weeks reduced soybean yield 7, 14, or 30 percent and full-season interference reduced yield 16, 33, or 65 percent (Rushing and Oliver 1998). If one common cocklebur 3 m^{-1} of crop row interfered for the whole season, soybean yield was reduced 3 to 12 percent (Bloomberg et al. 1982). Soybean yield, total dry weight, and pods per plant all increased as the length of time between soybeans and common cocklebur emergence increased. If common cocklebur emerged 4 weeks after soybeans, yield was reduced 7 percent. When common cocklebur was removed 6 weeks after soybean emergence, soybean yield was reduced less than 10 percent (Bloomberg et al. 1982).

Monks and Oliver (1988) studied the interaction between two soybean cultivars and common cocklebur, johnsongrass, Palmer amaranth, sicklepod, and tall morningglory. There was no reduction in soybean biomass for 6 weeks after emergence. Only common cocklebur and Palmer amaranth reduced soybean biomass during the growing season. The other three weeds grew more slowly and had no measurable effect on soybean biomass. Soybean, however, was an effective competitor because it reduced the biomass of all weeds 90 to 97 percent. The biomass of both soybean cultivars was reduced when they grew within 50 cm of Palmer amaranth. Soybean seed yield as distinct from biomass was reduced when the soybean grew within 25 cm of common cocklebur and Palmer amaranth or within 12.5 cm of the less-competitive tall morningglory (Monks and Oliver 1988). Study of competition of Palmer amaranth alone showed soybean yield was highly correlated with Palmer amaranth biomass 8 weeks after soybean emergence and to the weed's density (Klingaman and Oliver 1994b). Palmer amaranth densities of 0.33, 0.66, 1, 2, 3.33, and 10 plants m^{-1} of row reduced soybean yield 17, 27, 32, 48, 64, and 68 percent, respectively. Soybean yield reduction was approximately linear to about 2 Palmer amaranth m^{-1} of row suggesting that intraspecific interference between adjacent weeds began at relatively low weed densities.

The interaction between insect defoliation and weed interference was studied by Grymes et al. (1999). Interference was with common cocklebur, hemp sesbania, or johnsongrass at 2.5, 0.5, or 2 plants m^{-2}, respectively. Defoliation to simulate insect action, at R_2 (full bloom) and R_5 (beginning seed development), was done by removing 1 or 2 leaflets from each soybean trifoliate leaf, which approximated 33 or 66 percent defoliation. The weeds were not affected by this. Soybean height 3 weeks after defoliation at R_5 was not influenced by weed interference, soybean defoliation level, or defoliation stage. Averaged across defoliation levels and growth stages, johnsongrass, common cocklebur, and hemp sesbania reduced soybean yield 30 to 35, 15, and 14 percent, respectively. As soybean defoliation level increased, there was a linear decrease in soybean yield. For all three weeds and both defoliation stages, 33 and 66 percent defoliation reduced soybean yield 6 and 20 percent in one year and 12 and 33 percent in the second year. Defoliation at R_5 reduced yield 10 percent more than defoliation at R_2 in one year (Grymes et al. 1999).

Sims and Oliver (1990) compared interference from johnsongrass and sicklepod with and without irrigation. Johnsongrass reduced soybean growth early in the season, whereas sicklepod was the more effective competitor and was competitive all season with the effect being greatest during soybean's reproductive stage. Soybean seed yield was reduced 31 percent by full-season interference from sicklepod, 14 percent by johnsongrass, and the combination reduced yield 36 percent. Johnsongrass's dry matter and seed yield were reduced more than that of sicklepod by soybean interference. Soybean plus sicklepod reduced johnsongrass seed production 73 to 95 percent. Sicklepod produced 6 to 31 percent fewer seeds when it grew with johnsongrass and 47 to 75 percent fewer seeds when it grew with soybeans or soybeans and johnsongrass (Sims and Oliver 1990).

McWhorter and Anderson (1993) demonstrated that johnsongrass was slightly more competitive than hemp sesbania with an early-maturing soybean cultivar. Johnsongrass reduced soybean yield 32, 35, and 36 percent over 3 years when soybeans were harvested 1, 2, or 3 weeks after maturity. A late-maturing cultivar's yield was reduced 27, 29, or 39 percent when it was harvested 1, 2, or 3 weeks after maturity. The seed grade of both cultivars improved with delayed harvest, but that advantage was offset when johnsongrass was present. Hemp sesbania reduced soybean yield of the early maturing cultivar 23 percent when soybean was harvested 1 week after maturity and 26 percent when it was harvested on the other two dates. The late-maturing cultivar's yield was reduced 16, 22, or 28 percent when it was harvested 1, 2, or 3 weeks after maturity. Late harvest tended to decrease the value of the soybean yield because of increased foreign material, increased moisture, and damaged kernels (McWhorter and Anderson 1993).

While johnsongrass has not received as much research attention as common cocklebur, it has been and remains an important weed in soybeans. Vitta and Satorre (1999) showed why johnsongrass is usually more competitive early in the growing season by evaluating canopy characteristics. They found a significant linear relationship between the relative leaf area of johnsongrass and its contribution to the total biomass of the mixture of soybeans and johnsongrass, measured early in the growing season. In monoculture, crop and weed canopies developed simultaneously. They began to compete at a thermal time of 250 to 350°C days after sowing, which corresponded with the beginning of the active net growth period of johnsongrass biomass. Vitta and Satorre (1999) claimed that the relationship between soybean yield and the weed's leaf area was always linear but that the slope varied with crop sowing date. Their results suggest that measurement of johnsongrass leaf area may be a simple, effective way of predicting soybean yield loss.

Johnsongrass was a less-effective competitor than smooth pigweed because the latter captured 1.8 to 2.5 times more light and produced more dry matter at all densities of multispecies populations of smooth pigweed, johnsongrass, and soybeans (Toler et al. 1996). Nevertheless, johnsongrass presence is not to be neglected. The number of johnsongrass culms at harvest was more correlated with soybean yield loss than the number of plants per unit area 4 to 6 weeks after planting (Williams and Hayes 1984). Full-season johnsongrass competition reduced soybean yield 59 to 88 percent, and soybeans could not tolerate what Williams and Hayes (1984) called a heavy infestation for more than 5 weeks after planting without a yield loss.

Interference of velvetleaf with soybeans has also been studied frequently. Higgins et al. (1984) found that monocultural velvetleaf consistently exceeded velvetleaf grown with soybeans in leaf area, nodes with fully developed leaves, canopy width, branches, and number of capsules as early as 3 weeks after emergence. Velvetleaf without soybean competition developed more than nine times the dry matter of velvetleaf grown with soybean. When soybeans were partially defoliated to simulate damage from the green cloverworm (*Plathypena scabra* F.), the leaf area, number of leaves, and number of main stem nodes of velvetleaf decreased. Because the green cloverworm attacks soybeans late in the growing season, velvetleaf will obtain only a slight advantage and will have done its damage before the green cloverworm appears. In spite of the fact that soybeans compete well with velvetleaf, the latter is regarded as a major problem in most U.S. soybean-producing areas.

Velvetleaf is taller than soybeans for most of the growing season and has more branches, especially near the top of the canopy (Akey et al. 1990). Velvetleaf therefore has greater light interception ability than soybean, especially early and late on any day. The leaf canopies of velvetleaf and soybeans had similar total light interception on most sample days, but velvetleaf had higher light utilization efficiency (Akey et al. 1991). That is, velvetleaf converted more of the intercepted light energy to dry matter, especially with its emergent canopy in the middle and late parts of the growing season. To further explain velvetleaf's competitive ability, Akey et al. (1991) studied the relative competitive ability of velvetleaf and soybeans. The relative aboveground dry weight of soybeans in mixtures was higher than expected from monocultural values early in the season and lower than expected late in the season. Velvetleaf, on the other hand, had higher than expected values late in the season. Velvetleaf depressed seed yield of soybeans in all mixtures, and the relative seed yield of velvetleaf was greater in all mixtures than in monoculture. Soybean's relative growth rate (RGR), leaf area ratio (LAR), and net assimilation rate (NAR) did not differ significantly among mixtures and decreased over the season. Velvetleaf did not show any significant differences in RGR, LAR, or NAR over the growing season. Velvetleaf's RGR and LAR were highest early in the growing season and progressively declined. Velvetleaf is a good competitor, in part because it has a higher NAR and RGR early in the season even though competition is not significant then. During that time, velvetleaf gained resources at the expense of soybeans that enabled it to compete effectively in midseason and late season.

Begonia et al. (1991) postulated that soybean yield was inversely related to velvetleaf's height, which seems counterintuitive. This was related to velvetleaf's increasing interception of light with increasing height. Reductions in soybean yield and yield components was greater if velvetleaf was maintained at various heights for only 3 weeks rather than 6 weeks following soybean emergence. This was attributed to a longer duration of light competition by velvetleaf. Even when the weed's height was kept 25 percent below the soybean canopy for 4 weeks, soybean yield and pod and branch numbers decreased when velvetleaf was allowed to regrow for the rest of the season, but this was not true if the weed was removed after the first 4 weeks. Soybean yield was not affected if velvetleaf plants that were 25 percent shorter than soybeans were removed or allowed to regrow after an initial 6 to 8 weeks of clipping (Begonia et al. 1991).

Dekker and Meggitt (1983a) showed that the effects of low populations (2.4 to 4.7 plants m^{-2}) of velvetleaf were greatest on soybean yield and less on flowering node and dry weight production. Velvetleaf exerted its effect by its presence and not by changes in its density. Further work (Dekker and Meggitt 1983b) showed that velvetleaf had the adaptive ability of differential mortality at different population densities and soybean did not. The result is that the velvetleaf plants that remain grow large and are more competitive as the population declines due to death. Soybean plants do not die and release resources for the survivors; they become smaller and less competitive.

Velvetleaf's effects can be mitigated by adjusting soybean's planting date (Oliver 1979). Velvetleaf was planted at one plant per 61 or 30 cm of row with competition ranging from 4 weeks to full season. Velvetleaf that emerged with soybeans in mid-May was twice as competitive as velvetleaf that emerged with soybeans planted in late June. One velvetleaf per 30 cm of soybean row competing for the full season reduced soybean yield 27 percent for the early (mid-May) planting and only 14 percent for the late-June planting. Oliver (1979) attributed the difference to the short-day photoperiodic response of velvetleaf. Early growth stages of soybeans are competitive with velvetleaf. Ten weeks after emergence, velvetleaf competition reduced soybean growth and development. Oliver (1979) postulated that velvetleaf may not be an important problem in Arkansas (southern United States) because of its photoperiodic response and late-season competitiveness. However, when soybeans are planted early to gain a yield advantage, velvetleaf has proven to be an important weed. In slight contrast to several papers reported above, Munger et al. (1987) suggested that interspecific competition for soil water played an important role in the interactions between velvetleaf and soybeans but that the competitive interactions were due to resource limitations other than water. They showed that monocultural velvetleaf with 5 plants m^{-2} extracted water up to 1 m deep, whereas monocultural soybeans (32.5 plants m^{-2}) extracted water up to 1.5 m or more. Interspecific competition between soybeans and velvetleaf resulted in a 40 percent reduction in soybean seed yield and a 50 percent reduction in velvetleaf seed yield. Interspecific competition had little to no effect on soybean morphology before 8 weeks after planting (Munger et al. 1987).

Once acquired in a field, velvetleaf continues to be important because only 6.8 +- 0.5 percent of the soil seedbank emerges each year (Lindquist et al. 1995). In the absence of crop competition, a velvetleaf plant could produce 125 to 227 seeds. Velvetleaf that emerged early produced the largest number of seeds, but the seed production declined up to 82 percent with crop competition.

Other Weeds

If the number of papers in print is an appropriate criterion, then the preceding weeds (common cocklebur, velvetleaf, and johnsongrass) are the most important weeds in soybeans. The first edition of this book (Zimdahl 1980) noted that common cocklebur was the most important and detrimental weed in soybeans. Johnsongrass and velvetleaf studies were also reported in the first edition. The first edition reported on studies of 15 different weeds; more (28) are included here. Some were reported in a single manuscript and others were studied in three or four separate reports. There is no particular pattern of the research or the results, except that all weeds reduce soybean yield. These studies are summarized below in alphabetical order by the weed's common name.

Burcucumber—Sicyos angulatus

Burcucumber emergence was greatest in late May through mid-June and had almost ceased by early July (midsummer) regardless of the tillage system (no-till and reduced tillage) or the row spacing (38 and 76 cm) (Esbenshade et al. 2001). Preplant tillage increased burcucumber emergence 70 to 110 percent compared to no-tillage, but row spacing had no effect on emergence or biomass production.

Common Lambsquarter—Chenopodium album

With 32 common lambsquarters 10 m^{-1}, 10 weeks of interference were required to cause a 20 percent yield reduction when weeds were removed by hand. If a postemergence herbicide was used to kill the weed, a 20 percent yield reduction occurred if it was not applied prior to 5 weeks after emergence (Crook and Renner 1990). The authors attributed the difference to the fact that hand removal gave complete control whereas the herbicide did not. Work in Ohio (Harrison 1990) showed that common lambsquarters was a more vigorous competitor. When 5 percent yield loss was used as the threshold, regression analysis predicted a threshold density of 2 weeds m^{-1} 5 weeks after emergence and 1 weed m^{-1} 7 weeks after emergence. Each kg ha^{-1} of weed biomass resulted in an average soybean yield loss of 0.26 kg ha^{-1} (Harrison 1990).

Common Milkweed—Asclepias syriaca

The average yield reduction of soybeans from 11,000 to 45,000 common milkweed plants ha^{-1} was 12 to 19 percent, slightly higher than for corn (Cramer and Burnside 1982).

Common Ragweed—Ambrosia artemisiifolia

The damage threshold for full-season, in-row interference was 4 common ragweed 10 m^{-1} of row and they caused an 8 percent yield loss (Coble et al. 1981). Soybean yield was not reduced by a natural population of common ragweed if the period of interference was 6 weeks or less after emergence. Soybeans kept weed free for 2 weeks or longer after emergence in a dry year produced normal yields but 4 weeks of weed-free maintenance was required when water was adequate early in the growing season. Eight weeks after emergence, common ragweed averaged 25 cm taller than soybeans, and the weed intercepted 24 percent of the incident radiation. Coble et al. (1981) used these data to determine the economic threshold (when to control) for common ragweed in soybeans.

Common Sunflower—Helianthus annuus

Soybeans required 4 to 6 weeks free of common sunflower to obtain maximum yield (Irons and Burnside 1982). In Kansas, soybean yield reductions ranged from 17 to 19 percent with 0.3 common sunflowers m^{-2} and 95 to 97 percent with 4 to 6 plants m^{-2} (Geier et al. 1996). Interference was primarily for light. Evidence was provided to show that

0.3 common sunflower m^{-2} reduced photosynthetically active radiation (PAR) at the plant canopy by 300 to 390 μmol m^{-2}s^{-1} or 18 to 24 percent. The ability of common sunflower to intercept PAR above the soybean canopy is, in the author's (Geier et al. 1996) view, an important component of its interference capability in soybeans. These findings agree with those of Allen et al. (2000). They found that soybean yields tended to decrease as the weed-free period occurred later in the growing season and soybeans had a larger canopy. Early-season weed-free periods (2 to 4 and 4 to 6 weeks after planting) allowed common sunflower to become established before soybeans had a well-developed canopy. Yield reductions were 15 to 80 percent. If the weed-free period occurred 6 to 8 or 8 to 10 weeks after planting, the effect on yield was minimal because the common sunflowers survived only a few weeks after establishment and they did not produce seed.

Cutleaf Groundcherry—**Physalis angulata**

Cutleaf groundcherry was identified as an inconsequential and easy to control weed in work by Bell and Oliver (1979). At densities as high as 60 weeds m^{-1} of row, in the row, there were no significant reductions in soybean leaf area index, height, dry weight, growth rate, or seed yield.

Eastern Black Nightshade—**Solanum ptycanthum**

One study emphasizes the effect of soybeans on eastern black nightshade seed production (Quakenbush and Andersen 1984). Without soybean interference, one eastern black nightshade planted in May produced 7,000 berries and 800,000 seeds. If a plant was planted alone in mid-July, it produced up to 100 berries and if planted in August it produced no berries. However, when eastern black nightshade was planted with soybeans in May, a plant produced less than 85 berries. If planted in June, berry production dropped to none to 3 and a July planting produced no berries. If soybeans were defoliated in July to simulate hail damage, then an eastern black nightshade plant that had been planted in May produced up to 1,600 berries, and those planted in July produced up to 58 berries. Quakenbush and Andersen (1984) concluded that one need only control eastern black nightshade through June to prevent berry (and seed) production if there is no subsequent hail damage.

A second study emphasized the effects of shading on interference (Stoller and Myers 1989a). Shade clearly suppressed eastern black nightshade growth (table 5.2). Eastern black nightshade plants that emerged with soybeans and were between 75-cm rows produced 43 g of shoots and 264 berries. Those that grew in the row and emerged 6 weeks after soybeans produced only 1 g of shoot and 16 berries. Further illustration of the importance of light is shown by their finding that shoot growth and berry production increased from 80 to 200 percent in 2 weeks between the initiation of soybean leaf abscission and maturity.

Table 5.2. Effect of Shading on Shoot and Seed Production by Eastern Black Nightshade

Time (weeks)	Light condition	Shoot production (g)	Berry production (No.)
20	full sun	243	5957
11	full sun	38	576
20	94% shade	3	23
11	94% shade	1	1

Source: Stoller and Myers (1989a).

Florida Beggarweed—**Desmodium tortuosum**

The influence of water stress on interference is well illustrated by the work of Griffen et al. (1989). Soybean leaf area and aboveground biomass were greater than that of Florida beggarweed under optimum water conditions in a greenhouse study but were equal to or less than the weeds under water stress. Soybeans were more competitive with adequate soil moisture but less competitive than Florida beggarweed under water stress. In short, water stress favored the weed over soybeans.

Giant Ragweed—**Ambrosia trifida**

The injury threshold for giant ragweed was less than 2 per 9 m^{-1} of row. Full-season interference at this density reduced soybean yield 46 to 50 percent, and the critical duration was 2 to 4 weeks in one year and 4 to 6 in a second year (Baysinger and Sims 1991). Webster et al. (1994) attributed most of giant ragweed's competitive effect to its ability to initiate and maintain axillary leaves and branches within the soybean canopy. They determined that the economic threshold was 0.03 to 0.08 giant ragweed plants m^{-2}.

Green Foxtail and Fall Panicum—**Setaria viridis** *and* **Panicum dichotomiflorum**

Soybeans that were free of a natural mixed stand of giant green foxtail and fall panicum for 2 weeks after soybean emergence yielded the same as plots that were weed free for the growing season (Harris and Ritter 1987). If the grasses grew with soybeans for 8 weeks, soybean yield was reduced because of a decrease in pods per plant. With a drought, yield reduction did not occur until the weeds had grown with soybeans for 12 to 16 weeks after emergence. Hand-established weed densities of 1 grass plant per 7.5 cm^{-1} of soybean row reduced yield 0 to 11 percent. Natural grass infestations of unspecified density present for the season reduced soybean yield 21 to 41 percent (Harris and Ritter 1987).

Hemp Dogbane—Apocynum cannabinum

Hemp dogbane densities of 28 to 40 shoots m^{-2} reduced predicted soybean yield 58 to 75 percent or 62 to 94 percent with the rectangular hyperbolic or linear regression models, respectively (Webster et al. 2000). The study was done over 3 site years and differences between sites were attributed to rainfall and temperature. There was delayed soybean canopy closure and higher yield loss when soil moisture remained high and temperatures were relatively cool. When the two predictive models were applied to field populations of hemp dogbane, between 19 and 36 percent and 20 and 29 percent of soybean yield loss could be expected from within hemp dogbane patches for the rectangular hyperbolic and linear regression models, respectively. Webster et al. (2000) concluded that while the rectangular hyperbolic model appeared to describe the relationship between soybean yield loss and hemp dogbane density accurately, the relationship was dominated by the model's initial linear phase and may be inappropriate. Schultz and Burnside (1979) observed high infestations of hemp dogbane in soybeans in Nebraska and yield losses from 28 to 41 percent from season-long infestation.

Hemp Sesbania—Sesbania exaltata

Norsworthy and Oliver (2002b) studied interference of hemp sesbania in drill-seeded, glyphosate-resistant soybeans in an experiment nearly identical to their work on pitted morningglory (Norsworthy and Oliver 2002c). Soybean densities were 217,000, 371,000, and 521,000 plants ha^{-1}. Hemp sesbania densities were 0, 4, 10, or 16 plants m^{-2} with and without glyphosate applied at the V4 and V6 soybean growth stage. Soybean seed yield was reduced 43 percent by full-season interference of 16 untreated hemp sesbania m^{-2}, which was less than the effect of pitted morningglory (62 percent) at the same density. Glyphosate-treated hemp sesbania did not affect soybean yield. Illustrative of the importance of crop population shown by so many studies, when yield loss was averaged over all soybean populations, it was reduced from 44 to 22 percent by more than doubling soybean population from 217,000 to 521,000 plants ha^{-1}.

Itchgrass—Rottboellia cochinchinensis

Lejeune et al. (1994) used area of influence procedures to evaluate interference of itchgrass and soybeans over 2 years. Soybean seed weight within 20 cm of itchgrass was reduced 15 to 21 percent. In one year, seed weight reduction of 9 percent was detected 40 to 60 cm from an itchgrass plant. Weight reductions were attributed to decreases in seed number of 12 to 22 percent within 40 cm of a weed compared to a control area. Itchgrass interference increased soybean height within 40 cm of a weed, but soybean canopy width was not affected. Soybean interference did not affect height of itchgrass plants but reduced stem numbers 89 to 94 percent compared to weeds growing alone. This finding affirms that one of the best ways to reduce weed infestation is to plant a crop. When itchgrass interference was 8 weeks or less, itchgrass fresh and dry weight were similar when the weed grew alone or in the soybean row. Both were reduced 80 percent when itchgrass competed with soybeans for 10 weeks (Lejeune et al. 1994).

Ivyleaf Morningglory—Ipomoea hederacea

Ivyleaf morningglory was grown at 1 plant per 7.5, 15, 30, 60, or 90 cm of row in 2 years. Each density competed for 22 to 46 days after planting or for the full season in one year and for 29 to 60 days after planting or the full season in the second year (Cordes and Bauman 1984). The best indicators of the competitive effect were changes in leaf area index, dry weight, and yield. Ivyleaf morningglory similar to pitted morningglory exerted its greatest competitive effect during soybean's reproductive stages. The primary competition was apparently for nutrients because photosynthetic irradiance measurements and soil water measurements showed that ivyleaf morningglory did not compete for light or water. All densities of the weed could compete for 46 days after emergence in one year and 90 days in the second year without reducing soybean yield, but full-season competition from 1 weed m^{-1} of row reduced yield 13 percent in one year and 36 percent in a second year (table 5.3). The weed's effect was

Table 5.3. Effect of Several Weeds on Soybean Yield

Weed species	Density	Yield reduction	Source
Common cocklebur	One 1.8 m^{-1} row	7%	Rushing and Oliver 1998
	One 0.9 m^{-1} row	14%	
	One 0.3 m^{-1} row	30%	
Common cocklebur	One 3 m^{-1} row full-season	3 to 12%	Bloomberg et al. 1982
Common sunflower	Full season	47 to 72%	Allen et al. 2000
With irrigation			Mosier and Oliver 1995a
Entire leaf morningglory		21%	
Common cocklebur		57%	
Both		64%	
Without irrigation			
Entire leaf morningglory			12%
Common cocklebur		60%	
Both		76%	
Hemp dogbane	Full season	28 to 41%	Schultz and Burnside 1979
Hemp sesbania	16 m^{-2} -full season	43%	Norsworthy and Oliver 2002b
Jerusalem artichoke	Full season		
	1 tuber m^{-1} of row	31%	Wyse et al. 1986
	2 tubers m^{-1}	59%	
	4 tubers m^{-1}	71%	
	4 tubers m^{-1} for		
	4 weeks after planting	9%	Wyse et al. 1986
	6 weeks after planting	10%	
	8 weeks after planting	38%	
	20 weeks after planting	82%	
Jimsonweed	0.3 m^{-1} of row, full-season	8%	Kirkpatrick et al. 1983
	1.6 m^{-1} of row,		
	2 weeks	7%	
	4 weeks	14%	
	full season	41%	
Johnsongrass	Full season	59 to 88%	Williams and Hayes 1984
Johnsongrass with early maturing cultivar	1 week after soybean with early maturity	32%	McWhorter and Anderson 1993
	2 weeks after soybean maturity	35%	
	3 weeks after soybean maturity	36%	
Johnsongrass with a late maturing cultivar	1 week after maturity	27%	McWhorter and Anderson 1993
	2 weeks after maturity	29%	
	3 weeks after maturity	29%	
Ivyleaf morningglory	1 plant 15 cm of row full season	13 to 36%	Cordes et al. 1984
Pitted morningglory	1 plant 10 m^{-2} full season	47%	Norsworthy and Oliver 2002c
	16 m^{-2}—full season	62%	
	62 m^{-2}—full season	81%	
Quackgrass	Natural stand for		Young et al. 1982
	6 weeks	11%	
	8 weeks	23%	
	Full season	33%	
Sicklepod	Full season	31%	Sims and Oliver 1990
Johnsongrass	Full season	14%	
Sicklepod + johnsongrass	Full season	36%	
Velvetleaf			
Mid-May planting	One 30 cm^{-1} of row full season	27%	Oliver 1979
Late June planting	One 30 cm^{-1} of row full season	14%	Oliver 1979

greater when warm early-season temperatures favored rapid weed growth.

Jerusalem Artichoke—**Helianthus tuberosus**

One paper reports that a density of 1, 2, or 4 tubers m^{-1} of row reduces soybean yield 31, 59, or 71 percent (Wyse et al. 1986). Soybean's leaf area and relative growth rate were reduced by 2 and 4 tubers m^{-1} of row and the net assimilation rate was reduced by 4 tubers m^{-1} of row. With 4 tubers m^{-1} of row for 4, 6, 8, or 20 weeks (full season), soybean yield decreased 9, 10, 38, or 82 percent, respectively. Wyse et al. (1986) concluded that Jerusalem artichoke should be controlled within 6 weeks after planting.

Jimsonweed—**Datura stramonium**

As the duration of jimsonweed competition increased, soybean yields decreased, and as jimsonweed emergence was delayed after soybean emergence, soybean yield increased (Kirkpatrick et al. 1983). As few as 0.3 jimsonweeds m^{-1} of row reduced yield 8 percent and 1.6 weeds m^{-1} reduced it 24 percent. Full-season competition from 1.6 weeds m^{-1} reduced yield up to 41 percent. Jimsonweed growing in the soybean row had little influence on vegetative characteristics of soybean during the first 12 weeks of growth (Henry and Bauman 1991). The influence of a single jimsonweed was not evident until 10 weeks after planting and it then extended 20 cm in the row. By harvest, the influence of a single weed extended 50 cm in the row and soybean yield within the area of influence (1.2 m of row) was reduced 12 percent. Jimsonweed that was 60 cm apart in the row reduced yield 18 percent. Henry and Bauman (1991) reported that while jimsonweed affected soybean growth, the reverse was even more evident. Soybean interference with jimsonweed increased steadily during the season and reduced the size of jimsonweed plants in the row 80 to 93 percent compared to free-standing plants. In contrast, Oliver et al. (1991) demonstrated that jimsonweed was not particularly competitive in soybeans but was very competitive in cotton. Its influence was reduced by lack of rain and the fact that soybeans are more competitive than cotton. Soybean yield was reduced 16 percent by 64 jimsonweeds per 12 m^{-1} of row, whereas cotton's was reduced 56 percent by the same density. Interspecific interference from soybeans caused a third more reduction in fresh weight and capsules per plant of jimsonweed than cotton did (Oliver et al. 1991).

Perennial Sowthistle—**Sonchus arvensis**

A field experiment determined that an average of 78 perennial sowthistle shoots m^{-2} in 71-cm soybean rows reduced soybean yield by 49 percent (Zollinger and Kells 1993). In a second, drier year, 96 shoots m^{-2} reduced soybean yield 87 percent. One cultivation 5 weeks after planting increased crop yield, improved seed quality, and decreased perennial sowthistle density.

Pitted Morningglory—**Ipomoea lacunosa**

Murdock et al. (1986) used three soybean cultivars seeded in 30, 61, or 91 cm rows to achieve a uniform plant population of 323,000 plants ha^{-1}. The narrower row spacings tended to shade the row earlier, and some cultivars developed a shading canopy faster. In one year, the maximum soybean yield was obtained with 2 weed-free weeks for 30 and 61 cm rows but no competition was tolerated by soybeans in 91 cm rows. In a second year, 2 weed-free weeks were tolerated by all row spacings and all three cultivars. Soybeans were grown in conventional 1 m rows and narrow (20 cm) rows with a soybean population of 23 plants m^{-2} in 1 m rows and 50 plants m^{-2} in 20 cm rows (Howe and Oliver 1987). Pitted morningglory density was 3.3, 10, 20, or 40 plants m^{-2}. Pitted morningglory interfered with soybean growth earlier in conventional rows due to the rapid increase in its leaf area index and biomass between 4 and 8 weeks after planting. The weed was competitive until soybean's reproductive stages 7 weeks after planting, and it decreased soybean yield 17 percent more in a dry year. The yield of narrow-row soybeans was equal to or greater than conventional rows at all pitted morningglory densities (Howe and Oliver 1987). Conventional-row soybean yields decreased an average of 42 and 81 percent at pitted morningglory densities of 3.3 and 40 plants m^{-2}, whereas the yield of narrow-row soybeans decreased only 6 and 62 percent at the same densities. The total seed production of pitted morningglory increased as its density increased and was always greater in conventional than in narrow rows. Narrow rows reduced pitted morningglory seed production an average of 90 and 68 percent when pitted morningglory densities were 3.3 or 40 plants m^{-2}. Norsworthy and Oliver (2002c) conducted field experiments to evaluate the role of photosynthetic efficiency in the interspecific competition between soybeans and pitted morningglory planted at 0, 10, 16, or 62 plants m^{-2} in drill-seeded glyphosate-resistant soybeans. Soybean's photosynthetic rate was not affected by the weed's density or glyphosate use 2 weeks after the herbicide was applied. Soybean's photosynthetic rate was reduced 12 weeks after glyphosate application by 21 and 91 percent when competition was with 62 glyphosate treated or untreated pitted morningglory plants m^{-2}. Ten weeds m^{-2} did not affect soybean's photosynthetic rate. Pitted morningglory was not killed by glyphosate, but its photosynthetic rate was reduced 2 and 12 weeks after glyphosate application by 64 and 80 percent, respectively. Soybean seed yield was not reduced by 10 or 16 glyphosate-treated weeds m^{-2}, but a 9 percent loss resulted when there were 62 weeds m^{-2}. This was partially due to the effect of glyphosate on the weed and partially due to increased shading by soybean. Glyphosate did not affect pitted morningglory's leaf area when the density was 10 or 16 plants m^{-2}, but its leaf area was reduced slightly when the density was 62 weeds m^{-2}. Glyphosate use prevented soybean seed yield reduction, whereas untreated pitted morningglory reduced soybean yield 47, 62, or 81 percent at densities of 10, 16, or 62 plants m^{-2}, respectively (table 5.3). Competitiveness of untreated soybeans increased with their seeding rate. There was 22 percent less yield loss when soybeans were planted at 521,000 than at 217,000 plants ha^{-1}.

Poorjoe—**Diodia teres**

In a unique experiment, Jordan (1989) used path analysis to compare growth differences and competitiveness of a weedy and a nonweedy (nonagricultural) population of poorjoe. Jordan (1989) analyzed the establishment rate, early and late growth rates, growth form, and final growth because each could be related to competitiveness. The mean aboveground biomass of the weedy population was roughly twice that of the nonweedy population whether it was grown alone or with soybeans. The weedy population of poorjoe had a greater establishment rate and greater early aboveground growth rate compared to the nonweedy population. The final growth rate of the two populations was similar whether soybeans were present or absent. Jordan (1989) postulated that there may have been genetic changes in the two populations that led to earlier establishment and faster early growth (characteristic of many weedy species) but not to an increased tolerance of soybeans or to intraspecific competition.

Quackgrass—**Elytrygia repens**

Quackgrass densities of 520 and 910 shoots m^{-2} reduced soybean yield 19 and 55 percent, but densities of 95 and 160 shoots m^{-2} did not affect soybean yield (Young et al. 1982). Interference by a natural stand of quackgrass for 6 or 8 weeks or for the full season reduced soybean yield 11, 23, or 33 percent. In a separate study, irrigation did not increase the yield of quackgrass-free soybeans but the yield of quackgrass-infested soybeans was increased by irrigation when soil water was limiting (Young et al. 1983). They concluded that adequate soil moisture can reduce quackgrass interference but not eliminate it because quackgrass was nearly the same height or taller than soybeans at all stages of soybean development, and it offered significant competition for light (Young et al. 1983). Sikkema and Dekker (1987) confirmed quackgrass competition for water and light, and that competition was partially relieved by irrigation. Sikkema and Dekker (1987) also showed that high levels of phosphorus and potassium did not overcome quackgrass interference, but its effects were highly variable with a 79 percent reduction in soybean yield from full-season competition in one year but only 39 percent in a second year.

Redroot Pigweed—**Amaranthus retroflexus**

As shown in studies reported above, narrow rows favor development of soybean leaf area that covers the interrow space quickly. Légère and Schreiber (1989) were among the first to study plant architecture as it influenced interference. They showed that by midseason, redroot pigweed contributed 43 percent of the total biomass when soybeans were grown in 76 cm rows but only 24 percent with 25 cm rows. Soybeans produced two to four times more leaf area than redroot pigweed during the first half of the growing season, but the advantage was diminished with wide rows. Redroot pigweed was 29 percent of the total leaf area when soybeans were planted in 76-cm rows but only 15 percent in 25 cm rows. The leaf area distribution suggested vigorous competition for light (Légère and Schreiber 1989).

Redroot pigweed interference in soybeans has not been studied as much as has the interference of several other weeds (e.g., common cocklebur, sicklepod, or velvetleaf) because it is not as prevalent in soybean growing areas. However, when it interferes in soybeans it can be very damaging. In a study of five annual broadleaf species, Shurtleff and Coble (1985a, b) showed that redroot pigweed at a density of 16 weeds 10 m^{-1} of row reduced soybean yield loss 22 percent, while the yield reduction due to common lambsquarters was 15 percent, common ragweed was 12 percent, and sicklepod was 5 percent. Eight common cocklebur 10 m^{-1} of row were vigorous competitors and reduced yield 11 percent. Soybean leaf area reductions corresponded with yield reductions for each weed. The increases in dry matter and height were slower for all five weeds in this study than for soybeans. The root:shoot ratio of soybeans was the highest of all plants but, in spite of its vigor as a competitor, that of redroot pigweed was lowest.

In one of the first multiple species studies to consider time of emergence of the weed relative to the crop, Cowan et al. (1998) showed that the time of emergence of redroot pigweed and barnyardgrass influenced the amount of soybean yield loss. The two weeds were sown together in soybeans when the latter was at the cotyledon stage of growth. The maximum soybean yield loss was 32 to 99 percent depending on the time of emergence. Redroot pigweed was more competitive (competitive index of 1 on a scale of 0 to 1) than barnyardgrass whose competitive index was 0.075 to 0.4.

Shattercane—Sorghum bicolor

Shattercane has been an important weed in midwestern U.S. agriculture for many years. It did not reduce soybean yield if it was removed by 2 weeks after emergence in one year, and soybeans resisted interference for 6 weeks in a second year (Fellows and Roeth 1992). Interference began when shattercane's height exceeded that of soybeans. Soybean yield declined up to 25 percent before the height differential exceeded 30 cm. This was important because that height differential was required before glyphosate could be applied with a wiper. There was a direct relationship between shattercane density and soybean yield that was accurately modeled by a rectangular hyperbola. Soybean's height, biomass, nodes per stem, pods per stem, pods per node, and beans per pod all decreased as shattercane density and the duration of interference increased (Fellows and Roeth 1992).

Spleen Amaranth—Amaranthus dubius

Soybeans were grown in pots with 1, 2, 4, 8, or 16 spleen amaranth plants in controlled environment chambers at 31/24 and 25/18°C day/night temperatures. Seventeen and 35 days after emergence, growth of both species had increased with temperature. After 35 days, even 1 spleen amaranth per pot decreased soybean growth, and the two highest densities had an equal effect (Wulff 1987). Soybeans were a more effective competitor than sorghum as demonstrated by the fact that shoot dry weights of spleen amaranth were significantly lower when it grew with soybeans under the same conditions. Linear regression showed that dry weight of the crop was more closely correlated with weed biomass than with the number of weeds, and soybeans were more affected by an increase in weed biomass than sorghum (Wulff 1987).

Volunteer Corn—Zea mays

A common (perhaps the most common) rotation in many midwestern fields is corn/soybeans/corn/soybeans. Corn frequently becomes a weedy presence in soybean fields. Soybean yield is inversely related to volunteer corn clump density, and soybean yield losses can reach 25 percent with 5,380 clumps of corn per acre. Such clumps may have as many as 10 corn plants (Beckett and Stoller 1988). Corn caused soybean yield losses of 2, 6, 12, 19, and 27 percent when it was not controlled for 2, 4, 6, 8, or 10 weeks after planting. A 10-corn-plant clump reduced soybean yield over a radius of 86 cm.

Wild Oat—Avena fatua

Wild oat is common in small grain crops but not usually a major problem in soybean. However, if it is present, losses can be significant. Season long competition of 1, 3, 9, or 30 wild oat m^{-1} of row reduced soybean yield an average of 6, 17, 32, or 51 percent (Rathmann and Miller 1981). Thirty wild oats m^{-1} of row did not affect yield if they were present for 4 weeks after emergence or less. If wild oat was present for 5, 6, 7, 8 weeks or for the full season, yield was reduced 29, 50, 63, 58, or 63 percent. The effect was more apparent on soybean pods per plant and seeds per plant than on seed weight.

Wild Poinsettia—Euphorbia heterophylla

Soybean canopy width was reduced about 10 percent beginning after 6 weeks of interference for distances of 0 to 10 and 10 to 20 cm from the weed. Soybean dry weights decreased 14 to 38 percent within 20 cm of the weed for 12 through 18 weeks of interference (Willard et al. 1994). Wild poinsettia interference resulted in a 9.5 percent yield reduction for the 0 to 10 cm distance from the soybean row compared to 80 to 100 cm. Soybeans were an effective competitor with wild poinsettia. Differences in wild poinsettia dry weight when growing alone and when growing with soybeans occurred after 6 to 8 weeks of interference. In a year when rainfall was twice that of the previous year, dry weight of wild poinsettia growing in the soybean row was reduced 82 percent compared to the weed growing alone.

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SUGARBEET—*BETA VULGARIS* L.

Sugarcane and sugarbeets are the world's primary sources of sugar, a completely nonessential but quite enjoyable part of the human diet. Sugar is a crop that has changed the course of human history in undesirable ways (Hobhouse 1986).

The response of a semiprostrate and an erect sugarbeet cultivar to nitrogen and to wild mustard and common lambsquarters was not identical. Timing of nitrogen fertilization did not influence crop biomass or yield and crop quality of the weed-free crop. Early nitrogen application resulted in opposite effects with the two weeds: higher crop biomass reduction in the presence of wild mustard and lower crop biomass in the presence of common lambsquarters. Root and sucrose yield responded similarly to weed competition. There was no difference in cultivar response to weed competition. The crop was favored by late nitrogen application if wild mustard was present but by early nitrogen application when common lambsquarters was the competing species (Paolini et al. 1999).

When wild mustard or perennial ryegrass were grown in the sugarbeet row or 2, 4, or 8 cm from the row, sugarbeet yield increased when the weeds were further from the crop row (Heisel et al. 2002). When the distance increased from 2 to 8 cm, sugarbeet yield increased 20 percent, regardless of the weed species. The number of neighbors described a sigmoidal yield decline of single sugarbeet plants. Results of image analysis (analysis of leaf cover) showed that about 33 g of sugarbeet yield was lost in October/November for each percent of projected leaf cover of weeds in May (Heisel et al. 2002).

Kropff and Spitters (1992) proposed an ecophysiological simulation model based on how the sugarbeet and common lambsquarters use light and water for dry matter production. The distribution of the leaf area of the competing species over the sugarbeet canopy was used to determine absorbed radiation in relation to canopy height. The CO_2 assimilation light response of individual leaves was used to calculate the canopy's CO_2 assimilation profile. A daily CO_2 assimilation rate was calculated for each species. Soil moisture and drought were considered. Subsequent work showed that 98 percent of the variation in yield loss (range -6 to 96 percent) was explained by the simulation model (Kropff et al. 1992). The primary factor responsible for difference in yield loss between experiments was the number of days between crop and weed emergence (0 to 31 days). Water shortage only influenced the competitive ability of the weeds when they were shorter than the crop. Temperature in the period between crop and weed emergence was also an important determinant of competitive ability. Kropff et al. (1992) recommended that the time between crop and weed emergence should be expressed "as a developmental measure (i.e., degree days) instead of days." The wisdom of this suggestion has been recognized by many. Kropff et al. (1992) also reported that morphological characteristics such as relative growth rate of leaf area and height are the primary determinants of competitive ability whereas physiological traits such as maximum rate of photosynthesis are less significant. In competition, morphology (size) is more important than physiology in most cases.

Sugarbeet root yield was reduced by competition from all densities of wild oat and wild mustard alone or in combination in Wyoming (Mesbah et al. 1995). Root yield reduction was less than additive when the two weeds were mixed. Root yield decreased as the duration of interference increased but percent sucrose was not affected. The maximum time a mixture of 0.8 wild mustard and 1 wild oat m^{-1} of row can be present without yield loss is 1.6 weeks after sugarbeet emergence.

Similar results were found for mixed densities and durations of competition from kochia and green foxtail (Mesbah et al. 1994). With these species, reductions in yield were additive at low densities but were less than additive (see above for wild oat and wild mustard) at high densities. Because sugarbeets were irrigated and fertilizer was applied to optimize yield, the authors concluded that both weeds competed primarily for light. The lowest densities of kochia and green foxtail were 0.3 and 0.06 plants m^{-1} of row, respectively. The minimum time that 0.5 kochia and 3 green foxtail m^{-1} of row can interfere with sugarbeets without economic loss of root yield is about 3.5 weeks after sugarbeet emergence (Mesbah et al. 1994), a longer time than was true for wild oats and wild mustard (Mesbah et al. 1994).

Interference of barnyardgrass with 10 or more plants m^{-1} of row caused more than 80 percent root yield decrease in spring-planted sugarbeets in California (Norris 1992). Yield loss was only 5 to 20 percent when there was 1 weed in every 2 to 3 m of row. The economic threshold density was about one barnyardgrass plant 5 to 20 m^{-1} of row. If barnyardgrass was present at densities less than 1 m^{-1} of row, sugarbeets experienced only interspecific competition and the weeds had no measurable effect. However, because barnyardgrass is a prolific seed producer, one weed 10 m^{-1} of row produced between 4,000 and 20,000 seeds m^{-1} of row (Norris 1992). The weed's presence in future crops is assured even though the damage to the present crop is minimal.

A series of experiments was conducted by Schweizer and colleagues in Colorado to determine the interference of different weed species in sugarbeets. When equal densities of kochia, redroot pigweed, and common lambsquarters were present at total densities of 3, 6, 12, 18, or 24 weeds in 30 m of row, sugarbeet root yields decreased not at all, 13, 24, 33, or 39 percent, respectively (Schweizer 1981). A linear equation predicted root yield loss with increasing weed density. The actual yield loss was always less than the predicted loss because the growth of weeds to which herbicides were applied was suppressed, but they remained competitive. Powell amaranth at 6, 12, 18, or 24 in 30 m of row was less competitive than the weeds above (Schweizer and Lauridson 1985) and reduced yield 7, 13, 23, or 24 percent. The minimum number of Powell amaranth required in 30 m of row to reduce yield was 9 in one year and 11 in a second year of study. Common lambsquarters at 6, 12, 18, or 24 in 30 m of row reduced yield 11–13, 27–29, 37–38, or 46–48 percent, respectively, in 2 years of study. It was more competitive than Powell amaranth because the minimum number of weeds required to reduce yield was 4 in one year and 6 in a second year of study (Schweizer 1983). Common sunflower was more competitive than velvetleaf when densities identical to those reported above were used. Yield reduction from common sunflower was 40, 52, 67, or 73 percent, whereas those from velvetleaf were only 14, 17, 25, or 30 percent for the same density (Schweizer and Bridge 1992). When both weeds competed with sugarbeet, yield losses were intermediate between those for either weed alone with sugarbeet, indicating interspecific competition between the weeds. The minimum number of weeds required to reduce sugarbeet yield was 1 common sunflower, 9 to 12 velvetleaf, and 2 to 7 when the weeds were mixed. Common sunflower was a more effective competitor because of its rapid early growth and large size late in the season. When sugarbeets were harvested, common sunflower averaged 240 cm tall, kochia was 157 cm, velvetleaf was 150, and sugarbeets only 50 cm (Schweizer and Bridge 1982).

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SUGARCANE—*SACCHARUM OFFICINARUM* L.

Sugarcane is an important cash crop in many parts of the world. In spite of its importance but because of its long growing period, dense foliage, height, and ready availability of several selective herbicides, weed competition has not been studied as much as it has in most annual crops.

Itchgrass germinates throughout the cane growing season and is a vigorous competitor. There was no difference in the sugarcane population, the yield of cane, or the sugar yield when itchgrass was allowed to interfere for the entire season, from early-season emergence until the last cultivation in mid-June, or from late-season (the last cultivation) until sugarcane harvest. Full-season interference reduced sugarcane population and cane and sugar yield an average of 34, 42, and 43 percent, respectively, compared with no interference in Louisiana (Lencse and Griffin 1991). Autumn-planted sugarcane seeded with 1 itchgrass in 30.5 m of row (= 1.8 itchgrass m^{-2})in early March lost an average of 7 percent of sugar yield after 30 days of interference (Millhollen 1992). After 30 days, itchgrass biomass rangedfrom 200 to 2,700 kg ha^{-1} but after 60 days it had increased to 1,400 to 2,900 kg ha^{-1} and sugar yield was reduced 17 percent. When itchgrass interfered until harvest (180 days), sugar yield was reduced 19 percent, and one must conclude that early interference is most damaging. The weed's primary effect was a reduction in sugarcane stalk density. When itchgrass was removed in the crop's second year (the ratoon crop) on May 1, June 1, or November 15, yield was reduced 3, 11, or 72 percent compared to a weed-free crop. However, sugarcane stand and yield recovered almost completely when the crop was maintained weed free in the second year following full-season itchgrass interference in the first crop year (Millhollen 1992).

Losses up to 40 percent of cane yield were caused by natural weed populations in the Sudan (Ibrahim 1984). Weed competition decreased millable stalks (32 percent), stalk thickness (15 percent), and the number of nodes per stalk (14 percent). Four hand weedings were no better than three weedings 3, 6, and 9 weeks after cane planting.

Johnsongrass, a tall perennial grass, decreased cane yield 36 percent and sugar yield 31 percent compared to weed-free plots in Louisiana (Ali et al. 1986). The weed's greatest effect was on cane density (i.e., stalks per plot) and effects were only observed when johnsongrass exceeded 15 to 35 percent of total plant density.

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VEGETABLES

Bean—*Phaseolus* spp. and *Vicia* spp.

The sensitivity of beans to weed competition is illustrated by work with redstem filaree (Blackshaw and Harker 1998). Maximum yield reduction from 100 to 200 weeds m^{-2} for wheat was 36 percent and oilseed rape was 37 percent. For beans, the maximum reduction was 82 percent and only pea was more sensitive to competition with a loss of 92 percent. Three weeks of competition from redstem filaree was sufficient to reduce bean yield and the mean yield reduction for bean per week of competition was 6.3 percent, higher than the other three crops.

Burnside et al. (1998) reported that the critical period for weed control (see chapter 6) in dry beans in Nebraska was 3 to 5 or 6 weeks after planting. Weed-removal timing had little effect on dry bean stand or 100 seed weight of harvested seed. Also in Nebraska, Wilson (1993) reported that wild proso millet was able to reduce bean yield between 12 and 31 percent at a density of 10 weeds m^{-2}. The rectangular hyperbolic model predicted the weed's effect on bean yield as weed density increased. Consistent with the work of Burnside et al. (1998), Wilson found a weed-free period of 4 weeks was sufficient to prevent yield loss.

As few as two hairy nightshade plants in a meter of row reduced bean (red bean) yield an average of 13 percent (Blackshaw 1991). If the weed was present during the first 3 weeks after bean emergence, bean yield was depressed. Dependent on the length of the growing season, 6 to 9 weeks of weed-free maintenance were required after emergence to prevent hairy nightshade from producing viable seed before frost killed the weed. Up to 9 weeks of weed-free maintenance were required to prevent bean yield loss.

As reported in chapter 6, when the critical period for white bean (also *Phaseolus* spp.) was defined as the beginning of the crop stage of growth when weed presence reduced yield by 3 percent and ending at the crop growth stage to which the crop had to be weed free to prevent a 3 percent yield loss, the critical period extended from the second trifoliate to the first flower stage of growth for all cultivars. The beginning of the critical period corresponded with the beginning of a rapid increase in total weed biomass (Woolley et al. 1993).

Bean cultivars varied in their competitive ability against a natural population of annual weeds in Ontario, Canada. Uncontrolled weed populations reduced bean yield as much as 70 percent. Two cultivars reduced weed growth 10 to 35 percent compared to a third cultivar (Malik et al. 1993). All cultivars were more competitive in medium-width (46 cm) and narrow (23 cm) rows than in wide (the traditional width) 69 cm rows. Neither the cultivar, row spacing, nor planting density alone had a significant effect on weed density. However, the combination of cultivar, row spacing, and planting density that maximized bean's leaf area index also minimized weed biomass (Malik et al. 1993). Each kg ha^{-1} increase in weed biomass increased white bean's yield loss by 0.38 kg ha^{-1}.

The time of common ragweed emergence and the weed's density affected bean yield at all locations in work by Chikoye et al. (1995). When 1.5 common ragweed plants emerged in a 1 meter of row at bean's VE (seedling) stage, seed yield loss was 10 to 22 percent. When emergence of the same density was delayed until bean's V3 (second trifoliate) stage, yield loss was only 4 to 9 percent. The time that common ragweed emerged was more important than its density as a determinant of bean yield.

Another of the few studies of interference of parasitic weeds was done, as many have been, in Spain. Crenate broomrape growth was weakly negatively correlated with the final shoot height or number of shoots of broad bean (Mesa-Garcia and Garcia-Torres 1984). The primary effect of crenate broomrape was on the number of bean pods. Second, the number of seeds in each pod was reduced when competition occurred at late crop growth stages, when pods had already developed. The average of 4 crenate broomrape plants parasitizing 1 broad bean plant reduced seed yield 50 percent. A second study, in northwest Syria (Manschadi et al. 1997), showed that the number of crenate broomrape attachments in one faba bean genotype was positively correlated with plant density. However, faba bean planting density had no significant effect on crenate broomrape in either cultivar. Resistance in a second genotype was due to three characteristics of the genotype. First it had reduced plant vigor and reduced root-length density. Second, just before or just after the parasite's penetration into the host's root, host cell necrosis occurred that effectively created a barrier to further penetration. Finally, the genotype had early flowering and pod set and thus matured more rapidly, which reduced the effects of the parasite observed on faba bean cultivars that were in the field longer.

When weeds emerged with beans, crop row spacings of 15 to 36 cm suppressed weed growth 18 percent compared to conventional 91 cm rows (Teasdale and Frank 1983). If the weeds were controlled for the first half of the growing season, 15 to 35 cm rows suppressed weed growth 82 percent compared to 91 cm rows. The effect of 46 cm rows was variable. Narrow rows suppressed weeds because the bean canopy closed sooner. Beans in 15, 25, 36, or 46 cm rows had similar yields that were an average of 23 percent higher than beans in 91 cm rows.

In fields where horsenettle had been grown for 3 years before beans were planted, bean yield was reduced 48 percent in one and 65 percent in another year (Frank 1990). Horsenettle that had been established for only 1 year reduced yield 18 to 20 percent. When horsenettle was 15, 30, or 60 cm from the bean row, yield was reduced 43, 29, and 15 percent in one year and 38, 26, or 11 percent in a second year, illustrating the vigor of horsenettle competition.

Eight horsenettle plants in 4.6 m of row reduced bean yield 36 percent and 16 reduced it 55 percent. If beans were planted in 15 cm rows, horsenettle fruit production was reduced 16 percent from that produced in 60 cm rows.

Intraspecific competition was always more severe than interspecific competition when red kidney beans (*Phaseolus* sp.) competed with black nightshade or barnyardgrass in California (Fennimore et al. 1984). By 47 days after planting, barnyardgrass and bean both reduced bean biomass and yield. Beans were better competitors than either weed.

In contrast, common cocklebur reduced bean yield 8 to 44 percent in one year and 2 to 55 percent in a second year by full-season competition from densities between 0.5 and 8 weeds m^{-2}. In one year, 1 weed m^{-2} was the damage threshold and 4 m^{-2} was the threshold in the second year. Snap beans could compete effectively only until the unifoliate stage. The critical duration of interference for common cocklebur that emerged with snap beans was between emergence and the full-bloom stage of snap beans (Neary and Majek 1990).

One study of interference of weeds in lima beans was found. Sicklepod was studied at densities between 2.7 and 43.1 weeds m^{-2} for 0, 2, 4, 6, 8, or 10 weeks after planting (Glaze and Mullinix 1984). Lima bean yield was inversely related to sicklepod density. In general, 2.7 and 10.8 sicklepod m^{-2} did not reduce lima bean yield. Bean yield decreased as the duration of competition exceeded 6 weeks.

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Lentil—*Lens culinaris* L. and chickpea—*Cicer arietinum* L.

Competition from four weeds during the first 30 days after planting decreased lentil grain yield an average of 17 percent. Losses increased with time of competition up to 69 percent for full-season competition (Singh and Singh 1990). Yield increased with the length of an early weed-free period up to 60 days after planting, after which the crop effectively suppressed weed growth.

In Jordan, competition from a natural weed stand with winter-planted, rain-fed lentil and chickpea was studied over 2 years (Al-Thahabi et al. 1994). Chickpea seed yield was reduced an average of 81 percent, and straw yield declined 63 percent after full-season competition. The critical period for competition was 35 to 49 days after chickpea emergence. Lentil seed yield decreased 63 percent and straw yield declined 55 percent after full-season competition. The critical period for lentil was 49 to 56 days after emergence. The critical period for both crops occurred when they were in "an advanced stage of vegetative growth" but before flowering.

There was a significant loss of biomass and yield in 3 of 4 years when round-leaved mallow competed with lentils. A two-variable model that considered early-season crop density loss and round-leaved mallow density best accounted for variation in lentil and wheat yield. Losses could be up to 100 percent in lentil from full-season competition (Makowski 1995). In lentil, 200 round-leaved mallow m^{-2} had a biomass of 200 to 1,000 g m^{-2}, nearly twice that of the weed in wheat.

An infestation of 32 or 65 wild oats m^{-2} for 5 weeks after lentil emergence did not reduce lentil yield (Curran et al. 1987). However, 32 wild oats m^{-2} reduced yield 32 percent if present for 7 weeks and 49 percent if present to harvest (11 weeks). Wild oats decreased grain yield 42 and 61 for 7 or 11 weeks when present at 65 m^{-2}.

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Onion—*Allium cepa* L.

A density of 18 London rocket m^{-2} reduced onion yield 6 weeks after planting (Menges and Tamez 1981b). Onion, a noncompetitive crop, also lost yield when 360 common sunflowers m^{-2} interfered for 6 weeks after emergence and when the same weed was present at a density of 50 or 5 m^{-2} for 12 or 15 weeks after emergence (Menges and Tamez 1981a). Onion yield did not decrease if the crop was kept weed free for 2 to 12 weeks after emergence. Climate factors (soil water, soil temperature, and irradiance) were more useful than weed density to explain the differential interference of common sunflower in onion between years.

Work in irrigated onions in Colorado showed that the duration of competition expressed in thermal time units with a base of 7.2°C explained 65 percent of the reduction of onion's relative yield (Dunan et al. 1996). The first significant reduction in onion yield occurred at 90 thermal time units. A polynomial multiple regression model, including duration of competition and weed load (weed density and an estimate of weed competitiveness), accounted for 75 percent of the variation in relative onion yield. Onion's relative yield was more sensitive to the duration of weed competition than to the specific weed competitors.

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Pea—*Pisum sativum* L.

The sensitivity of beans to weed competition is illustrated above in work with redstem filaree (Blackshaw and Harker 1998). Peas were the most sensitive of the four crops studied with a maximum yield reduction of 92 percent. Three weeks of competition from redstem filaree was sufficient to reduce bean yield; the mean pea yield reduction per week of competition was 3.6 percent, lower than for bean.

Vined pea yield ha^{-1} was reduced by weeds by a constant amount across a range of densities (Lawson 1983). In general, weeds had effects similar to the effects of increasing pea crop density, but without the added contribution the extra pea plants made to yield. Higher density pea crops suppressed weeds effectively but were as vulnerable to yield loss as crops with lower density except the adverse effects of weeds were diminished by the interspecific competition of peas. Weeds impaired pea vegetative development, especially by reducing tillering in low-density crops. Therefore, low-density crops had fewer pods per plant at harvest. The presence of the pea crop, independent of its density, did not materially alter the composition of the weed flora (Lawson and Topham 1985). The crop did not (could not) replace the dominant weed species in high-density plots (194 plants m^{-2}), but it did reduce the growth of all species.

Mayweed chamomile produced similar amounts of leaf area and dry matter in wet and dry years (Ogg et al. 1993a). Peas, however, produced 20 percent more leaf area and 100 percent more dry matter in wet years. The weed's height and dry weight increased throughout the growing season, but peas reached a maximum between bloom and pod set and then declined. Initially, the relative growth rate of mayweed chamomile was three times that of pea, but 40 to 48 days after planting the rates were equal. One might assume early rapid growth would give the weed an advantage, but the relative yield of the two species and the relative crowding coefficients showed peas were 3 to 20 times more competitive and the weed was in fact a weak competitor (Ogg et al. 1993b). In further studies of the same relationship, Ogg et al. (1993a) found root interference was primary and soil water was more important than nitrogen. If soil water was limiting, mayweed chamomile became more aggressive than pea. Nitrogen fertilization (20 mg wk^{-1}) had no affect on pea yield but more than doubled the weed's size. Pea was the stronger competitor in all cases. The weed's leaf area, root weight, and shoot weight decreased 55 to 87 percent with shoot and root interference and 27 to 60 percent from only root interference.

Wild mustard competed with a traditional cultivar and a semileafless cultivar that were planted at the recommended rate of 172 kg ha^{-1} and at 86 kg ha^{-1}. Twenty wild mustard m^{-2} reduced pea seed yield nearly the same amount at the two seeding rates (2 to 35 percent). The semileafless cultivar was more competitive with the weed at the standard seeding rate than at the lower rate. Seeding rate had only a modest effect on yield of the traditional cultivar. Both cultivars were more affected by the weed in years with normal to high rainfall (Wall et al. 1991).

Volunteer barley reduced pea seed yield 1.7 to 5.4 percent over 2 years (O'Donovan and Blackshaw 1997). This may not seem like a large loss, but it was caused by only 2 to 6 volunteer barley plants m^{-2}. There was no advantage in attempting to manipulate pea density above 100 plants m^{-2} to diminish weed competition. There was, however, a slight (and unusual among weed-crop studies) economic gain if the barley was harvested that could partially offset the loss in pea yield.

The beginning of the critical weed-free period in competition with wild oat or tartary buckwheat at two Canadian locations was 1 or 2 weeks after pea emergence (Harker et al. 2001). Weed-free pea yields at the more northerly location were always two to three times higher than at the second (more southerly) location. Early competition with tartary buckwheat at one location in all years did not reduce pea yield, and early competition from wild oat did not reduce yield in 1 of 3 years. In general, wild oat began to reduce pea yield 2 weeks after pea emergence, and the reduction was linear for the next 2 weeks with a loss of 97 kg ha^{-1} per day. At the second location, early weed competition caused yield losses in all years with the onset of losses beginning 1 to 2 weeks after pea emergence. Similar to the first location, yield loss was linear for the next 2 to 3 weeks with a lower average rate of decrease of 45 kg ha^{-1} per day. Yield losses after full-season competition ranged from 40 to 70 percent at both sites (Harker et al. 2001).

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Pepper—*Capsicum annuum* L.

Weed interference periods of 40 to 60 days reduced bell pepper fruit number and weight 10 and 50 percent, respectively (Frank et al. 1992). Foliage weight of bell pepper declined 10 and 50 percent with interference periods of 20 and 50 days, respectively. There was no significant difference in insect infestation of fruit related to the time of weed interference.

Purple nutsedge densities up to 200 plants m^{-2} linearly reduced shoot dry weight at flowering and fruit yield of bell pepper and tomato in Florida as weed density increased (Morales-Payan et al. 1997). For each percentage unit of bell pepper shoot dry weight lost at flowering, fruit yield was reduced 1 to 2.0 units, with total losses up to 32 percent. Bell pepper and tomato both decreased total shoot dry weight of purple nutsedge.

The maximum weed infestation period of a natural weed stand ranged from 0.7 to 3.2 weeks after transplanting to avoid no more than a 5 percent yield loss in chili pepper in Mexico (Amador-Ramírez 2002). To prevent total yield decline, weeds had to be removed no later than 2.1 weeks after transplanting. However, to prevent a decline of marketable yield, only 0.9 weeks of competition after transplanting was permitted. The minimum weed-free period ranged from 6.7 to 15.3 weeks after transplanting with an average of 12.2 weeks of weed-free maintenance to prevent more than a 5 percent yield loss.

Spurred anoda usually emerges in New Mexico after chili peppers are thinned to a final stand (Schroeder 1993). When 3, 6, 12, 24, or 48 spurred anoda plants were present in 9 m of row, yield decreased 31 to 49 percent when peppers were thinned when they were 10 cm tall and 12 to 27 percent when they were thinned when 20 cm tall. Spurred anoda that emerged after thinning decreased yield and ease of harvest but not the quality of the harvested crop.

Zancada et al. (1998) studied the influence of root-knot nematode [*Meloidogyne incognita* (Kofoid & White) Chitwood] on competitive interference between pepper and black nightshade. Very few studies of the interaction of other pests and weeds have been done. Root-knot nematode reduced all growth parameters of pepper but did less harm to the weed. Black nightshade was a stronger competitor than pepper with and without nematode infestation. Nematode's effect on pepper yield was less than that of weed competition, but the effects appeared to be additive.

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Tomato—*Lycopersicon esculentum* L.

Work on interference of weeds in tomatoes includes the typical studies that report how many of weed X reduce the yield of tomato by Y amount after Z time. However, work has also been done on competition for light, nutrients, interaction with soil temperature, and water stress.

The minimum weed-free period varied between 7 and 9 weeks after direct seeding over 3 years in Ontario, while the maximum period of weed infestation was 5 to 6 weeks after direct seeding (Weaver and Tan 1987; Weaver 1984). Thus, the critical period for weed control was between 5 and 9 weeks after direct seeding. A minimum of two weed control operations of some kind were required during the critical period to prevent yield reduction. In contrast, Weaver and Tan (1983) demonstrated that the critical period for weed control in transplanted (as opposed to direct-seeded) tomato was 28 to 35 days after transplanting and a single weeding was adequate to prevent yield loss. Yield losses in direct seeded tomatoes were attributed to reduction in light level to tomato by weed shading and weed competition for water, which resulted in stomatal closure in tomato (Weaver and Tan 1987). In transplanted tomatoes, growth analysis showed that differences in plant dry weight and fruit number compared to weed-free plots were not apparent until 56 to 70 days after transplanting (Weaver and Tan 1983). Interference and yield losses were due primarily to shading and not to water stress.

The role of light intensity was affirmed by studies of black and eastern black nightshade, which had unequal effects on tomato. Black nightshade was never taller than tomato and did not affect photosynthetically active radiation (PAR) at the top of the tomato canopy (McGiffen et al. 1992). When density of either species increased (up to 4.8 m^{-2}), the number of tomato fruits decreased, but eastern black nightshade reduced yield more than black nightshade, because the former was taller and reduced PAR at the top of the tomato leaf canopy. PAR at the top of the tomato canopy was positively correlated with tomato yield and negatively correlated with eastern black nightshade density. Reduction of PAR during anthesis and early fruit set did not affect tomato yield if PAR during the time of rapid fruit development was not reduced (McGiffen et al. 1992).

Losses due to eastern black nightshade and hairy nightshade always caused greater losses in direct-seeded than in transplanted tomatoes (Weaver at al. 1987). Stomatal conductance and transpiration rates of seeded tomato decreased more rapidly than they did in transplanted tomatoes with increasing nightshade density. The value of population density as a weed control technique is illustrated by the finding that seeding tomatoes in twin rows with 33,300 and 45,000 plants ha^{-1} produced higher yields than those seeded in single rows with populations of 12,500 and 22,500 ha^{-1}.

The relative yield of eastern black nightshade and tomato increased as the proportion of the weed increased in pots, and Perez and Masiunas (1990) concluded that the weed was less competitive than tomato. However, the weed was an effective competitor in the field. Tomato yield was reduced by two-thirds if 3 eastern black nightshade m^{-1} of row grew more than 6 weeks after transplanting. The percentage of marketable tomatoes decreased from 73 without eastern black nightshade to 49 percent when the weed was present for 12 weeks. The importance of weed and crop emergence times was demonstrated. When eastern black nightshade and tomato were transplanted together, tomato yield was 9,000 kg ha^{-1} and 49 percent of the fruit was marketable. If the weed was transplanted 9 weeks after tomato, yield was 30,000 kg ha^{-1} and 70 percent of the fruit was marketable (Perez and Masiunas 1990).

If tomato was planted late in southeast France, and low densities of black nightshade were present, two weed-control treatments at the 5- to 6-leaf stage of crop growth and at the onset of flowering were sufficient to prevent yield loss (Caussanel et al. 1990). However, the data also show the vigor of black nightshade competition. If only 12.8 black nightshade plants ha^{-1} emerged between the crop's 2- to 3- and 5- to 6-leaf stage, they still caused a significant loss if they remained until harvest.

Weaver et al. (1988) compared the relative time of emergence of four weeds and tomato at five alternating temperatures and five levels of available soil moisture. In general, total emergence decreased for all species as soil moisture decreased, and the species differed in the optimum temperature for emergence, but they were nearly insensitive to soil moisture. If one knows the effects of temperature and moisture on weed species, this information can be used to develop optimal crop planting dates and to estimate potential crop yield losses (Weaver et al. 1988).

Prevailing weather influenced the competitive effect of jimsonweed, tall morningglory, and common cocklebur about equally (Monaco et al. 1981). If they were present for the whole season, densities of 11, 43, or 86 plants m^{-2} reduced tomato yield in a warm year. The second year of study was wetter, slightly cooler, and the crop was irrigated. Then densities between 2.7 and 11 of each weed m^{-2} reduced yield.

Barnyardgrass density of 16 plants m^{-1} of row reduced tomato yield 26 percent, while a density of 64 weeds m^{-1} of row reduced yield 84 percent. As crop growth progressed, tomato shoot dry weight decreased at all barnyardgrass densities. Season long interference decreased fruit number and fruit weight at all weed densities (Bhowmik and Reddy 1988a).

Increasing aggregation of barnyardgrass plants (more clumped distribution) increased intraspecific competition, but interspecific competition from tomato decreased (Norris et al. 2001a). The primary influence of different spatial arrangements of the weed was its effect on shading of tomato. Clumped barnyardgrass caused less shading than random or regular distribution of the weed along the tomato row. With a density of 10 tomatoes m^{-1} of row, yield losses were 10 to 35 percent in one year and 8 to 50 percent in a second year when barnyardgrass was clumped. The same barnyardgrass densities reduced tomato yield 20 to 50 percent in one year and 11 to 75 percent in a second year for the regular and random arrangements. Norris et al. (2001a) predicted the single-season economic threshold density for a tomato planting of 10 plants m^{-1} of row would be 25, 19, or 15 barnyardgrass plants m^{-1} of row for the regular, random, and clumped arrangements, respectively.

When barnyardgrass was grown at densities of 0, 0.25, 0.5, 1, 2, 5, and more than 50 plants m^{-1} of row in a regular, random, or clumped pattern with tomato at densities of 0, 5, 10, or 20 plants m^{-1} of row in a regular pattern, crop and weed density or spatial arrangement had little effect on phenological development of the weed (Norris et al. 2001b). In the absence of tomato, a barnyardgrass plant produced more than 400,000 seeds without intraspecific competition but only 10,000 seeds when plant density exceeded 50 m^{-1} of row. Clumped distribution reduced seed production 30 to 50 percent when density was 1 to 5 plants m^{-1} of row. Tomato interference reduced barnyardgrass seed production, but the magnitude of reduction depended on tomato and weed density. Nearly 700,000 seeds m^{-2} were produced when the weed's density exceeded 50 plants m^{-1} of row. The most significant conclusion of these studies (Norris et al. 2001a, b) was that barnyardgrass seed production at the single-season economic threshold density was sufficient to maintain the soil seedbank and require "high levels of weed control in subsequent years." Preventing seed production was recommended as the best long-term management strategy, a recommendation that is biologically and economically wise but one that has not been widely accepted.

When common lambsquarters and wild mustard were grown with tomato in additive and replacement series studies in the greenhouse, both species had similar effects on shoot dry weight at low densities (2 or 5 plants per pot) but wild mustard was more competitive at higher densities (15 to 20 plants per pot) (Quasem and Hill 1994). Weed competition did not affect N, P, K, Ca, or Mg content of tomato shoots, but total tomato dry matter and total nutrients were reduced with increasing density of both weeds. These findings are similar to the earlier study of Sanders et al. (1981), which found few instances of differences in nutrient content of tomato and the leaf tissue of jimsonweed, tall morningglory, common cocklebur, or large crabgrass. There was no clear relationship between the concentration of N, P, K, Ca, Mg, or S and weed density. More tomato fruit was produced in weed-free plots per kg of total assimilated N, P, and K than in weedy plots (Sanders et al. 1981). Quasem and Hill (1994) reported N, P, K, and Mg concentrations were higher in shoots of common lambsquarters. Reduction of growth of common lambsquarters was associated with a reduced ability to accumulate K. The competitive index of common lambsquarters decreased with its proportion in a mixture but the opposite was true for wild mustard. Common lambsquarters was nearly 3.5 times as competitive as wild mustard, and their relative competitive ability was closely related to the growth of their root systems, a factor overlooked in many competition studies.

In another study, common lambsquarters's density ranged from 16 to 64 plants m^{-1} of row, and the weed fresh weight ranged from 26,360 kg ha^{-1} with 16 plants ha^{-1}, to 46,000 kg ha^{-1} with 64 weeds m^{-1} of row. Season-long interference of common lambsquarters varied from 17 percent at the low density to 36 percent yield loss at the high density. Nitrogen concentration in tomato leaves was unchanged during the vegetative and flowering stages but declined regardless of the weed's density at the early-fruit stage and at harvest (Bhowmik and Reddy 1988b). Similar to other studies, weed density did not affect P, K, or Ca levels in tomato leaves.

Field experiments in California were conducted with four tomato cultivars to determine if there were cultivar traits that could be associated with competitiveness against velvetleaf (Ngouaijo et al. 2001). The weed's competitive effects varied with year and cultivar. When velvetleaf density was 5 m^{-1} of row, the yield of one cultivar was reduced 8 percent in one year and 60 percent in a second year. For another cultivar, the variation was 58 to 80 percent between the years. Crop growth rate and aboveground dry biomass of tomato cultivars grown with velvetleaf were generally less than when the cultivars were grown in monoculture. Yield loss with high weed density was similar among the four cultivars but it was variable at low weed density.

Relative yield analysis indicated that tomato is a stronger competitor than either purple or yellow nutsedge. Both nutsedge species are strong intraspecific competitors (Santos et al. 1997). When either nutsedge species was grown with tomato for 40 days, tomato dry weight per plant increased and that of the nutsedges decreased. This was due primarily to the ability of the tomato leaf canopy to shade nutsedge, which is particularly susceptible to shading. Field experiments demonstrated that the fungus *Dactylaria higginsii*, a native of Florida, isolated from purple nutsedge, produced tomato yields equivalent to a weed-free control when 10^6 conidia ml^{-1} were applied. Purple nutsedge was present in the pots at densities of 40, 80, 160, or 320 tubers m^{-2} (Kadir et al. 1999).

Another of the very few studies of interference from parasitic weeds investigated the effect of lespedeza dodder on tomato (Goldwasser et al. 2001). The primary finding was that some tomato commercial hybrid varieties are at least partially resistant or tolerant to parasitism by dodder. In the field, dodder seed germinated, emerged, and began to twine around tomato stems, but in tolerant cultivars, haustoria attachments were 75 percent less and dodder growth was reduced up to 70 percent.

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Other Vegetable Crops

Cabbage—Brassica oleracea L.

Cabbage yield was reduced if plots were not kept weed free for at least 3 weeks after planting or if weeds competed more than 4 to 5 weeks after planting (Weaver 1984). If one attempted to manage weeds by planting a higher crop population (narrower rows), it was counterproductive because the result was smaller crop plants and earlier competition from weeds and a shorter time during which the crop could withstand weed competition. Weaver (1984) did not identify a true critical period for weed competition in cabbage.

Miller and Hopen (1991), in Wisconsin, identified the critical weed-control period in cabbage as 2 weeks in one year and 4 weeks in a second year with a natural weed stand. Season-long velvetleaf densities of 1.2 or 3.6 plants m^{-2} reduced cabbage yield 52 and 76 percent in one year and 76 to 92 percent in a second year. All velvetleaf densities planted 0, 1, or 2 weeks after cabbage reduced cabbage yield, but planting 4 or 6 weeks after cabbage had no effect on yield.

A study in the subtropical environment of Taichung, Taipei, determined the effect of planting cabbage in fields after rice harvest (Horng 1980) to give cabbage a longer growing period. Cabbage was transplanted into rice fields 3 to 12 days before rice harvest or 5 days after harvest. Cabbage transplanted before rice harvest began to grow before pale smartweed had germinated. Its yield was reduced when the weed was allowed to grow more than 4 weeks from the time beds were formed around cabbage which was about 5 days after rice harvest. If cabbage was transplanted 5 days after rice harvest, pale smartweed had emerged and cabbage yield was reduced when the weed grew for only 2 weeks after beds were formed. Cabbage has to be kept weed free for a minimum of 4 weeks after transplanting to prevent yield reduction (Horng 1980).

Cucumber—Cucumis sativus L.

A natural infestation of yellow nutsedge with densities up to 955 plants m^{-2} had a 5 percent reduction in cucumber yield with a yellow nutsedge density of about 15 plants m^{-2}. Yellow nutsedge was a more effective competitor in uneven or nonuniform cucumber stands. Uniform cucumber stands maximized the crop's competitive ability (Johnson and Mullinix 1999).

Cucumber yield was reduced if plots were not kept weed free for up to 4 weeks after planting or if weeds competed more than 3 to 4 weeks after planting (Weaver 1984). If one attempted to manage weeds by planting a higher crop population (narrower rows), it was counterproductive because the result was smaller crop plants and earlier competition from weeds and a shorter time during which the crop could withstand weed competition. Weaver (1984) did not identify a true critical period for weed competition in cucumbers.

Leek—Allium ampeloprasum L.

Leek and most *Allium* spp. (e.g., onion, garlic) are weak competitors. They have minimal shoot structure and do not readily cover the soil surface. Studies were done to determine if celery could be used as a companion crop to suppress weeds in leek (Baumann et al. 2000). Intercropping leek and celery in a row-by-row design shortened the critical period for weed control in the intercrop compared to monocropped leek. The relative soil cover of weeds that had emerged at the end of the critical period was reduced by 41 percent in the intercrop. The biomass of common groundsel that was planted 20 days after crop establishment was reduced 58 percent in the intercrop and seedlings emerging from the planted common groundsel were reduced 98 percent compared to monocropped leek. In addition, the relative yield total of the intercrop exceeded the pure stand by 10 percent, which Baumann et al. (2000) attributed to more optimal use of resources. However, leek quality was reduced. The idea of intercropping or companion cropping for weed management is not new but its potential has not been adequately investigated.

Lettuce—Lactuca sativum L.

Seven weeks of interference from spiny amaranth reduced lettuce head weight 20 percent and 8 weeks reduced head weight 24 percent. When phosphorus was banded, the effect of spiny amaranth was reduced, but the interference between the species was not due to competition for phosphorus. The weed's density and the duration of interference had little to no effect on the phosphorus content of lettuce (Shrefler et al. 1994b). The addition of phosphorus made lettuce and spiny amaranth equally competitive at low densities but spiny amaranth was four times more competitive at high densities in a greenhouse/pot study (Shrefler et al. 1994a). The weed produced 2.4 times more biomass than lettuce when competition was intraspecific and four times more when it was interspecific. Spiny amaranth was more competitive than lettuce regardless of the phosphorus level, but phosphorus increased the competitiveness of lettuce. The total lettuce shoot biomass per pot and the weight per plant increased 39 and 44 percent in response to phosphorus (Shrefler et al. 1994a).

Radish—Raphanus sativus L.

Radish and shepherd's-purse have similar height, leaf area, and root biomass, and they often occur together. In mixtures, radish was the stronger competitor. Its total dry matter and tuber production were affected only slightly or not at all in mixtures with shepherd's-purse. In monoculture, the two species had similar leaf areas, but that of shepherd's-purse was greatly reduced in mixtures because of the ability of radish to intercept light. Radish was able to grow taller in mixture than it did in monoculture (Perera and Ayres 1992).

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WHEAT—*TRITICUM AESTIVUM* L.

This chapter claimed (see Rice, above) that rice is the world's most important crop because more people depend on it for their daily sustenance than on any other crop. If the number of acres on which a crop is grown or the range of latitude over which the crop is grown are the appropriate criteria, then wheat, not rice, is the world's most important crop. It is grown on about 213.6 million ha each year over a wider latitudinal range than other major crops. It is grown where the weather is too dry or too cold for rice or corn. The annual crop is 576.3 million metric tons with an average worldwide yield of 2,698 kg ha^{-1} (United Nations 2000). Clearly wheat is one of the world's most important crops.

Challaiah et al. (1983, 1986) used a field study to select wheat cultivars that were competitive with downy brome. Downy brome reduced the grain yield of all cultivars 9 to 21 percent at one site and 20 to 41 percent at a second site in the same year. Wheat tiller number, canopy diameter and height were all negatively correlated with downy brome yield, but changes in these parameters did not always result in an increase in wheat grain yield. In this study (Challaiah et al. 1983, 1986), wheat height was most closely correlated with a decrease in downy brome yield.

Légère and Bai (1999) included rapid and uniform seedling emergence, tillering, early biomass accumulation, canopy closure, and a height advantage over competing weeds to evaluate the effects of no-tillage practices on growth and productivity of oats, barley, and wheat. All three crops were grown with and without soil tillage, and the cereal growth parameters were measured six or seven times during the growing season. Grain yield and yield components were determined at crop maturity. Oats and barley were little affected by tillage but wheat populations were reduced 16 to 20 percent by no-tillage. Height in no-tilled systems was similar or greater than in tilled systems for all three cereals (Légère and Bai 1999). Leaf area index and biomass accumulation were also comparable in both systems for all three cereals, except for wheat, which was greater in tilled systems but only on two sampling dates. Légère and Bai (1999) found that the response of annual dicot weeds to tillage was inconsistent in all crops. Perennial dicots dominated no-tillage systems and perennial monocots were more abundant in tilled systems for all three cereals. Yield of all three cereals (except barley in one year) was comparable or greater in no-till plots and wheat production was maintained in spite of reduced plant establishment (Légère and Bai 1999).

Cousens and Mokhtari (1998) studied the ability of wheat cultivars to maintain yield in the presence of weeds over several locations and in successive years. They found that the magnitude of the yield advantage for some cultivars differed a lot between years and locations. More important, there was little correlation between competitiveness at different sites in one year or between years. Cousens and Mokhtari (1998) found only one cultivar that was a consistently good competitor and two that were consistently poor. Their quest was to identify cultivars that were consistently more competitive so they could be recommended to farmers, but their data did not provide any basis for consistent, good advice to farmers.

Wicks et al. (1994) suggested that winter wheat cultivars that are more competitive help control weeds in rotational crops. Cultivars that averaged 90 to 109 cm tall were consistently more competitive than those that were 80 to 89 cm or 69 to 79 cm tall. When sorghum was grown in fields that had grown the more competitive wheat cultivar, weed biomass in sorghum was 61 percent less than in fields that had grown the less-competitive wheat cultivars. Sorghum yield was also higher when it was grown after more-competitive wheat cultivars.

Christensen (1994) used oilseed rape as a substitute for weeds to determine if there was a significant interaction between the competitive ability of wheat, barley and rye cultivars and herbicide performance. A target level of 5 g of weed dry matter m^{-2} was used. He found that one winter wheat cultivar required a 154 percent higher herbicide dose than a winter barley cultivar, whereas for winter rye, herbicide dose could be reduced 31 percent.

Rather than crop cultivars, Wilson and Wright (1990) studied the role of growth and competitiveness and ranked the competitive order of 12 annual weeds in winter wheat. Weeds that senesced in midsummer were less competitive than those with a growth pattern similar to wheat. In one year, most weeds had little effect on wheat because crop density was high. Crop yield–weed density relationships for all species in one year and for catchweed bedstraw in a second year were described well by the rectangular hyperbola. Wilson and Wright (1990) proposed that a competitive index, derived from yield density relationships and expressed as the percent yield loss for a weed m^{-2}, is more likely to reflect a weed's competitive ability in a crop than is an index derived from a plant's weight in the crop.

Some of these relationships may be explained by the work of Barnes et al. (1990), who demonstrated the importance of canopy structure as a determinant of the light interception and carbon gain in mixed and pure stands of wheat and wild oat. In mixtures, the fraction of the simulated canopy photosynthesis contributed by wheat declined during the growing season and the decline was closely related to reduction in the amount of leaf area in the upper canopy. Canopy photosynthesis for both species was most sensitive to change in leaf area and leaf inclination in the middle and upper canopy. Changes in leaf area index and leaf inclination affected carbon gain differently in mixtures and monoculture and differently for the two species (Barnes et al. 1990). Total leaf area alive and functioning at one time in each species was the most important determinant of competitive success. Light competition in the mixture of wheat and wild oat was influenced heavily by differences in positioning of leaf area in the upper canopy, which determines the amount of light intercepted (Barnes et al. 1990).

Wells (1979) studied the effect of the density of five broadleaved weed species at five different sites on the yield of wheat at three levels of applied nitrogen. The relationship between dry matter production and population density for all but one of the five weeds was curvilinear but the curvature was slight and the effects of competition of the weeds in wheat was linear for four of the five weeds. Nitrogen increased wheat yield at all sites but the effects of weed competition did not change (Wells 1979).

Gill and Blacklow (1984) investigated the effect of great brome on the growth of wheat and its uptake of nitrogen and phosphorus. Shoot dry matter of wheat was reduced from 1.4 g per plant to 0.5 g per plant after it competed for 71 days with 400 great brome m^{-2}. Competition with 400 great brome m^{-2} reduced the concentration of nitrogen in wheat shoots with three tillers (Feeke's scale 3) from 4.1 to 3.2 g and phosphorus from 0.77 to 0.58 g. Gill and Blacklow (1984) determined that nitrogen and phosphorus concentrations in wheat shoots were reduced before any detectable reductions in dry matter. One can conclude that great brome competed with wheat for these nutrients, but competition for water during grain filling caused the greatest reduction in grain yield.

Dhima and Eleftherohorinos (2001) studied the influence of nitrogen on competition between winter wheat and sterile oat. Dry weight of wheat, barley, and triticale were not affected by sterile oat (110 plants m^{-2}) until March of the year after planting, but yields were reduced by sterile oat competition after that time. Grain yield of wheat and barley were reduced 61 percent by 110 sterile oats m^{-2} but barley yield was reduced only 9 percent. Nitrogen (150 kg ha^{-1}) slightly increased yield of all crops in monoculture, and it increased sterile oats dry weight and its competitive ability against wheat and triticale (Dhima and Eleftherohorinos 2001). When 50 kg of nitrogen ha^{-1} was applied before planting and followed by 100 kg ha^{-1} in early March, there was a slightly higher increase in sterile oats dry weight compared to one nitrogen application before planting. The results indicate that, for winter wheat in Greece, the time of nitrogen application could be used to give a slight advantage to the crop and that barley is more effective at limiting a sterile oat infestation than wheat or triticale.

The competition between sterile oat and six wheat cultivars, each with a different maturity time, was studied in a greenhouse experiment by González-Ponce (1988). He determined that competitiveness was similar for all cultivars, but the cultivars with the longest time to maturity were affected most because they were consistently shorter. This is because most of the stem extension and some of the grain formation took place after the sterile oat panicles had expanded above the wheat canopy. Intraspecific competition was always greater than interspecific competition.

The interference of four weeds in wheat has been studied more than all of the 25 other weeds that have been studied. The four weeds are the ryegrasses (especially Italian ryegrass), *Bromus* spp. (especially downy brome), blackgrass, and jointed goatgrass. None of these has been studied as extensively as other species have been studied in corn and soybean.

Liebl and Worsham (1987) studied the interference of Italian ryegrass in wheat in North Carolina. Wheat yield declined 4.2 percent for every 10 Italian ryegrass plants m^{-2} when the weed density ranged from 0 to 100 m^{-2}. The weed's effect was primarily a reduction in wheat tillering. Italian ryegrass densities as high as 80 m^{-2} had little to no effect on wheat head or kernel weights. Liebl and Worsham (1987) also found that Italian ryegrass responded more than wheat to added nitrogen and potassium. The net uptake of the two nutrients was twice as great for the weed as it was for wheat, so there was probably some level of competition for nutrients.

Italian ryegrass had significantly greater biomass in monoculture than in competition with wheat because wheat seedlings were much larger than the weed seedlings for the first 20 days after emergence. Thus, the results of this study were affected by the weed's effect on tillering of wheat, some competition for nutrients, and wheat's initial advantage of greater seedling size.

Ghersa et al. (1994) (in Argentina and Oregon) took a different approach and asked if the radiation environment during winter-wheat establishment could be manipulated to favor wheat. The percentage of total radiation and the ratio of red (660 nm) to far-red light (730 nm) that reached the soil surface were important regulators of Italian ryegrass germination, growth, and subsequent interference with wheat. If the total radiation that reached the soil surface was reduced to about 10 percent of full sunlight while the red:far red ratio was maintained at about 1.0, wheat grain yield fell 40 percent compared to weed-free wheat in full sunlight. Reducing total radiation to only 3 percent of full sun and reducing the red:far red ratio to 0.2 reduced wheat grain yield in the presence of Italian ryegrass by 35 percent compared to wheat yield in full sun. In both the pure Italian ryegrass and the mixed stands, Italian ryegrass dry matter production was reduced by low irradiance and the low red:far red ratio. The combination of low irradiance and low red:far red ratio reduced dry matter production to about 50 percent of that in the control. Red light enrichment beneath the plant canopy, to achieve a red:far red ratio of 1.3, increased Italian ryegrass germination by 20 percent compared to normal light. Ghersa et al. (1994) did not define the mechanism, but clearly demonstrated that manipulation of radiation during the early stages of crop growth may be a good weed management technique.

Hashem et al. (1998) used an addition series experiment to study interference of Italian ryegrass in wheat. In monoculture, 80 to 85 percent of the variation in wheat biomass was explained by crop density (plants m^{-2}). However, in mixtures, initial wheat density and initial weed density explained 74 to 80 percent of wheat total biomass and 68 to 79 percent of the total biomass of Italian ryegrass. Interspecific competition was apparent 15 to 90 days after emergence for wheat but not until 90 to 170 days after emergence for Italian ryegrass. The maximum intraspecific competition occurred in wheat 170 days after emergence, whereas maximum interspecific competition with Italian ryegrass occurred during wheat's reproductive stages. This was because 200 days after emergence the leaf area index of Italian ryegrass was 6.6 times that of wheat. The weed reduced the photosynthetically active radiation reaching wheat up to 68 percent at wheat's booting stage (Hashem et al. 1998). Wheat's grain yield could be reduced up to 92 percent by Italian ryegrass. As few as 9 weeds in 100 wheat plants m^{-2} reduced wheat yield as much as 33 percent. In a subsequent study, Hashem et al. (2000) looked at the competitive effect of winter wheat planted in a square arrangement with Italian ryegrass planted randomly, on biomass yield of each species, Italian ryegrass seed yield, nitrogen use efficiency, and progeny seed germination. Increases in wheat density up to 800 plants m^{-2} reduced Italian ryegrass seed yield up to 87 percent but increased its harvest index up to 42 percent. Density and species interaction accounted for 66 to 73 percent of the total variation in each species biomass, and association (Italian ryegrass and wheat growing together) was less harmful to Italian ryegrass. Both inter- and intraspecific competition increased nitrogen content of wheat grain, whereas only interspecific competition affected nitrogen content of Italian ryegrass seed. Hashem et al. (2000) found that wheat's nitrogen uptake was three times greater than that of Italian ryegrass, but the latter was twice as efficient as wheat was at producing a unit of biomass per unit of nitrogen. In contrast to the results of Dhima and Eleftherohorinos (2001), nitrogen was not the main limiting factor in competition between the two species.

Stone et al. (1998) examined aboveground and below-ground interference of Italian ryegrass and wheat in the greenhouse. They found that aboveground interference of Italian ryegrass had no effect on wheat and that the volume of soil (pot volume of 90, 950, or 3,800 ml) in which 1 wheat plant grew with 9 Italian ryegrass plants had no effect on interference interactions. However, if Italian ryegrass interference was restricted to roots, the weed had a competitive advantage.

Carson et al. (1999) considered the relative ability of wheat and Italian ryegrass in adequately watered and dry environments. When Italian ryegrass was grown alone for 14 weeks, it produced a greater leaf area, greater dry weight of stem and roots, and more tillers than monocultural wheat. Because wheat had larger seeds, grew taller, and had a larger initial leaf area, it was able to produce a greater final leaf area and stem dry weight when grown with Italian ryegrass. Wheat was able to maintain a greater leaf expansion rate during drought and a greater leaf area afterward and thus had greater growth than Italian ryegrass in pure cultures of each. But when drought was relieved, the relative competitive ability of Italian ryegrass in mixtures with wheat was enhanced.

In contrast to other studies, Tanji et al. (1997) showed in greenhouse studies and separate field studies in Morocco that wheat was an effective competitor with Italian ryegrass and cow cockle. One wheat plant was as competitive as 11 Italian ryegrass plants in the greenhouse and as 19 Italian ryegrass in the field. One wheat plant was as competitive as 3 or 24 cow cockle plants. Shoot dry weight was the easiest, fastest, and least-expensive parameter to measure, and it was employed, but, as other studies have shown (e.g., Hashem et al. 1998; Stone et al. 1998), it may not have been the best parameter to measure. Growth analysis (Tanji et al. 1997) showed, as Carson et al. (1999) showed, that wheat had a greater leaf area, shoot and root dry weight, and absolute growth rate than either weed, especially early in the growing season. Tanji et al. (1997) concluded that if wheat density was 120 to 240 m^{-2}, wheat alone could minimize the competition of each weed and acceptable wheat yields could be obtained under Morocco's dryland conditions.

Two papers have explored interference of two other ryegrass species: rigid ryegrass (Lemerle et al. 2001) and perennial ryegrass (Wright and Hebblethwaite 1983). The paucity of papers on rigid ryegrass was surprising given its importance in Australia. However, much of that work has emphasized control and management in light of problems with herbicide resistance and that work is not reviewed here.

Lemerle et al. (1995) studied the competitive ability of eight winter crops with the annual, rigid ryegrass. The purpose was to determine if one or more of the crops could be used as part of a weed management program to suppress rigid ryegrass. The order of decreasing competitive ability with the range of percent yield reduction for each species in competition with 300 rigid ryegrass plants m^{-2} was: oats (2–14 percent), cereal rye (14–20 percent), oilseed rape (9–30 percent), wheat (22–40 percent), barley (10–55 percent), field pea and lupine (100 percent). There were differences in the competitive ability of the two cultivars chosen for each species, but competition was more strongly influenced by the different growing conditions in each year. The study (Lemerle et al. 1995) demonstrated competition for the three major nutrients and for light. Rigid ryegrass dry matter and seed production were negatively correlated with yield of each crop. Lemerle et al. (1995) concluded that competitive crops offered promise for suppression of grass weeds, especially in the case of grain legumes.

Medd et al. (1985) determined that wheat's planting arrangement had little influence on rigid ryegrass competition independent of crop density. However, rigid ryegrass's effect on wheat yield was substantially reduced by increasing wheat plant density from 40 or 75 to 200 plants m^{-2}. The reciprocal yield model was a good predictor of yield reduction, especially when it included the ratio of weed to crop density. Lemerle et al. (2001) also studied the relative competitive advantage of 12 commercial wheat varieties at several sites in southeastern Australia over 3 years (see Cousens and Mokhtari 1998 and Christensen 1994 for similar work). Nearly all (81 percent) the variation in wheat yield was attributed to variety x environment effects with only 4 percent due to variety x weed x environmental effects. Three varieties exhibited environment-specific competitive advantages, and at least three others were poor competitors in some environments. Lemerle et al. (2001) proposed that greater genetic variability was required in wheat to improve competitiveness. They also suggested the older tactic of increasing wheat seeding rate as a useful management technique. Varieties that showed a competitive yield advantage also suppressed growth of rigid ryegrass. Lemerle et al. (2001) concluded that Australian wheat breeders may inadvertently select for competitive advantage against weeds when they select for traits such as early vigor.

Wright and Hebblethwaite (1983) demonstrated, as others have, that perennial ryegrass seed yield in the presence of wheat depended on wheat density and the number and weight of perennial ryegrass tillers (its density). The greatest reduction in perennial ryegrass seed yield occurred, as expected, in the presence of high (300 plants m^{-2}) wheat density. When wheat density was low (80 plants m^{-2}), ryegrass seed yield was reduced much less, but the number of live wheat plants gradually decreased. Between 0 and 300 perennial ryegrass m^{-2}, a 1 percent loss of perennial ryegrass seed yield occurred for every 10 wheat plants m^{-2}. The work demonstrates the effectiveness of crop density as a weed management technique.

Blackgrass has been a much greater concern in the UK than in the United States. The seriousness of the management problem was illustrated by Moss (1983) who showed that over 95 percent of blackgrass seed was shed before winter wheat was harvested, and 70 percent of all seed produced was shed between mid-July and mid-August prior to wheat harvest. Barley, because it is harvested a bit earlier in the UK, had fewer seeds shed prior to harvest. Wilson (1979) stressed the need for early control, especially when blackgrass and wild oats were both present in wheat.

In northern Turkey, Mennan et al. (2002) determined that the economic threshold for blackgrass was 23 to 39 plants m^{-2}, whereas it was only 11 to 20 plants m^{-2} for wild oat, at densities of 2, 5, 10, 20, or 40 plants m^{-2}.

The effect of weed density, nitrogen fertilizer, crop planting date, and weed emergence on competition between wheat and blackgrass was studied in the greenhouse by Exley and Snaydon (1992). Root competition affected the growth of wheat and blackgrass more than shoot competition, although shoot competition affected blackgrass survival more than root competition. Nitrogen fertilizer partially alleviated the effects of root competition but did not affect root competition because each species has similar needs. If either species emerged later than the other, its competitive ability was reduced, particularly when competition was restricted to roots.

Work by Melander (1995) did not quite confirm the effect of planting date on competitive ability of blackgrass and silky bentgrass. Melander used two planting dates spaced 14 to 16 days apart. Planting date had an inconsistent effect on weed populations in spring, but seedling emergence of both weeds appeared to be delayed when later and early planting were compared. The delay could partially explain the reduced competitive ability of both weeds with the later planting (emergence) date. In some cases, seed population per plant was lower with later planting, but in other cases, there was no effect. Reduced seed production by each weed was caused more by a reduction in the number of inflorescences per plant than by planting date. In spite of variable results, Melander (1995) concluded that planting dates should be considered as a useful part of any management program for annual grass weeds in small grains.

The interference of three *Bromus* species has been studied in winter wheat. Stahlman and Miller (1990) found that densities of 24, 40, or 65 downy brome m^{-2} reduced wheat yield 10, 15, or 20 percent when downy brome emerged within 14 days after wheat emergence. Downy brome that emerged 21 or more days after wheat did not affect wheat yield. With downy brome densities up to 100 m^{-2}, the quadratic equation best described wheat yield loss as a function of weed density when the weed emerged within 14 days of wheat.

Blackshaw (1993) affirmed that the time of downy brome emergence relative to wheat emergence affected the magnitude of wheat yield reduction, and time of emergence was more important than downy brome density. Blackshaw (1993) showed that when wheat and downy brome had comparable density, the weed caused two- to five-fold greater reductions in yield when it emerged within 3 weeks after wheat than when it emerged 6 weeks after wheat or in early spring. Late-emerging downy brome could cause significant wheat yield or biomass losses, but only at densities of 200 to 400 plants m^{-2}. The lack of effect of late-emerging downy brome was due to shading (70 to 90 percent light reduction) of the weed by wheat for most of the growing season. When downy brome emerged early, it could reduce wheat biomass up to 59 percent and wheat seed yield up to 68 percent (Blackshaw 1993). In a subsequent study, Blackshaw (1994) clearly demonstrated that crop rotation and soil management influence downy brome density. In continuous wheat, downy brome density increased from 24 to 970 plants m^{-2} over 5 years. Weed densities were often higher with no-tillage. When fallow or spring canola were used in rotation with winter wheat, downy brome density decreased to less than 55 to 100 plants m^{-2}, respectively, over 6 years. Clearly, as Blackshaw points out (1994), continuous winter wheat will only worsen the downy brome problem in areas where the weed is prevalent, and, therefore, crop rotation is a desirable management practice.

Koscelny et al. studied the effects of winter wheat row spacing, cultivar, seeding rate, water, and nitrogen on competitiveness of hard red winter wheat with cheat (1990). In a separate experiment, they examined the interaction of wheat seeding rate and row spacing on interference by cheat (1991). When row spacing decreased from 23 to 8 cm, yield of weed-free wheat increased at two of three locations and the yield of cheat-infested wheat increased in 6 of 10 experiments. Increasing seeding rate from 265 to 530 seeds m^{-2} increased wheat yield. No wheat cultivar consistently suppressed cheat seed production. In the second study (1991), increasing wheat seeding rate (from 67 to 101 kg ha^{1}) and decreasing row spacing (from 22.5 to 15 cm) decreased cheat density, biomass, and seed harvested with wheat at two of three locations and increased wheat yield. The suppressive effect of wheat was greatest when it was seeded in September rather than later in the fall.

McCloskey et al. (1998) studied the interaction of a third brome species, poverty brome, with catchweed bedstraw, corn poppy, and wheat. Poverty brome was the most effective competitor of the four species. Its population increased tenfold under minimum tillage and declined with plowing. Corn poppy densities remained low in all trials, and catchweed bedstraw increased on organically fertilized, minimum-tillage plots except when poverty brome was present. High densities of poverty brome reduced the population of catchweed bedstraw. In the first season of this work (McCloskey et al. 1998), fertilizer had the greatest influence on crop yield, but subsequently poverty brome's density was the most important determinant of crop yield. Mccloskey et al. (1998) concluded that the interaction of weed species and crop yield was weak. Such interactions could be observed but only at high weed densities, and the interactions are unlikely to be of great economic importance.

Pollard (1982) provides a good, but not quantitative, box diagram (see fig. 1 of his paper) of the life cycle of poverty brome in winter cereals in the UK. Using the diagram, Pollard developed an arithmetic model of changes in poverty brome's population.

Fleming et al. (1988) included downy brome and jointed goatgrass in their study of competitive relationships with winter wheat. A replacement series study was used with all possible combinations of the three species. In growth chambers with ample fertility and water and a day/night temperature of 18/10°C, the relative total yield of the three species was similar, and the authors concluded that they likely competed for the same resources. Wheat and jointed goatgrass had greater plant growth and a higher relative crowding coefficient than downy brome. Wheat was generally slightly more competitive than jointed goatgrass at lower soil temperatures (18/10°C) and higher soil water potentials (-33 kPa). Jointed goatgrass was much more competitive than downy brome.

Gill et al. (1987) reported that ripgut brome was an aggressive weed in wheat in Australia, especially on light soils. They developed an exponential model that adequately described yield loss of wheat due to competition from ripgut brome. The yield loss had been determined before the crop reached the grain-filling stage, and Gill et al. (1987) suggested that this diminished the importance of competition for water in wheat–ripgut brome mixtures. Production of fertile tillers was the wheat-yield trait that was most sensitive to ripgut brome competition.

Anderson (1993) showed that jointed goatgrass and wheat had similar soil water extraction depths in the U.S. central Great Plains. Jointed goatgrass development was similar to the winter wheat cultivar Vona over two seasons with different rainfall. The weed at a density of 18 m^{-2} reduced winter wheat yield 27 or 17 percent when it emerged with wheat or up to 42 days after wheat. Jointed goatgrass that emerged in late fall still reduced wheat yield, but removing jointed goatgrass by early March of the following year prevented wheat yield loss.

Ogg and Seefeldt (1999) set out to identify the competitive traits of seven cultivars of soft white winter wheat in competition with jointed goatgrass. The measures were increased wheat yield and reduced jointed goatgrass seed production. In a dry year, wheat that grew tall rapidly was able to maintain yield and reduce the weed's seed production. In a wet year, the number of wheat flower heads per plant, the rate of water use, and weight gain were all positively correlated with maintaining wheat yield. Jointed goatgrass seed production was lower in a wet year compared to a dry year but Ogg and Seefeldt (1999) were not able to identify any cultivar traits correlated with the reduction.

The efficacy of wheat seeding rate in management of jointed goatgrass in winter wheat was shown in work by Kappler et al. (2002). Winter wheat grain contamination (dockage) was reduced by 6 percent for every 10 additional wheat plants m^{-2} above the threshold density of 70 wheat plants m^{-2} at one Wyoming location and by only 0.5 percent for each additional ten wheat plants above a threshold density of 110 wheat plants m^{-2} in western Kansas. Increased wheat density reduced jointed goatgrass reproductive tillers in four of six location-year combinations and biomass in two of four location-year combinations. Kappler et al. (2002) acknowledged that the response of jointed goatgrass to wheat density was not consistent over locations or years, but advocated the use of increased wheat density in jointed goatgrass management programs.

The first edition of this book reported 17 studies of wild oat competition in wheat. Wild oat competition has been studied for many years in many crops. Cereals compete, but not well, with wild oat because of its normally slower germination. Among the first studies of wild oat competition were those of Pavlychenko and Harrington (1935) who demonstrated in careful, now classic, ecological studies that competition began under the soil surface when root systems mingled and water and nutrients became limiting. Barley competed more effectively than wheat because it provided a larger number of seminal roots 5 days after emergence and developed more crown roots 22 days after emergence than other cereals. Wheat's root system was 30 times larger than that of ball mustard (which depressed wheat yield up to 40 percent), but wheat was more severely depressed by wild oat which had a root area four times greater than wheat. All cereals grown alone had crown root systems and much larger root systems than when grown under the stress of intra- or interspecific competition. Cereals grown in 6-inch rows often failed to develop any crown roots. Intraspecific competition reduced total root system length 81 to 99 times in wheat, rye, and wild oat when single plants grown in 10-ft squares were compared to 18 to 20 plants ft^{-1} in 6-inch rows (Pavlychneko 1937). When wheat was drilled and wild oats or ball mustard were planted between crop rows, a further six- to tenfold reduction in total root length was observed.

In early work, Chancellor and Peters (1974) demonstrated that high densities of wild oats are required to depress yield observably, and that effects only become visible late in the wheat's growth. Wild oats affected yield in only 3 of 7 experiments and in each case at a population greater than 150 plants m^{-2}. No significant yield reduction occurred at 20 to 100 wild oat m^{-2}. Friesen (1960) found 135 wild oat yd^{-2} reduced wheat yield 77.5 percent, compared to 14 yd^{-2}. In early studies, Thurston (1962) confirmed that wild oat can be effectively suppressed by a dense crop of any autumn-sown cereal in the United Kingdom, but even the densest stand did not completely suppress the weed. The effect was mainly due to decreased seedling growth.

In Canada, Bowden and Friesen (1967) obtained contrary results because 10 to 40 wild oats yd^{-2} reduced yields of wheat grown on either summer fallow land, or on stubble land when ammonium phosphate was added; also, effects became evident early in the growth. (The rainfall and soil moisture patterns of the relatively wet UK are quite different from dryland Canada.) One Canadian winter fallow could reduce wild oat populations by 97 percent. Two consecutive fallow years reduced wild oat density to less than 0.2 m^{-2} (Philpotts 1975). Without added ammonium phosphate, 70 to 100 wild oats yd^{-2}, a density approaching that in Friesen's (1960) study, were required to reduce yield. Soil fertility (nitrogen status), Bowden and Friesen (1967) suggested, was a more important determinant of the effect of wild oat on wheat than moderate densities.

These early studies were all reported in the first edition of this book (Zimdahl 1980) and are included again to make the point that the wild oat problem, which has been studied extensively since 1980, is not new but has occupied the attention of weed scientists for many years. Leggett (1983) reported that dockage due to weed seed in wheat had averaged 2.6 percent (the range was 2.3 to 4.7 percent) from 1971 to 1981 at two Canadian terminals. Wild oat had accounted for up to 25 percent of the dockage. Leggett (1983) assumed the dockage due to wild oat had decreased but reported the dockage percentage had remained quite constant. It is safe to assume, as Leggett (1983) did, that the wild oat problem has diminished with time, but the evidence of continued study reported here affirms that it has not disappeared.

Gillespie and Nalewaja (1988), working with wild oats and wild mustard, showed that wheat yield was the greatest when both weeds were controlled at or before wheat's 2-leaf stage. The weeds were classified as equally competitive. Pollard et al. (1982) demonstrated the importance of cultural practices in work that showed that dicots tended to dominate or become dominant when soil was disturbed regularly, whereas perennials and annual grass weeds were favored by reduced cultivation. They suggested, and time has verified, that the shift away from plowing will favor annual grass weeds. Pollard and Cussans (1981) found, consistent with others, that wild oat was favored by reduced tillage. O'Donovan and Sharma (1983) offered the generalizations related to wild oats and wheat that increasing seeding rate reduces weed competition, and adding P_2O_5 at planting, especially with barley, favors the crop over wild oats, but adding nitrogen seems to benefit weed and crop equally. Morrow and Gealy (1983) provided at least some justification for the effects of tillage by showing that wild oat emerged in silt loam from depths up to 17.5 cm in a greenhouse study and from 15 cm in the field. There was no emergence from greater depths, and the greatest emergence was from 5 cm. Thus, decreasing tillage will not bring seed near the surface where germination is favored.

Martin et al. (1987) studied the effects of varying wheat density on competition from wild oat and winter wild oat. Both species reduced wheat grain yield by reducing the number of wheat tillers, but the effect could be reduced by increasing wheat stand density. When wheat stand density was increased beyond the weed-free optimum was unsatisfactory for wild oat control.

Balyan et al. (1991) investigated the relative competitive ability and discovered that winter wild oat reduced wheat yield 17 to 62 percent depending on the wheat cultivar. Wheat dry matter and grain yield were not correlated with wild oat dry matter. Wheat height and dry matter accumulation were reliable predictors of a cultivar's competitive ability but tiller number was not. Walker et al. (2002) studied the effectiveness of competition from three wheat densities in separate plots in competition with winter wild oat and hood canarygrass. Maximum crop yield and reduced weed-seed production was achieved for hood canarygrass with 80 wheat plants m^{-2} and a full herbicide rate. For winter wild oat, these things were achieved with 130 wheat plants m^{-2} and 75 percent of the full herbicide rate. The same effects were also achieved when wheat density was 150 plants m^{-2} but only 50 percent of the full herbicide rate was required. When wheat density was high (150 m^{-2}), the full herbicide rate tended to reduce yield particularly with the herbicides effective against winter wild oat. This quite logically also decreased suppression of weed-seed production. Walker et al. (2002) strongly advocated that more-competitive wheat cultivars and higher crop densities have the potential to improve weed control and reduce herbicide rates.

Martin and Field (1987) studied competition of wild oats with wheat in a replacement series and in a separate experiment where the effects on roots and shoots were separated. In association, the two species competed for the same resources and the interaction tended toward mutual exclusivity. Wild oats are more competitive than wheat as Martin and Field (1987) illustrated by wild oats' greater aggressivity relative to wheat, their relative yields, and their shoot dry weights. They attributed wild oats' greater competitiveness to their greater root competitive ability. The species were similar in terms of shoot competitiveness, but the effects of root and shoot competition were additive. Martin and Field (1988) also showed that wild oats were more competitive than wheat when they were planted simultaneously and that competitiveness was due to greater root competition. If wild oats were planted 3 or 6 weeks later than wheat, wheat was most competitive and the number of wild oat panicles was reduced. They also attributed this to wheat's greater root competitive ability with delayed wild oat planting. Shoot competition by wheat was also greater, but the difference was attributed to root effects.

Cousens et al. (1991) used a replacement series and found in the UK that wild oats were much slower to establish than winter wheat or winter barley but had a faster rate of growth after establishment than either cereal. In monoculture, wild oats grew more slowly than either cereal but were the largest of the three species by the end of the study. The switch from cereal dominance to wild oat dominance was likely related to wild oats' root development, as Martin and Field (1987) noted, and it occurred late in the season, at the flag leaf emergence stage of cereal growth. Cousens et al. (1991) were not able to predict, on the basis of their work, that wild oats were always most competitive. In one case, barley was equally competitive, and in a second location, barley was the least competitive of the three.

The vigor and importance of root competition is affirmed in the work of Satorre and Snaydon (1992), who demonstrated in box studies that separated root and shoot competition, that competition for soil resources (especially nitrogen) was more severe than competition for aerial resources (i.e., light). When both root and shoot competition occurred, oats and barley were more competitive than wheat, but there were significant differences among cultivars of all cereals. Although nitrogen was a major factor in competition, nitrogen fertilization did not change the ranking of the cultivars. Cultivars also differed significantly in shoot competitive ability, but these differences were apparently not due to height differences (Satorre and Snaydon 1992). Henson and Jordan (1982) had previously shown that increasing nitrogen fertilization did not eliminate the depressing effect of wild oats on wheat growth or yield.

Cudney et al. (1989) used replacement series and additive series to study wheat–wild oat competition. In contrast to Martin and Field's (1987) and Cousens et al. (1991) work in the UK, Cudney et al. (1989) showed, in California, that in a replacement series study, wheat and wild oats were equally competitive, and the yield of wheat grain was linearly proportional to the relative density of wild oats. On a per plant basis, the shoot dry weight and leaf area index of wild oats were less than those of wheat at wheat anthesis. The relative density of wild oats gave a better fit in a regression equation than the absolute wild oat density. In a separate study, Cudney et al. (1991) showed that wild oats grew taller and had a greater proportion of their canopy above 60 cm at maturity in competition with wheat, thus confirming the results of Cousens et al. (1991). However, in contrast to Satorre and Snaydon (1992), who found root competition to be most important, Cudney et al. (1991) proposed that interference from wild oats was due to a reduction in wheat's leaf area at early growth stages when wild oats' density was low or the plants were not interfering because of the distance between small plants. They proposed a mathematical model to predict the reduction in wheat growth caused by wild oats. The model is based on the light penetration to wheat leaves at later growth stages and with higher wild oat density. For mixed culture the model is:

$$X_t = \frac{\sum_{h=1}^{h=n} (LAI \times \%light\ penetration)_h\ for\ mixed\ culture}{\sum_{h=1}^{h=n} (LAI \times \%light\ penetration)_h\ for\ mono-culture}$$

where, x = ratio of growth rate of wheat in mixed culture to the growth rate in monoculture, t = time, LAI = leaf area index, and h = each 10-cm increment of height (Cudney et al. 1991).

Green foxtail competition with wheat has been studied, primarily in Canada, because it was among the most prevalent weeds in the 1970s. Yield losses ranged from 2 to 25 percent. Green foxtail was not as competitive as wild oats and wild mustard. Blackshaw et al. (1981a) showed that as few as 100 green foxtail m^{-2} significantly reduced the yield (21 percent) of a normal height wheat cultivar (Napayo) and of the semidwarf cultivar Norquay by 44 percent. In the same year, 1,600 green foxtail m^{-2} reduced the yield of Napayo 67 percent and Norquay 82 percent. However, in one year (1977) 1,600 green foxtail m^{-2} did not reduce yield of the cultivar Sinton, a cultivar of normal height, but yield was reduced 43 and 54 percent by 800 and 1,200 green foxtail m^{-2} in a second year. Thus, the intensity of competition was not determined by density alone. There was also no correlation between the level of green foxtail competition and the date of seeding. However, Blackshaw et al. (1981b) found that the soil temperature and soil water at time of planting strongly influenced the early growth of green foxtail and were the most important determinants of the vigor of competition. A soil temperature decrease from 20 to 15°C caused a 53-hour delay in the time to reach 50 percent germination of green foxtail seed. Soil water had an even greater effect; at -650 kPa, green foxtail seed did not germinate at all. In the field, when soil was warm (20 to 25°C) and moist (0 to 400 kPa), green foxtail emerged within a few days of wheat. If soil was dry (-400 to -650 kPa) and temperature was 15 to 20°C, green foxtail emerged 7 to 14 days after wheat and competition was significantly reduced. Wheat normally emerged within 6 to 8 days after planting, but green foxtail took 7 to 21 days to emerge and the differences were more pronounced at low temperature and moisture. Blackshaw et al. (1981b) clearly illustrated the effect of time of emergence on competition of green foxtail in wheat (table 5.4).

Cool temperatures give early-seeded spring wheat a competitive advantage over kochia and Russian thistle (Nord et al. 1999). Fresh weight of wheat was greater at 15°C than it was for either weed. When growth-chamber temperatures were 23 or 30°C, fresh weights of the weeds were greater than wheat's.

Peterson and Nalewaja (1992) also demonstrated that yield reductions of hard red spring wheat varied with the prevailing environment in field experiments conducted over 3 years in North Dakota. Yield reductions ranged from 0 to 47 percent from 720 green foxtail m^{-2}. When yields were regressed based on weed density alone, the coefficient of determination was only 0.12. Similar to the work of Blackshaw (1981a, b), the coefficient of determination improved to 0.62 when multiple regression analysis included early season temperature, soil texture, and foxtail density. Wheat yield reduction decreased as green foxtail planting and emergence were delayed after wheat.

O'Donovan (1994) confirmed the poor relationship between weed density or weed dry weight and crop yield for competition of green foxtail and pale smartweed with wheat, barley, and canola in studies over 4 years in Alberta. He suggested this was indicative of the weeds' being poor competitors with the crops. If the crops emerged ahead of the weeds and soil moisture was not limiting, yield losses were minimal.

The competition of yellow foxtail and barnyardgrass with barley and spring wheat was studied by Vezina (1992) over 3 years in Quebec. Yellow foxtail infestations of 850 and 240 plants m^{-2} reduced wheat yield in 2 years only when the crop was planted late. Barnyardgrass at 830 to 920 plants m^{-2}

Table 5.4. The Effect of Time of Emergence of Green Foxtail Relative to That of Two Wheat Cultivars on the Competitive Effect of Green Foxtail on Wheat

	Time to 50% emergence (days)		Yield reduction[a] (%)		Green foxtail seed yield (kg ha^{-1})	
Planting date	Wheat	Green foxtail	Sinton	Norquay	Sinton	Norquay
First year						
May 24	6	8	12[b]	22[b]	161	273
June 2	8	16	12[b]	15[b]	59	220
June 17	7	7	6	18	61	73
Second year						
May 28	7	13	23[b]	38[b]	389	610
June 5	7	15–21	7	15[b]	103	152
June 11	6	16	9	42[b]	269	472

[a] Wheat yield compared to weed-free plots.

[b] Significant yield reduction, $p = 0.05$ using Tukey's HSD.

reduced wheat yield in only one year when the crop was planted late. When either of the cereals was planted late, the weeds emerged at about the same time as the crop. But if the crop was planted early (late April to the first few days of May), the weeds did not affect crop yield.

The interference of 19 other weeds, most represented by only a single report, has been studied in wheat. Because there is no apparent logic to the choice of weed studied by the several researchers involved, the weeds will be listed alphabetically.

Canada Thistle (*Cirsium arvense*)

In eight of nine trials over 5 years, wheat yield decreased linearly as Canada thistle shoot density increased (Donald and Khan 1992). There was no difference in the effect of Canada thistle between no-till and chisel-plowed plots. The effect of Canada thistle on wheat yield was greater in years with more rainfall. In further work (Donald and Khan 1996), Canada thistle decreased wheat density (stand) in 3 of 4 years, which was the primary cause of reduced wheat yield. The reduction of the number of wheat spikes per plant and seeds per spike varied between years. In contrast, Mamolos and Kalburtji (2001) found over 4 years with Canada thistle densities of 0, 4, 16, or 64 plants m^{-2} that the main factor in wheat yield reduction was nitrogen concentration. Second, Canada thistle biomass and last its density contributed to wheat yield loss.

Canarygrass, Littleseed and Short-spiked (*Phalaris minor* and *P. brachystachys*)

Two studies conducted in Greece (Afentouli and Eleftherohorinos 1996, 1999) showed that the competitive ability of the two species of canarygrass was similar but littleseed canarygrass had a faster growth rate and more panicles. Wheat yield was not affected by a weed density of 76 m^{-2} but was reduced 36 to 39 percent by 304 weeds m^{-2}. Neither species affected wheat yield when the weather was cold and dry during early growth stages. When the weeds were present at harvest, wheat yield was reduced 23 to 28 percent.

Common Lambsquarters (*Chenopodium album*)

A replacement series, conducted in the greenhouse, noted that competitive interference for phosphorus and, to some extent, for nitrogen was the major limit to wheat growth in the presence of common lambsquarters. Wheat noncompetitively restricted potassium uptake by the weed. Increasing weed density significantly reduced wheat grain size and yield (Bhaskar and Vyas 1988).

Common Milkweed (*Asclepias syriaca*)

In an additive study, wheat yield was reduced 47 percent at the highest density of 12 common milkweed m^{-2}. A simple linear model was as precise as more-complex models for yield loss prediction because common milkweed competed late in wheat's development (Yenish et al. 1997).

Common Sunflower (*Helianthus annuus*)

Sunflowers are commonly grown in rotation with wheat in the U.S. upper Midwest, consequently volunteer sunflowers frequently are a weed in wheat. When averaged over all planting dates and locations, season-long common sunflower competition from densities of 3, 9, or 23 plants m^{-2} reduced wheat yield 11, 19, and 33 percent, respectively (Gillespie and Miller 1984). Characteristic of most weeds in wheat, common sunflowers were more competitive when wheat was planted in late than in early May. Wheat yield was reduced 22 percent when 24 common sunflowers m^{-2} competed until wheat was in the flag leaf stage. Gillespie and Miller (1984) concluded that common sunflower densities of 9 plants m^{-2} or higher should be removed before the flag leaf stage to prevent wheat yield loss.

Corn Cockle (*Agrostemma githago*)

A natural stand of corn cockle had only a negligible effect on barley but reduced winter wheat yields 10 percent when crop density was a quarter of normal (Doll et al. 1995). When crop density was normal, the weed did not affect wheat yield. Doll et al. (1995) concluded that crop density was more important as a weed management technique than it was for crop yield. Both crops were effective competitors with corn cockle. Each species used growth resources better in mixture than when grown alone because the relative yield totals in mixture were always greater than unity.

With 3 years of data, Rydrych (1981) concluded that if corn cockle was removed monthly from emergence to harvest, wheat's yield decrease was not significant if the weed was removed before February in winter wheat that had been seeded the previous October. Corn cockle densities of 170 to 340 plants m^{-2} lowered wheat yield an average of 18 percent when competition was eliminated in March. Season-long competition, however, lowered yield 60 percent, whereas competition only in the fall had no affect on yield.

Dog Mustard (*Erucastrum gallicum*)

Greenhouse studies suggested that dog mustard was less competitive than wheat but had competitiveness similar to flax. Competition from both crops reduced the leaf area, shoot dry weight, height, and seed production of the weed compared to its growth on summer fallow. Wall (1997) concluded that dog mustard was not a vigorous competitor with wheat or flax.

Field Poppy and Field Violet (*Papaver rhoeas* and *Viola arvensis*)

Competition between field violet, field poppy, and wheat was studied in two experiments in two successive years in the UK (Wilson et al. 1995). The effects of varying crop and weed density were modeled in terms of weed biomass over time, weed-seed production, and crop yield. Weed biomass declined and a maximum was reached earlier with increasing crop density. Intraspecific competition was always higher in the absence of the crop, and it increased with time and weed density. If wheat density (population) was halved, the June biomass of field violet increased 74 percent and field violet increased 63 percent. Crop yield losses due to increasing weed density were consistently greater with low wheat density. Field poppy was a more vigorous competitor than field violet in both years. When summer drought restricted late weed growth, wheat yield losses were lower. As crop density decreased, weed-seed production increased to a maximum in weed monoculture.

Ivyleaf Speedwell (*Veronica hederifolia*)

Angonin et al. (1996) demonstrated the importance of choosing the right nitrogen fertility level for the weed to be controlled and for the desired level of wheat production. They used three different nitrogen fertility treatments, that is, 60 kg ha^{-1} at tillering plus 80 kg ha^{-1} at the time of first stem elongation, a total of 140 kg ha^{-1} applied at three times, 60 kg ha^{-1} applied at tillering, 60 kg ha^{-1} applied at the first node of stem elongation, and no nitrogen. The competitive effects of 17 to 192 weeds m^{-2} were greatest in the year when ivyleaf speedwell had the best early growth. Yield losses, described with a nonlinear model, changed each year because of differences in tiller mortality and the variable effects of nitrogen deficiency at stem elongation and flowering. In general, late nitrogen application increased wheat grain weight and decreased the weed's effects on the wheat.

Lanceleaf Sage (*Salvia reflexa*)

When lanceleaf sage was grown with nitrogen and phosphorus, it was more competitive than *Phalaris aquatica.* Stress from defoliation or drought adversely affected *P. aquatica's* competitive ability. Lanceleaf sage was more competitive with a summer crop of sorghum than with winter wheat (Weerakoon and Lovett 1986).

Quackgrass (*Elymus repens*)

Studies in Denmark (Melander 1994) showed that wheat was less competitive with quackgrass than rye, but, in contrast to many studies but similar to other studies in Denmark, more competitive than barley. When quackgrass density was 100 primary shoots m^{-2}, the yield loss in rye was about 8 percent and that in wheat was slightly higher. Yield losses were caused mainly by early competition that caused large reductions in ear number per unit area and kernel number per ear, but seed weight reductions were not greatly affected.

Redstem Filaree (*Erodium cicutarium*)

Among four crops (oilseed rape, pea, and dry bean), wheat was the most competitive with redstem filaree (Blackshaw and Harker 1998). Maximum yield reduction of 36 percent occurred with redstem filaree densities of 100 to 200 plants m^{-2}. Yield progressively decreased as the duration of redstem filaree interference increased. Three weeks of interference after crop emergence was sufficient to reduce wheat yield (and the yield of the other three crops). The mean yield reduction for each week of interference was 1.6 percent for wheat. Based on their results, Blackshaw and Harker (1998) suggested control of redstem filaree should be considered and early control is required. A second study by Blackshaw et al. (2000) determined that redstem filaree was most competitive with wheat (as nearly all weeds are) when it emerged before or with wheat and when rainfall in May and June was plentiful. Redstem filaree growth was significantly inhibited by drought. Increasing the wheat seeding rate from 50 to 300 kg ha^{-1} reduced redstem filaree seed production and biomass by 53 to 95 percent over 3 years, but wheat yield did not increase significantly above a seeding rate of 50 kg ha^{-1}. But, when redstem filaree was present, increasing wheat seeding rate from 50 to 300 kg ha^{-1} increased wheat yield from 56 to 498 percent. The increased seeding rate also decreased redstem filaree presence in the soil seedbank by 79 percent over 4 years. Thus, similar to several other studies reported here, crop seeding rate is an important component of integrated weed management.

Round-leaved Mallow (*Malva pusilla*)

Friesen et al. (1992) studied the relatively minor interference of round-leaved mallow in wheat and flax. In 6 of 7 trials, wheat yield loss due to round-leaved mallow was insignificant. In one trial with round-leaved mallow density of 237 plants m^{-2}, the yield loss was only 15 percent. The weed was severely suppressed by wheat. Eight weeks after emergence, the lamina area of round-leaved mallow was less than 3 percent and it produced less than 1 percent of the seed of plants growing alone. Wheat was so competitive with this mainly recumbent weed because wheat reduced photosynthetically active radiation (PAR) reaching the weed by 80 to 90 percent beginning 4 weeks after crop emergence and lasting for 6 more weeks. In contrast, Makowski (1995) found that round-leaved mallow was competitive with wheat in two of three experiments. They used a two-variable model that incorporated early-season crop density loss and round-leaved mallow biomass to account for wheat yield loss. Losses of up to 60 percent were recorded for wheat in years and locations where the weed emerged before the crop and affected crop emergence. In wheat, round-leaved mallow density of 200 m^{-2} decreased wheat biomass by 100 to 500 g m^{-2}**.**

Russian Thistle (*Salsola iberica*)

Young (1988) conducted 2- to 3-year field studies of the interference of Russian thistle with winter wheat. The wheat yield loss was 0.5 to 0.6 percent for each percentage of the total plant biomass contributed by Russian thistle. This was far below the predicted yield loss of about 10 percent. In one year, rainfall was 46 percent below normal and the highest Russian thistle density (200 m^{-2} seeded) produced more than 70 percent of the total plant biomass and reduced wheat yield more than 50 percent. The yield was not affected until after 6 weeks of interference. However, when rainfall was 65 percent above normal, the same density of Russian thistle produced only 20 percent of the total plant biomass and reduced yield only 11 percent. The differences in the effect of Russian thistle between years was related to the rainfall and its pattern, shading by the weed, the time of crop planting, and the relative time of emergence of the weed and wheat. In another study, Young (1986) compared the competitive effects of Russian thistle in winter and spring wheat. During the crop growing season, winter wheat suppressed the weed more than spring wheat. After harvest, the dry weight of Russian thistle that grew in wheat stubble suppressed up to 75 percent in winter wheat compared to spring wheat stubble. Young (1986) concluded that because winter wheat reduced seedling establishment, suppressed plant growth, and reduced the weed's seed production more than spring wheat, winter wheat should be planted in areas where Russian thistle is known to be a problem. One must assume that the wheat played an important role, but one must also assume that the season was responsible for many of the observed effects on the weed.

Rye (*Secale cereale*)

Pester et al. (2000) studied rye, a growing weed problem in winter wheat in Colorado, Kansas, Nebraska, and Wyoming. Wheat density was held constant at the recommended planting density for the site in each state, and rye density was 0, 5, 10, 25, 50, or 100 plants m^{-2}. A negative hyperbolic yield function was used to determine interference relationships. The parameters I (the percent wheat yield loss as rye density approached zero) and A (the maximum yield loss as rye density increased) were estimated with nonlinear regression. The I parameter was more stable among years within locations than across locations within years, whereas A was more stable across locations and years. Pester et al. (2002) said environmental conditions were important determinants and proposed based on dry versus wet years during the experiment, that economic threshold values of rye in wheat may be a function of soil moisture and temperature in addition to rye density. On average, the economic threshold was between 4 and 5 rye plants m^{-2}, but the large variation caused the authors to discourage others to use the values to make management decisions.

Tartary Buckwheat (*Fagopyrum tataricum*)

When 30 tartary buckwheat plants m^{-2} were present at wheat emergence, wheat yield decreased 22 percent. Yield loss was best represented by a linear equation

$$Y = 5.04 + 3.05 \sqrt{x}$$

where Y = percent yield loss and x = plant density (de St. Remy et al. 1985).

Wild Mustard (*Brassica kaber*)

Two experiments over 3 years investigated the competitive abilities of two spring wheat cultivars against wild mustard in the UK (Wright et al. 1999). The two cultivars with contrasting growth habits were grown with 10 or 70 percent of field capacity. In one year, wild mustard was less competitive and wheat losses were lower in dry soil than in moist soil. In both years, wild mustard seed production was reduced by competition and moisture stress, and seed produced in dry soil was smaller and had negligible dormancy. Wright et al. (1999) concluded that wild mustard's competitiveness and its potential to produce persistent seed may be reduced in dry years.

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OTHER SMALL GRAIN CROPS

Only five studies of weed interference in other small grain crops were found: two in rye, two in oats, and one in a *Setaria* spp.

Downy brome reduced rye yield most when it emerged within 3 weeks of rye emergence but downy brome densities of more than 100 m^{-2} were required to reduce rye yield 20 to 30 percent (Blackshaw 1993). The greatest reduction in rye biomass (28 percent) and seed production (33 percent) occurred when 400 downy brome m^{-2} emerged with rye. If the same density emerged 6 weeks after rye emergence or in early spring (rye is a winter crop in Alberta), biomass and seed yield were reduced less than 10 percent. Winter rye effectively shaded downy brome thereby reducing its competitive effect. Among the cereal grains, rye is a vigorous competitor. It is more competitive than wheat or barley (Melander 1994).

Kochia interference (30 plants m^{-2}, the highest density studied) reduced oat yield in 2 of 5 years in North Dakota (Manthey et al. 1996). Kochia interference did not affect oat height, grain test weight, groat percentage, or protein content.

As reported above (see Wheat), no-tillage reduced wheat population but it did not affect the population of oat or barley (Légèe and Bai 1999). The authors concluded that no-tillage, compared to tilled management systems, appears to be a good weed management technique for oat, despite the interference offered by different weed species.

In one experiment, Nandi setaria (*Setaria anceps*) aboveground dry weight and seed yield was reduced similarly by 20, 40, 80, or 160 goosegrass plants m^{-2}. The dry matter yield of 20 to 164 goosegrass plants m^{-2} did not differ significantly. If *S. anceps* density varied from 6 to 9.3 plants m^{-2}, there was little effect on yield of either species (Hawton and Drennan 1980). In one experiment, when goosegrass emerged 2 weeks or more after *S. anceps*, yield was not affected whether the crop was planted in rows or broadcast. In a second experiment, aboveground dry matter of the crop was reduced 21 percent when goosegrass emerged 2 weeks after the crop. If *S. anceps* was weeded for 13 days after planting, goosegrass did not reduce crop yield.

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STUDIES OF DIVERSE CROPS

It is well known that forage grasses are susceptible to competition from several other grasses and broadleaved species. Large crabgrass was more competitive than southern sandbur in forage bermudagrass (Walker et al. 1998). In late season, without competition, bermudagrass covered 96 percent of the ground. If southern sandbur was present, bermudagrass cover was reduced to 81 percent and large crabgrass reduced bermudagrass cover to only 72 percent, a significant decrease in forage yield.

Broadleaf dock is perceived as a major problem in intensively managed permanent grassland in Switzerland. Niggli et al. (1993) planted young broadleaf dock into established pure stands of Italian ryegrass, perennial ryegrass, meadow foxtail, or Kentucky bluegrass, and studied the effects of cutting interval (every 4 or 6 weeks) and nitrogen (120, 240, or 480 kg ha^{-1}) on broadleaf dock's dry matter production and stem growth. A cutting interval of 6 weeks was more favorable to broadleaf dock than the shorter interval. Nitrogen fertilizer favored the weed, which increased from 2 percent of total herbage yield at 120 to 18 percent with 480 kg nitrogen ha^{-1}. Of the four pasture species, only Italian ryegrass (well known as a vigorous competitor) was able to "substantially" hinder broadleaf dock's growth. Niggli et al. (1993) concluded that broadleaf dock could not be managed in permanent pastures of any of the four grasses by competition from the grasses, cutting or cutting frequency, or nitrogen fertilization.

One to three rhizomes of white kyllinga reduced the shoot fresh weight of two bermudagrass stolons to 56 percent of the control, but green kyllinga did not reduce shoot fresh weight significantly (Kawabata et al. 1994). Increased planting densities of both kyllinga species linearly increased the weed's shot fresh weight and decreased bermudagrass's shoot fresh weight. White kyllinga had greater leaf fresh weight, leaf area, roots, and rhizomes than green kyllinga, which produced more shoots and inflorescences.

The effect of a natural weed stand on 30 weeded and 30 unweeded 2-year old willow tree plots was determined. As one would expect, willow growth in the first year was greater in weeded plots (Sage 1999). However, in the second year willow growth was not different between plots, and losses over 2 years reflected only the effects in the first year of the study. Soil moisture and nutrient content measured in midsummer were not different between plots in either year. Because height was greater in weedy plots and stem number and canopy density were lower in the second year in weedy plots, the authors concluded that competition from tall weeds in the first year was primarily for light.

Similar to the study of willow, the effects of herbaceous weeds on loblolly pine grown on plantations in the southern United States have been studied. Seedling tree-height response to weed control was significantly related to the percentage of the soil covered by weeds, 7 weeks after control was initiated, and to weed biomass at the end of the growing season. The primary competition was for soil moisture that weeds depleted rapidly (Nelson et al. 1981). Rapid pine growth results when weeds are controlled early, but Nelson et al. (1981) were unable to predict which sites might benefit most because of the variable effects of rainfall and varying levels of weed competition. Britt et al. (1990) showed that loblolly pine with a low level of weed interference (percent ground cover = 1 to 7) had more aboveground biomass than trees grown with a high level of weed interference (percent ground cover = 62 to 82). Differences between levels of weed interference were created by using no control, herbicide in the first year, or herbicide in the second year of growth to control a natural weed stand. Trees in plots with a low level of weed control were 5 to 10 times larger than those in plots with a high level of weed interference. Trees grown with a high level of weed interference had a lower percent of their biomass in foliage and a higher percentage allocated to stems (Britt et al. 1990). Changes in carbon partitioning with lower allocation to development of leaf area were suggested to be the drivers of accelerated growth associated with lower weed interference.

After 19 years, ponderosa pine trees were 1.6, 1.9, or 5.7 m tall with no control of bearmat (A), phenoxy herbicide control (B), or a combination of herbicide and clipping (C), respectively (Tappeiner and Radosevich 1982). There was a 75 percent net wood reduction after 50 years of bearmat competition. Seedling survival was only 6 to 12 percent in management system A, 52 to 88 percent in system B, and 80 to 100 percent in system C. There was little mortality after 3 years.

The relative competitive ability of squirreltail (a native perennial range grass) and medusahead (an exotic annual range grass) was measured in a series of experiments in western Oregon (Clausnitzer et al. 1999). Over 3 years, the study included a very dry, a dry, and a wetter than normal year. Squirreltail is a desirable species on rangeland, but the greater interspecific competition of medusahead suggested that it will be difficult if not impossible to establish the desirable forage species in an existing stand of medusahead unless the weed is controlled. Squirreltail seedlings established and grew well without medusahead competition.

Gorse, a perennial introduced from Europe, is regarded as a weed in most places, but it was introduced to Oregon as an ornamental. The possibility of management with perennial ryegrass is shown by the work of Ivens and Mlowe (1980) in New Zealand. Without cutting, shoot growth of gorse exceeded that of perennial ryegrass over 22 weeks in monoculture, but gorse was more inhibited by competition from perennial ryegrass than the grass's growth was reduced by competition from gorse. The gorse root system was small compared to that of perennial ryegrass. If both species were cut three times at 2 to 4 cm, it reduced total growth of both, but gorse was affected more. The implications identified by Ivens and Mlowe (1980) are that pasture grasses such as perennial ryegrass should be established as quickly as possible after gorse clearing to limit seedling invasion because a gorse monoculture will yield more than a perennial ryegrass monoculture. Gorse control will also be aided by grazing animals.

One study of weed interference in cassava, a dietary staple of importance in much of Africa, Brazil, and India, was found. Giant sensitive plant interference for 12 months at densities of 10,000, 20,000, 30,000, or 40,000 plants ha^{-1} and a natural population of 630,000 plants ha^{-1} was compared. All of the weed populations reduced cassava root yield after 12 months of interference. Yield reduction from the natural population was 85 percent (Alabi et al. 2001).

Oil palm seedlings are commonly started in poly bags. Initial weeding of the polybags and the surrounding area delayed for 16 weeks after planting did not decrease seedling growth if weeding every 2 to 6 weeks followed (Iremiren 1986). When initial weeding was delayed until 20 weeks after planting and subsequent weedings were 8 weeks apart, seedling growth decreased, particularly seedling height. The authors demonstrated a connection between weed and disease occurrence by showing that when initial weeding occurred 4 or more weeks after planting and the subsequent weeding interval was longer than 2 weeks, weed growth progressively increased as did the number of oil palm seedlings affected by *Rhizoctonia lamellifera* Small and *Pythium splendens* Braun. Population was not affected. Iremiren (1986) recommended that 4 to 6 weedings of oil palm seedings in a poly bag nursery in the 12 months after planting are as efficient as the normal practice of monthly weeding.

Shoot and root competition of tropical weeds from planting until harvest reduced the tuber yield of white yam 76 to 79 percent, over 3 years of study, compared to weed-free conditions (Unamma and Akobundu 1989). Without physical contact between crop and weed roots, leachate from the weed foliage reduced tuber yield 38 to 42 percent, which the authors noted was clear evidence of allelopathy.

In view of the importance and value of tobacco, it is surprising that no studies were reported in the first edition of this book (Zimdahl 1980), and only one has been done since. Presumably because of its value, one is not concerned with whether or not weed control is necessary or when it must be done. It is required. Tobacco yield increased significantly with weed-free periods of 3 or 4 weeks and decreased if weed interference lasted more than 3 to 4 weeks after transplanting (Lolas 1986). As opposed to the effects of weeds on most crops, when tobacco yield decreased, there were also effects on chemical composition of the crop.

The density of *Crotalaria goreensis*, a weedy tropical legume, when varied from 10, 20, 40, to 200 plants m^{-2}, produced successive reductions in the yield of *Macroptilium atropurpureum*, a pasture crop, and successive increases in *C. goreensis* yield (Hawton and Drennan 1980). When *M. atropurpureum* density was varied between 2.3 and 6 m^{-2}, there was no effect on yield of either species. The weed lowered the aboveground dry matter yield of *M. atropurpureum* only when it emerged 2 weeks earlier. Removal of *C. goreensis* 12 days after planting was sufficient to prevent a reduction in dry matter yield of *M. atropurpureum.* It is interesting to note that the species were not mutually exclusive or harmful, and their mutual effects were always related to soil and climate conditions. In mixtures, *C. goreensis* provided physical support and enabled *M. atropurpureum* to intercept more light energy than it could in monoculture.

Container-grown ornamentals are valuable and normally are weeded regularly to promote good growth and prevent undesirable transfer of weeds when the plants are purchased and replanted. Few studies of the necessity of weed management are done because the necessity does not need to be demonstrated to nursery owners. Walker and Williams (1988) showed that barnyardgrass, large crabgrass, and giant foxtail interfered with container-grown redosier dogwood as soon as 21 days after transplanting. By the end of their study (83 days after transplanting), 5 weeds per container reduced redosier dogwood shoot dry weight as much as 72 percent. Independent of the number of weeds in a container, the same 3 weeds reduced shoot dry weight of container-grown bush cinquefoil as much as 75 percent after 83 days of interference (Walker and Williams 1989).

WEED-WEED INTERFERENCE

A few studies have been done on the interaction or interference between two weeds. Often these are designed to determine why one weed is more competitive and to understand the underlying biology of interference. These studies are briefly described below.

Seven days after planting at 1, 2, 4, or 8 cm, barnyardgrass emerged 96, 90, 83, and 27 percent, whereas redroot pigweed emerged 84, 73, 62, and 0 percent from the same depths (Siriwardana and Zimdahl 1984). Intraspecific competition of barnyardgrass was greater than interspecific competition from redroot pigweed. When planting depth increased from 1 to 4 cm and soil moisture increased for 30 to 50 percent (low) to 100 percent (high) of field capacity, the competitive ability of redroot pigweed decreased.

Lolas and Coble (1980) provided reasons for the competitiveness of johnsongrass. All growth characteristics (height, leaves per plant, number of tillers, fresh weight of rhizomes and shoots) were significantly increased as the length of planted rhizome segments increased from 2.5 to 25 cm. Johnsongrass derived from longer rhizome segments that were maintained by limited tillage, coupled with the plant's rapid growth rate, interfered with crops earlier than plants grown from shorter rhizome segments.

Japanese millet competed well with yellow nutsedge primarily via root interference (Thullen and Keeley 1980). Japanese millet reduced yellow nutsedge dry weight and the number of plants with tubers without any effect on millet.

The relative competitiveness of atrazine-resistant and atrazine-susceptible populations of common lambsquarters and lateflowering goosefoot was investigated by Warwick and Black (1981). The susceptible (S) biotype of common lambsquarters outcompeted the resistant (R) biotype, but the biotypes of lateflowering goosefoot were equally competitive. Both populations of common lambsquarters had greater total and reproductive biomass and earlier flowering than lateflowering goosefoot. The susceptible population of common lambsquarters had greater total and reproductive biomass than the resistant population and was more competitive than the susceptible population of lateflowering goosefoot. Weaver and Warwick (1982) did a similar study with redroot pigweed and Powell amaranth. For both species, the susceptible population had greater competitive ability with respect to total biomass and seed production. The susceptible population of Powell amaranth was more competitive than the susceptible or resistant population of redroot pigweed. Redroot pigweed's resistant population was more competitive than Powell amaranth's but was about equal to the competitiveness of susceptible redroot pigweed (Weaver and Warwick 1982).

Perennial ryegrass was more competitive than white clover when grown in the greenhouse in boxes that permitted separation of root and shoot competition (Martin and Field 1984). Both can be regarded as weeds but both are also primary components of pastoral agriculture in New Zealand. The success of the association depends on the nitrogen supplied by the white clover and, therefore, maintenance of white clover is required. Perennial ryegrass is more competitive than white clover with or without nitrogen, at any harvest time. When harvest was 8 weeks after planting, root competition dominated. For later harvests (16 and 20 weeks), shoot competition dominated. For later harvests, nitrogen application increased perennial ryegrass competition.

The competition of three perennial grasses (roughstalk bluegrass, poverty brome, and Yorkshire fog) with poverty brome, used to establish grass strips as field margins, was studied by Rew et al. (1995) in the UK. Each was grown from seed in additive mixtures with each species, separately. There was no significant difference between the relative total yield of poverty brome in additive mixture with the other grasses indicating they were competing for the same resources. Poverty brome produced significantly more reproductive tillers and seed after nitrogen was applied and production was greater in the absence of competition.

In monoculture, shoot dry weight and leaf area of spurred anoda and velvetleaf were similar. In mixed greenhouse culture, spurred anoda exceeded velvetleaf in leaf area per plant and shoot weight (Patterson 1990). One spurred anoda was equal in competitive ability to 2.5 velvetleaf plants.

Redstem filaree and round-leaved mallow were grown in monoculture with 2, 4, 8, or 12 plants in each 20-cm diameter pot and in all possible combinations of equal density. The leaf area per plant was similar for both species, but round-leaved mallow grew taller and produced more shoot biomass than redstem filaree in monoculture. The response in mixed culture varied with the proportion of each species. When mixed, round-leaved mallow gained leaf area and shoot biomass indicating it was the superior competitor by about a factor of 2 (Blackshaw and Schaalje 1993).

When the competitiveness of wild, dog, and ball mustard was compared, dog mustard had the lowest leaf area. In a replacement series, wild was the most competitive and greater than ball, which was greater than dog (Wall 1995).

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Weed-Crop Competition: A Review, Second Edition
Robert L. Zimdahl

6

The Effect of Competition Duration

It is a common but erroneous assumption that removing weed competition early in the crop's growing season, often prior to crop emergence, is the best weed management plan. However, substantial evidence verifies that early weed control, while not per se wrong, is not essential. The assumption that the earlier weeds are removed, the better, may be true for pragmatic reasons such as convenience, combination with other operations, or preparation for irrigation. Conversely, the assumption may prove false if crop growth and final yield are the operative criteria. Unquestionably, the longer weeds compete after crop emergence, the greater their potential effect. However, no effect of any magnitude occurs (exclusive of allelopathic effects) until competition begins when environmental resources (principally water, nutrients, and light) cease meeting the needs of two or more plants in an area (Clements et al. 1929). Therefore, the mere presence of weeds cannot automatically be judged to be damaging, and it does not follow that yield will be reduced if the weeds are not controlled immediately. Early in the growing season, when plants are small, competition may not occur because the small plants are far apart. When the small plants grow so that they are in close proximity, the competition that occurs, early in the season, is primarily for nutrients and water. Later in the growing season, when plants are larger, competition may be primarily for light because plants shade each other.

It seems obvious that if one weed is, or several weeds are, present for 1 day in the life of a crop, it will have no measurable effect on final yield. But what if the weed(s) is present for 2, 10, or 100 days? The question of duration of competition has been addressed 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 the growing season. The second, frequently complementary, study asks, what is the effect when the crop is kept weed free after crop emergence for certain periods of time and then weeds are allowed to grow for the rest of the growing season? These studies, when combined, can be used to define what is usually called the critical weed-free period.

Minotti and Sweet (1981) said, "weed scientists have conducted a substantial number of so-called 'critical period' studies." This review and the first edition of this book (Zimdahl 1980) affirm their claim. Minotti and Sweet (1981) note that relatively noncompetitive crops such as onion or garlic require a weed-free period of three months or more. More competitive crops such as corn or soybeans require only three to four weed-free weeks.

Research to determine the critical period is still done (35 studies reported here that have been done since 1980) for many crops, and some argue that the concept is useful (Evans et al. 2003; van Heemst 1985). It is useful because one wants to know when weed control should be done. Control is clearly not required, for competitive reasons, when both crop and weed are small. The time when weed management is performed is determined as much by how the weeds are to be managed as by the knowledge of the existence of a critical period. Preemergence herbicides have been more dominant than they are now, and they are applied before crop or weed emergence, as the label requires, without any consideration of the existence of critical period. Now, as Knezevic et al. (2002) point out, the widespread use of postemergence herbicides, especially those used with herbicide resistant crops (HRCs), may, but there is no guarantee, make the critical period more useful and more used. In contrast, van Heemst

(1985) argues that it is not the beginning of the critical period that is important but its end. The end of the critical period defines how long weed control must be maintained before crop competition will suffice. Van Heemst (1985) defined the beginning and end of the critical period for 16 crops and the end of the period for 9 other crops.

Jackson et al. (1985) state, as many others have, that the time of weed removal is as important as the extent of removal. Weed density is also important. The greater the weed density, the shorter the time the crop can tolerate early-season competition and the longer the required weed-free period will be (Weaver et al. 1992). Weaver et al. (1992) also state that the length of time a crop can tolerate early-season competition is related more to the availability of soil water and possibly nutrients than it is to limitations of light. Many critics of the development and use of critical periods agree that the length of the period (or perhaps its existence) has to vary with location and year (Van Acker et al. 1993) and, thus, a determination of the critical period for a crop-weed combination in one place cannot be valid, except as a guide, to what the period may be in other places. The point is confirmed by data from Harker et al. (2001) who showed that weed-free pea yields varied between locations by two- to threefold and that affected the length of the critical period observed. Halford et al. (2001) showed that estimates of the critical period vary for one crop from year to year and site to site. They also showed that the critical period of weed control was different for soybeans grown in a no-till system as opposed to conventional tillage.

In one of the first studies to determine the critical period, Vega et al. (1967) studied the effect of duration of weed control on rice. Weeds grew for no time at all or in intervals of 10 days up to 50 days after rice was planted. In separate field plots, they also allowed weeds to compete for 10, 20, 30, 40, or 50 days after planting and then kept the crop weed free thereafter. The data (table 6.1) show that yield is reduced when rice is weeded for only 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 does not have to be weeded immediately. On the other hand, weeds in rice cannot be present more than about 30 days or yield will go down. With the data from this study, Vega et al. (1967) defined the critical period for weed control in rice as being between 30 and 40 days after crop emergence.

Similar data are available for several crops, and corn illustrates this. However, the data from the

Table 6.1. The Effect of Duration of Weed Control and Weed Competition on Rice Yield

Weed control duration (days after planting)	Yield kg ha^{-1}
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

Source: Vega et al. (1967).

many studies do not provide a clear definition of the critical period when all studies are considered. Based on the studies reviewed for the first edition of this book (Zimdahl 1980), corn had to be kept weed free for three to five weeks after seeding or nine weeks after emergence, dependent on location and the weeds. However, when the additional studies reviewed for this book are included, the picture is not as clear (see tables 6.2 and 6.3). If provided with a weed-free period of three to five weeks after emergence, corn will compete effectively with weeds emerging afterward. Conversely, corn can withstand weed competition for three to six weeks, if it is then weeded and kept weed free for the remainder of the growing season. These data do not support a precise critical period for weeding. One must assume that the data for each study are accurate but because environment and cultural methods play such an important role, the data cannot be applied across different geographic regions.

These kinds of data have been used to derive the critical period for weed competition for many crops. Knezevic et al. (2002) present a complete discussion of the fact that the critical period has been defined in several ways and how the many, often conflicting, definitions detract from its potential usefulness (Gunsolus and Buhler 1999). Knezevic et al. (2002) also provide a very useful discussion and critique of the many ways the critical period has been determined and make good suggestions for proper statistical

Table 6.2. Weed-free Period Required to Prevent Yield Reduction in Corn

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, US	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	Ontario, Canada	Halford et al. 2001

Table 6.3. Length of Early Weed Competition Tolerated without Yield Loss in Corn

Weed-free weeks required 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		Spreading orach + Persian speedwell	England	Bunting and Ludwig 1964
4		Green foxtail	Ontario, Canada	Sibuga and Bandeen 1978
6		Giant foxtail	Illinois, US	Knake and Slife 1969
	6	Redroot pigweed	Oregon, US	Williams 1971
	2–3	Mixed annuals	New Jersey, US	Li 1960
	8	Itchgrass	Zimbabwe	Thomas and Allison 1975
4		Longspine	Colorado, US	Anderson 1997
9 to 13 leaves		Natural stand	Ontario, Canada	Halford et al. 2001
14 leaves		Natural stand	Ontario, Canada	Hall et al. 1992

analysis. Generally, the critical period is defined as the time between that period after crop seeding or emergence when weed competition does not reduce crop yield and the time in the crop's life after which weed presence does not reduce yield.

A critical period has been found for several crops. As figure 6.1 illustrates, it is a *time between* the early weed-free period required and the length of competition tolerated. It's not a fixed period for any crop because it varies with location, season, soil, and the weeds and their density. Even with its lack of constancy across environments and seasons, it can be a useful measure because it gives evidence about when to weed. For example, potatoes, if kept weed free for four to 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 kept weed free. Therefore, weeding of potatoes must be done sometime between four to 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. This affirms that the method chosen to control weeds often dictates when weeding must be done. One of the useful lessons of critical period studies is that weed control does not have to be done in the first few weeks after crop emergence. Although, for other management reasons, it often is.

Although knowing the critical period may have practical weed management value, Mortimer (1984) points out that a limitation is that all weeds are considered equally injurious and no distinction is made between the kinds of competition that can occur. In spite of the fact that about 100 studies are identified here, few, if any, general principles have emerged. Part of the reason for this is found in the many ways the studies have been done (Knezevic et al. 2002). Perhaps another important reason is that such studies are relatively easy to conduct, and one rarely builds on what has been done. Each is done to determine the critical period, and the only guiding hypothesis is that there must be one. There is a lack of development and testing of hypotheses of mechanism.

The literature reviewed for the first edition of this book relative to critical periods is included in this edition in the hope that further hypotheses will be developed. These citations have been compiled in tables 6.4 and 6.5. Some were assembled previously by Dawson (1970, 1971). Later, Dawson (1986) generalized that the need for weed control is not based on a number threshold but on a period threshold that helps to predict when weed control must be applied. The periods are the early-season threshold or "the time after crop emergence before which weeds must be controlled to prevent yield losses." This threshold is opposed to what Dawson called the late-season threshold or "the time after which no

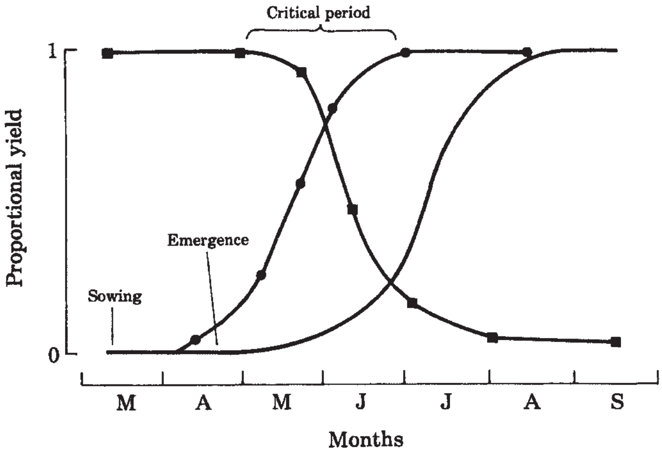

Fig. 6.1. The critical period of competition illustrated for onions. Changes in crop dry weight from planting to harvest (smooth curve). Yield response from delaying the start of continuous weeding (■); yield response from delaying the termination of weed removal (●). (From Mortimer 1984 as adapted from Roberts 1976)

further control measures are needed." The data for a particular crop on the presence or length of these thresholds periods are not very consistent when several reports are reviewed. Variations in the length of required weed-free or critical period usually relate to differences in competing weeds, geographic region, or the year and environment in which the study was done and illustrate the importance these factors have. An important difference in the data developed since 1980 is that a few authors have specified the percent yield loss that they used to determine the critical period. Earlier studies did not mention the percent yield loss used. It was assumed that the crop yield was reduced significantly and that was all that mattered. A few subsequent studies (Amador-Ramírez 2002; Baziramakenga and Leroux 1994; Eyherabide and Cendoya 2002; Woolley et al. 1993) have introduced the additional factor of the percent yield that counts as a loss. Other studies have added the crop's growth stage rather than just time in correct recognition of the fact that crops in different environments do not reach the same growth stage in the same time. Smith et al. (1990) studied the critical period for velvetleaf interference in cotton and determined (using only one weed density) that an inverse linear relationship existed between velvetleaf dry weight and cotton lint yield but "a non-linear equation best described percent lint yield loss as a function of critical-period interference interval."

Specific comparisons are difficult when data cover beans to yams, and range from the West Indies to Argentina and England. There are some conclusions that can be drawn concerning the effect of competition duration.

As stated, the critical period for weed control generally defines the time between when weeds present from the beginning of the crop cycle must be removed, or the point after which weed growth no longer affects crop yield (Nieto et al. 1968; Knezevic et al. 2002). Not all studies have been designed to define a critical period; hence, it is not possible to decide if such a period exists for every crop or to know its length. It is reasonable to assume that the difference between the length of weed-free period required (table 6.5) and length of weed competition tolerated (table 6.4) represents the critical period, but a clear division is not present for many crops. The crops for which a critical period may exist are shown in tables 6.6 and 6.7.

The conclusion of the data in tables 6.6 and 6.7 is challenged by work from England that indicates the absence of a critical period for weed competition in red beets (Hewson and Roberts 1973a), summer lettuce (Roberts et al. 1977), summer cabbage (Roberts et al. 1976), and broad beans (Hewson et al. 1973). Ismail (1988) claimed that barley grown in Qatar had neither a critical period nor a threshold density below which no yield loss occurred. Tables 6.4 and 6.5 reveal differences in the periods for these crops, but a single weeding at an intermediate point in time sufficed. However, the circumstance varied for onions (Hewson and Roberts 1973b; Roberts 1973), a crop that has slow germination, slow early growth, and susceptibility to weed competition for a major portion of the growing season. The extrapolations in tables 6.6 and 6.7 also can be questioned on the basis of differences in competition from specific weeds as illustrated by the data on soybean competition with giant foxtail (Knake and Slife 1969), and tall morningglory (Oliver and Schreiber 1973). The giant foxtail data support the existence of a critical period, but those for tall morningglory do not. This emphasizes the importance of each specific weed-crop competition environment and year and that conclusions cannot be drawn from one example.

Additional complications arise when fertility or plant spacing are included as experimental variables, as they ought to be. Li (1960) proposed that the first 24 weeks after crop emergence were the most important period of weed competition in corn. During this time, weeds completed 16 to 18 percent of their total growth, but corn grew only 2 to 3 percent. Weedy corn yield decreased as competition period lengthened at high fertility, but not at low fertility (table 6.8). These data were confirmed by Bowden and Friesen's (1967) study of wild oats in wheat and flax and Bell and Nalewaja's (1968) work with the same weed in barley and wheat.

Oliver et al. (1976) illustrated the predictable relationship between competition duration and weed spacing. Tall morningglory spaced 15, 30, or 61 cm in the soybean row needed 6, 8, and 10 weeks of competition before yield was negatively affected. Several studies, a few cited below, support the role of plant spacing (Alley 1965; Asberry and Harvey 1969; Berglund and Nalewaja 1969; Buchanan and Burns 1971a, b; Dawson 1976; Ivy and Baker 1970; Knake and Slife 1962; Mohler 2001; Moolani et al. 1964; Smith and Tseng 1970; Smith 1968; Vandiver and Wiese 1969; Vesecky et al. 1973**;** Weatherspoon and Schweizer 1971; see chapter 8 for additional citations).

Table 6.4. Length of Early Weed Competition Tolerated Without Yield Loss by Crops

Crop	Length (weeks) of competition tolerated after		Competing weed(s)	Location	Source
	Seeding	Emergence			
Barley	4–6 leaf stage of crop		Wild oats	UK	Peters 1984
Bean	8		Barnyard grass	Washington, US	Dawson 1964
Bean		3–5 after 50% emergence	Mixed annuals	England	Glasgow et al. 1976
Bean	3		Mixed annuals	Chapingo, Mexico	Nieto et al. 1968
Bean		4	Redroot pigweed	Oregon, US	Williams 1971
Bean, broad		4 after 50% emergence	Mixed annuals	England	Hewson et al. 1973
Bean, green	4		Purple nutsedge	Brazil	William and Warren 1975
Bean, lima	6		Sicklepod	Georgia, US	Glaze and Mullinex 1984
Beets, red		4 after 50% emergence	Mixed annuals	England	Hewson and Roberts 1973a
Cabbage		3–4	Mixed annuals	England	Roberts et al. 1977
Cabbage		4	Purple nutsedge	Brazil	William and Warren 1975
Carrot		5	Redroot pigweed *Acnida* sp. Ladysthumb	Wisconsin, US	Shadbolt and Holm 1948
Carrot	3 var. Kuroda; 5–7 var. Nantes		Purple nutsedge	Brazil	William and Warren 1975
Corn	3		Mixed annuals	Veracruz, Mexico	Nieto 1970
Corn		4	Mixed annuals	Mexico City	Aleman and Nieto 1968
Corn	4		Mixed annuals	Chapingo, Mexico	Nieto et al. 1968
Corn	2–4		Spreading orach Persian speedwell	England	Bunting and Ludwig 1964
Corn	4		Green foxtail	Ontario, Canada	Sibuga and Bandeen 1978

Crop	Length (weeks) of competition tolerated after: Seeding	Emergence	Competing weed(s)	Location	Source
Corn	6		Giant foxtail	Illinois, US	Knake and Slife 1969
Corn		6	Redroot pigweed	Oregon, US	Williams 1971
Corn		2–3	Mixed annuals	New Jersey, US	Li 1960
Corn		8	Itchgrass	Rhodesia	Thomas and Allison 1975
Corn	4		Longspine sandbur	Colorado, US	Anderson 1997
Corn with no-till	9–13 leaves		Unknown	Ontario, Canada	Halford et al. 2001
Corn	14 leaves		Unknown	Ontario, Canada	Hall et al. 1992
Cotton, winter		17	Mixed annuals	Sinaloa, Mexico	Ramirez and Nieto 1968
Cotton, spring		9	Mixed annuals	Sonora, Mexico	Martinez and Nieto 1968
Cotton		8	Mixed annuals	Alabama, US	Buchanan and Burns 1970
Cotton	2		Mixed annuals	India	Singh et al. 1971
Cotton		2	Smooth pigweed Apple-of-Peru	Rhodesia	Thomas and Schwerzel 1968
Cotton	9		Mixed annuals	Arizona, US	Arle and Hamilton 1973
Cotton		6	Prickly sida	Alabama, US	Buchanan et al. 1973
Cotton		4	Yellow nutsedge	California, US	Keeley and Thullen 1975
Cotton	8.8		Hemp sesbania	Mississippi, US	Bryson 1990
Cotton		6	Johnsongrass	Texas, US	Bridges and Chandler 1987
Cotton		9	Barnyardgrass	California, US	Keeley and Thullen 1991a

(continues)

Table 6.4. Continued

Crop	Length (weeks) of competition tolerated after		Competing weed(s)	Location	Source
	Seeding	Emergence			
Cotton		8–12	Bermudagrass	California, US	Keeley and Thullen 1991b
Cotton	4		Bermudagrass	Georgia, US	Vencill et al. 1993
Cucumber	5		Purple nutsedge	Brazil	William and Warren 1975
Flax		2	Wild oat	N. Dakota, US	Bell and Nalewaja 1968
Flax		2	Wild oat	Manitoba, Canada	Bowden and Friesen 1967
Garlic	3		Purple nutsedge	Brazil	William and Warren 1975
Lentil		4.8–5.8	Unknown	Syria	Singh et al. 1996
Lettuce		3 after 50% emerg.	Mixed annuals	England	Roberts and Bond 1975
Oats	1		Mixed annuals	New Jersey, US	Li 1960
Okra	3		Purple nutsedge	Brazil	William and Warren 1975
Oil palm	16		Natural stand	Nigeria	Iremiron 1986
Onion		4 after 50% emerg.	Mixed annuals	England	Roberts 1976
Onion		4 after 50% emerg.	Mixed annuals	England	Hewson and Roberts 1973b
Onion		5	Redroot pigweed *Acnida* sp. Ladysthumb	Wisconsin, US	Shadbolt and Holm 1956
Onion		12	Redroot pigweed Kochia Annual grasses	Nebraska, US	Wicks et al. 1973
Peanut	6		Smooth pigweed Large crabgrass	Oklahoma, US	Hill and Santlemann 1969

	Length (weeks) of competition tolerated after				
Crop	Seeding	Emergence	Competing weed(s)	Location	Source
Peanut		4–6	Sicklepod + beggarweed	Alabama, Florida, US	Hauser et al. 1975
Peanut		4	Sicklepod + beggarweed	Alabama, Florida, US	Buchanan et al. 1976
Peanut		10	Wild poinsettia	Georgia, US	Bridges et al. 1992
Peanut		2	Common cocklebur	Florida, US	Royal et al 1997
Peanut		2 Seed yield decreased 4%	Bristly starbur	Alabama, US	Walker et al. 1989
Peanut		6 to 8	Horsenettle	Oklahoma, US	Hackett et al. 1987
Peppers, chili	0.7–3.2 with 5% yield loss deemed acceptable		Natural stand	Spain	Amador-Ramírez 2002
Potato, sweet	3		Unknown	West Indies	Kasasian and Seeyave 1969
Potato, sweet, Maize, and cocoyam intercrop	4		Natural stand	Nigeria	Unamma et al. 1985
Potato	4–6		Unknown	Haryana, India	Thakral et al. 1989
Potato	4		Goosegrass Torpedograss Smallflower galinsoga *Polygonum nepalense*	Java, Indonesia	Everaarts and Satsyati 1977
Potato	6		Redroot pigweed Common lambsquarters	Lebanon	Saghir and Markoullis 1974

(continues)

Table 6.4. Continued

	Length (weeks) of competition tolerated after				
Crop	Seeding	Emergence	Competing weed(s)	Location	Source
Potato	15 w/low infestation = 35–38 g m^{-2}	23–68 w/ high infestation = 135–158 g m^{-2} 3 w/medium infestation = 87–95 g m^{-2}	Quackgrass	Québec, Canada	Baziramakenga and Leroux 1994
Rice, paddy	3		Barnyard grass	Arkansas, US	Smith 1968
	7–9		Barnyard grass	Arkansas, US	Smith 1974
		4	Ducksalad Hemp sesbania	Arkansas, US	Smith 1968
Rice, paddy	6		Smallflower umbrella sedge	New South Wales, Australia	Swain et al. 1975
Rice, paddy	3 after transplanting		Barnyard grass	Philippines	Lubigan and Vega 1971
Rice, paddy	4 after transplanting		Barnyard grass	Philippines	Noda 1973
Rice, paddy		11.4	Spreading dayflower	Arkansas, US	Smith 1984
Rice, paddy		8	Bearded sprangletop	Arkansas, US	Carey et al. 1994
Rice, upland		8	Mixed annuals	Korea	Park and Kim 1971
Rice, upland		6	Mixed annuals	Philippines	Vega et al. 1967
Rice, wild	7		Common waterplantain	Minnesota, US	Ransom and Oelke 1982
Sorghum	4		Mixed annuals	Nebraska, US	Burnside and Wicks 1967
Sorghum	4		Pigweed spp.	Texas, US	Vandiver and Wiese 1969
Sorghum		6	Tall waterhemp	Kansas, US	Feltner et al. 1969
Soybean	7		Ivyleaf morningglory	Delaware, US	Wilson and Cole 1966
Soybean	4		Mixed annuals	Illinois, US	Wax and Slife 1967
Soybean	8–9		Giant foxtail	Illinois, US	Knake and Slife 1969
Soybean		4–8 dependent upon spacing	Tall morningglory	Arkansas, US	Oliver et al. 1976

Crop	Length (weeks) of competition tolerated after: Seeding	Emergence	Competing weed(s)	Location	Source
Soybean		2–4	Sicklepod	Alabama, US	Thurlow and Buchanan 1972
Soybean		6	Venice mallow	Kansas, US	Eaton et al. 1973
Soybean		3	Mustards	N. Dakota, US	Berglund and Nalewaja 1971
Soybean		2–4	Sicklepod	Alabama, US	Buchanan and Thurlow 1972
Soybean	8		Common sunflower	Missouri, US	Allen et al. 2000
Soybean	4		Common cocklebur	Arkansas, US	Rushing and Oliver 1998
Soybean	4		Mixed, natural stand	Illinois, US	Jackson et al. 1985
Soybean		4.3	Natural stand	Ontario, Canada	Van Acker et al. 1993
Soybean	4		Johnsongrass	Tennessee, US	Williams and Hayes 1984
Soybean		6	Common ragweed	North Carolina, US	Coble et al. 1981
Soybean, with no-till	R-1 = early flowering Soybean	8–10	Natural stand	Ontario, Canada	Halford et al. 2001
			Giant ragweed	Missouri, US	Baysinger and Sims 1991
Sugarbeet	12		Barnyard grass	Washington, US	Dawson 1965
Sugarbeet		4	Kochia	Colorado, US	Weatherspoon and Schweizer 1969
Sugarcane	4		Johnsongrass	Argentina	Arevalo et al. 1977a
Sugarcane	8		Mixed annuals	Argentina	Arevalo et al. 1977b
Sunflower	4		Mixed annuals	Georgia, US	Johnson 1971
Tomato	3.4 after transplant		Common ragweed Common lambsquarters Longspine sandbur	Ontario, Canada	Friesen 1979
Tomato	3 after transplant		Purple nutsedge	Brazil	William and Warren 1975

(continues)

Table 6.4. Continued

	Length (weeks) of competition tolerated after				
Crop	Seeding	Emergence	Competing weed(s)	Location	Source
Tomato	4 after transplant		Unknown	West Indies	Kasasian and Seeyave 1969
Wheat, spring		2	Wild oat	Manitoba, Canada	Bowden and Friesen 1967
Wheat, spring		4–5	Wild oat	England	Chancellor and Peters 1974
Wheat, winter	~22 (Oct., Mar.)		Downy brome	Oregon, US	Rydrych 1974
Yams	12		Unknown	West Indies	Kasasian and Seeyave 1969
Yam, white	16		Natural stand	Nigeria	Akobundu 1981

Table 6.5. Length of Weed-free Period Required to Prevent Crop Yield Reduction

	Weed-free period (weeks) required after				
Crop	Seeding	Emergence	Competing weeds	Location	Source
Barley	2-node stage		Wild oat	Idaho, US	Morishita and Thill 1988
Bean	5		Mixed annuals	Washington, US	Dawson 1964
Bean, broad		1–1.5 after 50% emergence	Mixed annuals	England	Hewson et al. 1973a,b
Bean, dry		6–9	Hairy nightshade	Alberta, Canada	Blackshaw 1991
Bean, dwarf		1–1.5	Unknown	West Indies	Kasasian and Seeyave 1969
Bean, snap	Unifoliate stage		Common cocklebur	New Jersey, US	Neary and Majek 1990
Beet, red		2–4	Mixed annuals	England	Hewson and Roberts 1973
Cabbage		2	Mixed annuals	England	Roberts et al. 1977
Corn		9	Mixed annuals	Mexico City	Aleman and Nieto 1968

	Weed-free period (weeks) required after				
Crop	Seeding	Emergence	Competing weeds	Location	Source
Corn	5		Mixed annuals	Veracruz, Mexico	Nieto 1970
Corn	3		Giant foxtail	Illinois, US	Knake and Slife 1965
Corn	after 7-leaf stage		Redroot pigweed	Ontario, Canada	Knezevic et al. 1994
Corn	3–14 leaves		Natural stand	Ontario, Canada	Hall et al. 1992
Corn, no-till	6 leaves		Natural stand	Ontario, Canada	Halford et al. 2001
Cotton		6	Mixed annuals	Alabama, US	Buchanan and Burns 1970
Cotton, spring		4	Mixed annuals	Sonora, Mexico	Martinez and Nieto 1968
Cotton		4	Johnsongrass	Texas, US	Bridges and Chandler 1987
Cotton		8–12	Bermudagrass	California, US	Keeley and Thullen 1991b
Cotton	7		Bermudagrass	Georgia, US	Vencill et al. 1993
Cotton		9	Barnyardgrass	California, US	Keeley and Thullen 1991a
Lentil		12.1–14.1	Natural stand	Syria	Singh et al. 1996
Lettuce		3 after 50% emergence	Mixed annuals	England	Roberts and Bond 1975
Pea	1 to 2		Wild oat + tartary buckwheat	Alberta, Canada	Harker et al. 2001
Peanut	3		Smooth pigweed Large crabgrass	Oklahoma, US	Hill and Santlemann 1969
Peanut		10	Sicklepod, Florida beggarweed	Alabama, US	Hauser et al. 1975
Peanut		8	Sicklepod, Florida beggarweed	Alabama, US	Buchanan et al. 1976
Peanut		12	Common cocklebur	Florida, US	Royal et al. 1997
Peanut		6 Yield decreased 3%	Bristly starbur	Alabama, US	Walker et al. 1989
Peanut		2	Horsenettle	Oklahoma, US	Hackett et al. 1987
Peppers, chili	0.9–2.1 after transplanting		Natural stand	Spain	Amador-Ramírez 2002
with 5 % yield loss	6.7–15.3 after transplanting				

(continues)

Table 6.5. Continued

	Weed-free period (weeks) required after				
Crop	Seeding	Emergence	Competing weeds	Location	Source
Potato	9		Redroot pigweed Common lambsquarters	Lebanon	Saghir and Markoullis 1974
Rice, paddy	6 after transplanting		Barnyardgrass	Philippines	Lubigan and Vega 1971
Rice, paddy	4.3		*Echinochloa* spp.	Haryana, India	Thakral 1989
Rice, paddy	4		*Echinochloa* spp.	California, US	Gibson et al. 2002
Rice, upland		3	Mixed annuals and sedges	India	Sibma et al. 1964
Rice, wild	9		Common waterplantain	Minnesota US	Ransom and Oelke 1982
Sorghum	3		Mixed annuals	Nebraska, US	Burnside and Wicks 1967
Sorghum	4		Mixed annuals	Nebraska, US	Burnside and Wicks 1969
Soybean	4		Tall morningglory Large crabgrass	Delaware, US	Wheatley and Cole 1967
Soybean	2		Redroot pigweed	Delaware, US	Wheatley and Cole 1967
Soybean	3		Giant foxtail	Illinois, US	Knake and Slife 1965
Soybean		4	Common cocklebur	Mississippi, US	Barrentine 1974
Soybean		6	Tall morningglory	Arkansas, US	Loomis 1958
Soybean	3–6		Venice mallow Velvetleaf Prickly sida	Kansas, US	Eaton et al. 1976
Soybean		6	Smooth pigweed Tall waterhemp Green foxtail	Nebraska, US	Burnside and Juricek 1967
Soybean	4		Shattercane	Kansas, US	Zaresky and Russ 1970
Soybean		After V-4 35 1–30 with 2.5% yield loss V-0 to V-3 or V-4 15–35, V-2 to V-4 stage with <10% yield loss	Annuals	Balcarce, Argentina	Eyherabide and Cendoya 2002

	Weed-free period (weeks) required after				
Crop	Seeding	Emergence	Competing weeds	Location	Source
Soybean	4–6		Common sunflower	Nebraska, US	Irons and Burnside 1982
Soybean, no-till	1st or 2d node		Natural stand	Ontario, Canada	Halford et al. 2001
Soybean	2 (dry year) 4 (adequate water)		Common ragweed	North Carolina, US	Coble et al. 1981
Soybean		8–10	Giant ragweed	Missouri, US	Baysinger and Sims 1991
Soybean	4		Johnsongrass	Tennessee, US	Williams and Hayes 1984
Sugarbeet		6	Kochia	Colorado, US	Weatherspoon and Schweizer 1969
Sugarbeet	10		Barnyardgrass Common lambsquarters	Washington, US	Dawson 1965
Sunflower	4–6		Mixed annuals	Georgia, US	Johnson 1971
Tomato, transplanted	5 after transplanting		Common ragweed Common lambsquarters Longspine sandbur	Ontario, Canada	Friesen 1979
Watermelon		6	Large crabgrass	North Carolina, US	Monks and Scholtheis 1998
Wheat, winter	2		Downy brome	Nebraska, US	Wicks 1966
Yam, white	8		Natural stand	Nigeria	Akobundu 1981

Table 6.6. Crops with a Critical Period for Weed Competition

Crop	Weed-free period required[a]	Length of competition tolerated[b]	Source
Corn	3–5 weeks	3–6 weeks	
Potato	4–6	9	Saghir and Markoullis 1974
Rice, paddy	4–6	4–9	Vega et al. 1967
Soybean	2–4 after planting	4–8 after planting	Several references in tables 6.4 and 6.5

[a] See table 6.5 for supporting data.
[b] See table 6.4 for supporting data.

Table 6.7. Crops with an Identified Critical Period

Crop	Critical period	Source
Barley infested with wild oat	2-node stage to maturity	Morishita and Thill 1998
Bean, snap infested with common cocklebur (Authors note the time is too long to be a critical period)	Emergence to full bloom of snap bean	Neary and Majek 1990
Bean, dry infested hairy nightshade	3–9 weeks after emergence	Blackshaw 1991
Bean, white 3% yield loss tolerated	2nd trifoliate to 1st flower stage	Woolley et al. 1993
Cotton infested with hemp sesbania	= <62 days after planting	Bryson 1990
Cotton infested with johnsongrass	4–6 weeks after emergence	Bridges and Chandler 1987
Cotton infested with barnyardgrass	3–6 weeks after emergence	Keeley and Thullen 1991a
Cotton infested with bermudagrass	4–7 weeks after emergence	Vencill et al. 1993
Intercropped sweet potato, maize and cocoyam	28 days after transplanting	Unamma et al. 1985
Lentil	7.7–9.3 weeks after emergence	Singh et al. 1996
Peanut infested with common cocklebur	2–12 weeks after peanut emergence	Royal et al. 1997
Peanut infested with bristly starbur	2–6 weeks after emergence for tolerated loss of 3–4%	Walker et al. 1989
Peanut infested with horsenettle	2–6 or 8 weeks after emergence	Hackett et al. 1987
Peanut infested with broadleaf signalgrass	6 weeks after planting, i.e., during flowering	Chamblee et al. 1982
Rice infested with bearded sprangletop	21–56 days after emergence	Carey et al. 1994
Rice, wild infested with common water plantain	7–9 weeks after planting	Ransom and Oelke 1982
Soybean	9–38 days after emergence = to 2nd node (V-2) to beginning pod formation (R-3) stage	Van Acker et al. 1993
Soybean infested with giant ragweed	4–6 weeks after emergence in one year and 2–4 weeks in a second year	Baysinger and Sims 1991
Soybean infested with johnsongrass	4–5 weeks after emergence	Williams and Hayes 1984
Tomato, transplants	24–36 days after transplanting	Friesen 1979
Watermelon infested with large	0–6 weeks after emergence	Monks and Scholtheis 1998
Yam, white	8–16 weeks after emergence	Akobundu 1981

Few data address the influence of weed planting date on competition because in many studies the weeds studied were those that emerged spontaneously and in other studies weeds are planted and emerge with the crop. Vengris (1963) checked growth and development of redroot pigweed and yellow foxtail as affected by time of seeding. The earliest seedings produced the tallest plants and highest weed yield. The interval between emergence and maturity decreased progressively as seeding date was delayed. Dawson (1976) showed that annual weeds emerging in sugarbeets after July 1 (the last cultivation) were suppressed by the crop and did not affect yield. Late-emerging weeds were competitive in a one-third or one-half stand. Planting prickly sida or Venice mallow with soybeans reduced yield 33 percent. When weeds were planted 10 days after soybeans, yield fell 20 percent; weeds planted 20

Table 6.8. The Influence of Soil Fertility on Weed Competition in Corn

Duration of weed competition	Yield of weedy plots Low fertility	 High fertility
(weeks)	(bu A)	(bu A)
2	111	130
3	114	110
5	114	101

Source: Li (1960).

days after the crop did not affect yield (Eaton et al. 1973). Giant foxtail seeded in a band over crop rows, three (or more) weeks after corn or soybeans, did not reduce yield of either crop (Knake and Slife 1965). When common lambsquarters was planted 7 days earlier than barley, it could not compete effectively but when it was planted 21 or 31 days before barley, barley could not compete effectively (Elberse and de Kruyf 1979). The time that tartary buckwheat competed with several crops contributed the most to yield loss (de St. Remy and O'Sullivan 1986). A loss of 0.4 percent per day for wheat, barley, and rapeseed and 1.1 percent per day for oats and flax was attributed just to the time the weed was present in the crop.

Another consideration emerges from the data of Welbank and Witts (1962) who showed that earlier planting and consequent early weed emergence may not favor crops because cultivation prior to later planting could destroy many seedlings as they emerge.

Kasasian and Seeyave (1969) proposed the working hypothesis that crops require a weed-free period of one-fourth to one-third of their growing period. Their data confirmed this for beans, tomatoes, sweet potatoes, pigeon peas, sugarcane, and yams. The study was based on an earlier paper by Nieto et al. (1968) reporting that beans and corn were most susceptible to weed competition during the first 30 days of a 130- to 135-day growth period. The data reviewed generally support Kasasian and Seeyave's (1969) hypothesis, but with the caveat that useful generalizations still must be confirmed with experimental data. That is, specific weed-crop interactions must be considered.

These concepts and data provide a basis for determining the required duration of weed control, regardless of how weeds are to be controlled, and for comparing the value of methods with varying persistence (Roberts 1976). Importance attaches to the specific crop(s) and weed(s) competing and to what resource they compete for under the environmental conditions of each study. All of the crops surveyed (tables 6.4 and 6.5) can withstand weed competition for some duration after planting. Yield-reducing competition is likely to occur much earlier in the season, if moisture, rather than light, is the primary limiting parameter (Dawson 1970).

In spite of the abundance of data that purport to define a critical period for weed management in several different crops, the critical period seems peripheral to most weed management decisions. It is clear that the period varies with the place where the work was done and the particular season (wet versus dry, hot versus cool, etc.). A casual review of the data assembled here also reveals that the period varies with each weed-crop combination, the relative time of emergence of the crop and weed(s), that is, the time competition begins. This agrees with Mohler's (2001) conclusion that "dependence of both the tolerated period of infestation and the minimum weed-free period on a wide variety of factors implies that application of the critical period concept to field situations requires both extensive data and careful judgement." Thus, while many critical period studies have been done, few have elaborated any general principles that permit wide application or generalization based on the data generated. Each is interesting and, in its own place, perhaps useful to reinforce what is already known—early weed control is almost always good compared to late weed control. But, critical period studies have not moved weed science closer to general hypotheses or new conclusions.

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Weed-Crop Competition: A Review, Second Edition
Robert L. Zimdahl

7
The Elements of Competition

It is accepted that crop yield reductions are generally, although not always (e.g., when allelopathy is present), in proportion to the amount of light, water, or nutrients weeds use at the expense of the crop (Roush and Radosevich 1985). 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, data are insufficient to define cause and effect and the generalization is accepted. For example (one among many), Menges and Tamez (1981) stated that soil water (which was not measured), soil temperature, and irradiance were more useful than weed density to explain the differences in competition between common sunflower and onions over two years. No careful measurements of any factor were made, but the generalization about the effects is similar to many others.

It is simple and neat to study the elements of competition (nutrients, light, and water) separately. Given the tradition of reductionistic science we have inherited, it is understandable why such studies are done. Reductionism has led to significant scientific advances in many fields. It is not wrong to separate the elements of competition experimentally. However, it is wrong to assume that plants separate things, as science can. It is impossible for plants to separate the elements of competition in nature. As mentioned in chapter 1, plants exist in environments where all elements of competition are active and attempts to separate them, while interesting, do not reflect the real world of inter- and intraplant competition in which plants exist.

There has been no intent to include every research report that mentions nutrients, light, or water in this chapter. Most reports included in this chapter have already been mentioned in chapter 5. This review reveals that while the elements of competition are mentioned frequently, there has been little attempt in the weed science literature to explain the mechanism of the effect.

deWit (1960) was among the first to point out the futility, the wrongness, of separating the elements of competition. His work advocated a change in the approach to the study of competition. He developed 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. deWit's view was consistent with current thinking in that species that best use or first capture environmental resources will succeed.

Only in recent years has research begun to consider the spatial distribution or where weeds are in a field and how that may affect weed-crop competition. Weed scientists have long been concerned with what weeds (the species) and how many weeds (the density) are present in a field. Control has been directed at the dominant weed or weeds (see Booth and Swanton 2002, chapter 4). 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 management systems usually without considering the patchiness or nonuniformity of weeds in fields. Control included the unstated and frequently incorrect assumption that weed distribution and density were uniform over the field. Thus, tillage or herbicides are nearly always applied uniformly over a field even though weed scientists and farmers 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 may be reduced or eliminated in some places. Weed distribution is heterogenous not homogenous.

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 developing (see Cousens and Mortimer 1995, chapter 7). There is 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.

THE ROLE OF TEMPERATURE

It is well known that the differential effects of temperature on photosynthesis and growth influence the competitive ability of C_3 and C_4 plants (Christie and Detling 1982; Pearcy et al. 1981). For example, at any temperature, smooth pigweed (a C_4 plant) was less competitive than common cocklebur or soybean (both C_3 plants) (Flint and Patterson 1983). Therefore, common cocklebur is more likely than smooth pigweed to compete effectively in early seeded soybeans. Wheat was a better competitor than jointed goatgrass at day-night temperatures of 18/10°C and -33 kPa whereas jointed goatgrass was superior at 27/10°C and -300 kPa under dry, pacific Northwest conditions (Fleming et al. 1988). Wild oat was more competitive than green foxtail at day-night temperatures of 22/16°C than at 28/22°C (Wall 1993). The maximum green foxtail leaf area was at 28/22°C whereas that of wild oat was at 16/10°C. Green foxtail's dry weight and leaf area increase occurred earlier at higher temperatures. Wild oat's leaf area ratio and relative growth rate did not differ between temperatures (Wall 1993). Green foxtail's leaf area ratio was higher, but its relative growth rate was lower at lower than at higher temperatures.

Temperature was the primary factor that controlled dominance in competition between Nandi setaria and goosegrass over a range of climatic regimes in Queensland, Australia (Hawton 1979, 1980). If mean temperatures were less than 23°C, Nandi setaria dominated in mixtures. If mean temperature was greater than 23°C, goosegrass dominated (Hawton 1979). Neither species dominated in the first three weeks of growth. Between three and six weeks and six and nine weeks, goosegrass was the superior competitor. Changes in competitive advantage were related to growth patterns of the two species. Goosegrass dominated at warmer temperatures, but there was strong indication that at temperatures less than 22.1°C, low light (an example of the interaction of factors) allowed goosegrass to gain a competitive advantage (Hawton 1980).

The time to 50 percent emergence of tomato and four weeds grown at five alternating temperatures decreased with increasing temperature and increased slightly with decreasing soil moisture (Weaver et al. 1988). Base temperatures and thermal times required for 50 percent emergence varied among species but were quite insensitive to soil moisture above a critical minimum. Weaver et al. (1988) suggested that knowing the response of weeds and crops to temperature could be used as a management technique to plan optimal planting time and to estimate potential crop yield loss.

Comparison of rate of germination, growth, and development of redroot pigweed, smooth pigweed, and Powell amaranth at day-night temperatures of 28/22°C and 22/14°C showed that Powell amaranth had faster germination and earlier height growth and leaf number than either of the other two species (Weaver 1984). When the three species were mixed in the field, Powell amaranth had greater competitive ability in terms of number of plants, aboveground fresh weight, and seed production.

Patterson et al. (1988) compared the effects of temperature and CO_2 concentration (350 to 700 ppm) on cotton, velvetleaf, and spurred anoda grown in growth chambers. Carbon dioxide enrichment decreased the weed-crop ratio for total dry weight. This may indicate a competitive advantage for cotton with elevated carbon dioxide even if temperatures are less than optimal for cotton. Cotton dry matter increased more (38 percent) than that of either weed with 700 ppm of CO_2 with day-night temperatures of 26° and 17°C. Cotton's advantage was greater (61 percent) when temperature was 32° and 23°C.

Ziska (2001) found that elevated CO_2 significantly stimulated leaf photosynthetic rate, leaf area, and aboveground dry weight of common cocklebur (a C_3 plant) more than that of sorghum (a C_4 plant) in monoculture. Leaf photosynthesis declined for both species when they grew together. "However, elevated CO_2 reduced the percentage decline in common cocklebur and increased it in sorghum by 35 days after sowing relative to ambient CO_2." Ziska (2001) proposed that "vegetative growth, competition, and potential yield of economically important C_4 crops could be reduced by co-occurring C_3 weeds as atmospheric carbon dioxide increases."

COMPETITIVE INTERACTIONS FOR NUTRIENTS

Patterson (1995) focused on environmental stress in weed-crop interactions. His review included 98 citations concerning water, nutrients, light, and temperature. The review also commented on the role of increasing levels of atmospheric carbon dioxide in future weed-crop interactions. Patterson (1995) distinguished between environmental conditions (i.e., temperature, wind, soil pH, photoperiod) and environmental resources (i.e., water, nutrients, CO_2, and O_2). Nearly all of the manuscripts reviewed by Patterson were included in the first edition of this book or are cited here and readers are referred to his review for additional details.

Tilman (1990) wrote about the mechanisms of competition for nutrients rather than what happens when competition occurs, which has been the appropriate and continuing emphasis in weed science. Tilman's emphasis was on understanding "the underlying mechanism of competition." Tilman acknowledged the extensive ecological and weed science literature that affirms the existence of competition and the equally extensive studies on the effects of environmental variables on competition. He then quoted Harper (1977, p. 369), "it is very doubtful whether such experiments have contributed significantly either to understanding the mechanism of 'competition' or to generalizing about its effects."

Most of the studies discovered for this review allude to competition for nutrients but do not go much beyond the assertion that it occurs. In Tilman's (1990) view, this is because the studies have focused on the phenomenon of competition for nutrients rather than on the mechanism. Phenomenological studies affirm that competition occurs but cannot be extended to predict what may happen in a different place, with different species, or as nutrients vary. The criticism is justified but, in spite of its general validity, the weed scientist's work has not been without value as pointed out by Radosevich and Roush (1990), who contrasted the quite different but equally justifiable objectives of weed scientists and ecologists. However, as Tilman (1990) charges, "Classical, density-based studies of plant competition have demonstrated its existence in nature, but have not led to a general theory capable of predicting the dynamics and outcome of plant competition."

Several studies that illustrate how nutrients have been studied by weed scientists follow. Young et al. (1984) suggested that when light and nutrients were not limiting, an adequate water supply can eliminate the effects of quackgrass on corn. High levels of phosphorus or potassium did not overcome quackgrass interference in soybeans although there was partial relief by irrigation (Sikkema and Decker 1987).

Broomrape infestations in tomato and tobacco were drastically reduced as higher levels (from none to 100 g per pot) of ammonium nitrate (an effect above 50 g per pot) or ammonium sulfate (an effect above 60 g per pot) were applied (Abu-Irmaileh 1981).

Henson and Jordan (1982) showed that wild oat competition reduced the effectiveness of nitrate to increase wheat's total plant weight, grain yield, and whole-plant percent nitrogen when it was applied every four days as K or $CaNO_3$ to pots in the greenhouse. The findings were confirmed by Carlson and Hill (1986) who showed that wheat grain yield decreased with fertilization in wild oat infested plots. In competition, wild oat was better able to use added nitrogen, thus gaining a competitive advantage and reducing wheat yield. Wheat was able to respond positively to added nitrogen only when wild oat density was less than 1.6 percent of total plant density. Their data illustrate the importance of consideration of the combined roles of weed density and response to nitrogen fertilization. Wheat yield decreases as wild oat density increases and as nitrogen fertility increases in the presence of weeds (table 7.1).

Giant foxtail growth in the field and greenhouse increased as nitrogen (from nitrate or ammonium) increased from 56, 112, to 225 kg ha^{-1} (Salas et al. 1997). The weed's total dry weight increased with increasing nitrogen, but seed production reached a maximum at about 150 kg nitrogen ha^{-1}. Giant foxtail did not show any preference for nitrogen form

Table 7.1. Yield of Wheat Grown in Competition with Wild Oat at Three Nitrogen Levels

Wild oat density	Wheat yield[a,b] Preplant nitrogen (kg ha^{-1}) 0	67	134	Average[c]
(Plants m^{-2})		kg ha^{-1}		
0[d]	4,280	4,840	4,800	4,640
3	3,990	4,670	5,030	4,560
9	3,230	4,120	3,740	3,700
18	3,560	3,570	2,980	3,370
42	3,280	3,300	2,740	3,107
100	2,860	2,260	2,170	2,429
Average[e]	3,533	3,793	3,578	

Source: Carlson and Hill (1986).

[a] Average wheat density = 285 plants m^{-2}.

[b] LSD (0.05) wheat yield means = 637.

[c] LSD (0.05) wheat yield means across nitrogen levels = 368.

[d] Control plots were treated with 1.1 kg ha^{-1} difenzoquat.

[e] Differences among nitrogen level means were not significant.

but seed production decreased when the high rates were applied as ammonium as opposed to nitrate N. Salas et al. (1997) concluded that use of ammonium fertilizer might be useful as a management technique to reduce seed production of giant foxtail.

Over two years, ivyleaf speedwell decreased wheat ear number per unit area for each nitrogen treatment shown below (Angonin et al. 1996):

Year 1—None and 60 kg ha^{-1} at tillering plus 80 kg ha^{-1} at the first node of stem elongation.
Year 2—None, 60 kg ha^{-1} at tillering, 60 kg ha^{-1} at the first node of stem elongation, and 140 kg ha^{-1} applied over three dates.

The authors explained this by an increase in tiller mortality and a nitrogen deficiency in wheat at the stem elongation and flowering stages. With late nitrogen application, individual wheat grain weight increased and the weed's effect on wheat yield was lowest.

When rice was grown in competition with late watergrass with nitrogen at 0, 60, 120, or 180 kg ha^{-1}, root dry weight was highly correlated with canopy structure for both species (Gibson et al. 1999). Late watergrass showed a significantly stronger response to nitrogen than rice. When the two plants were grown with roots separated or mingled, the results suggested that root competition for nitrogen (rather than light competition) was the primary locus of competition between the species.

Adding nitrogen fertilizer to apple orchards increased the nitrogen level in apples but did not completely overcome apple growth inhibition by Kentucky bluegrass, orchard grass, or Korean lespedeza (Shribbs et al. 1986).

The relative total yields of mixtures of barley and beans were significantly greater than 1 when the plant's root systems were mixed and were reduced when nitrogen fertilizer was applied (Martin and Snaydon 1982). A conclusion of the study was that the yield advantage of intercropping in this case was related to the different nitrogen sources used by beans and barley.

Blackshaw et al. (2003) studied the response of 23 weed species plus wheat and canola to 0, 40, 80, 120, or 240 mg kg^{-1} of soil. Shoot and root growth of all species increased with nitrogen rate but the magnitude of the response varied widely among the species studied. Fifteen weeds increased shoot biomass and eight increased root biomass more than wheat as N increased. Ten weeds had shoot biomass increases similar to canola whereas five increased root biomass more than canola. All species used more than 80 percent of available nitrogen at low soil N levels. It is accepted that available evidence shows that added fertility affects crop-weed interactions, and that weeds often gain a competitive advantage over crops with added fertility (Ditomaso 1995). Ditomaso verified the common assumption that weeds are more competitive than most crops at higher soil fertility levels, and weeds commonly accumulate higher concentrations of the principal fertility elements (N, P, K, Ca, and Mg). It is understood that growers routinely add nitrogen fertilizer to wheat and canola. It is not clear how data such as those generated by Blackshaw et al. (2003) can be used to change weed management practices in either crop. Ditomaso (1995) recommended understanding of the basic mechanisms of the timing of nutrient uptake by crops and weeds as the necessary means to develop fertilizing strategies that favor crops and disfavor weeds. These strategies could include:

- Deep band application
- Nitrification inhibitors
- Intentional shifting of the N sources to ammonium and urea to restrict growth of ammonium or urea-sensitive weeds
- Timing of fertilizer application to coincide with specific crop developmental stages and to avoid specific weed developmental stages
- Conscious selection of crop cultivars
- Alteration of crop row spacing or seeding rate to increase crop uptake of applied nutrients

It is clear that future weed management systems should consider the effect of rate and time of application of fertility on the crop-weed complex. The methods of doing so are not as clear or well developed.

Kleinig and Noble (1968) said that an important aspect of barnyardgrass's competitive ability is its capability of growing and tillering vigorously early in the season when light is abundant. Barnyardgrass tillers earlier than rice and addition of superphosphate stimulates tillering. Final tiller number is also influenced by nitrogen availability. Barnyardgrass competition with rice reduced the number of tillers, panicles, and spikelets per panicle. These effects were accentuated by high levels of nitrogen and phosphorus.

Gill and Blacklow (1984) emphasized the importance of nitrogen and phosphorus in the interaction between wheat and great brome. They noted a reduction in nitrogen and phosphorus concentration in wheat shoots earlier than in great brome and earlier than significant reduction in dry matter and suggested than great brome competed with wheat for absorption of both nutrients.

Phosphorus rates of 0.4, and 0.8 g L^{-1} of soil with plant densities of 2, 4, or 8 per 113 cm^2 pots, demonstrated that smooth pigweed was not responsive to P levels but luxurious consumption by the weed reduced the amount of P available to lettuce and, thus, its yield (Santos et al. 1998). Purslane, in contrast, increased in competitiveness in response to P but lettuce did not. Santos et al. (1998) concluded that P competition appears to be the main mechanism of common purslane interference in lettuce, especially when the crop is grown in low P soil.

Competitive interference for phosphorus and, to some extent, for nitrogen was noted between wheat and common lambsquarters (Bhaskar and Vyas 1988). Nutrient interference played "a major part in limitation of growth of wheat plants by" common lambsquarters, whereas wheat exhibited greater noncompetitive interference in restricting potassium uptake by common lambsquarters.

Several studies have reported on the concentration of nutrient elements in a crop and interfering weeds. The concentration of N, P, K, and Ca were highest in jimsonweed, intermediate in common cocklebur and tall morningglory, and lowest in large crabgrass when all competed in tomato (Sanders et al. 1981). Sanders et al. found a few differences in nutrient content in tomato and weed leaf tissue, but there was no clear relationship between concentration of N, P, K, Ca, Mg, and S and weed density. More fruit was produced per kg of total assimilated N, P, and K in weed-free than in weedy plots. Bhowmik and Reddy (1988) found no difference in nutrient content of tomato and barnyardgrass in one year, but in a second year, tomato-leaf N and K levels declined and P increased as barnyardgrass density increased.

Liebl and Worsham (1987) found that Italian ryegrass responded better to increasing soil levels of NO_3 and K than wheat. The net uptake of NO_3 and K was twice as high for Italian ryegrass as it was for wheat. Italian ryegrass responded more to changes in nutrients and had greater ion uptake rates compared to wheat. The weed had greater biomass than wheat when grown in monoculture, but due to initial seedling size, wheat seedlings were larger than Italian ryegrass seedlings for the first 20 days after emergence.

In an intercropped culture of corn/cowpea, three weeks after planting, weeds in weedy cropped plots had taken up two to four times as much N, P, K, and Ca + Mg as was taken up by the corresponding weed-free crops (Ayeni et al. 1984).

Ampong-Nyarko and DeDatta (1993) showed that in field competition between rice and itchgrass or junglerice, N availability increased canopy interaction light absorption and reduced the leaf area of rice exposed to sunlight. When no nitrogen was applied, there was a difference in dry matter yield between plants grown at 150 or 400 µmol $m^{-2}s^{-1}$. Dry matter increased with increasing light intensity, thus illustrating the connection between these two elements of competition that plants routinely integrate and research separates. We will now turn from nutrients to light as the second of the three major elements of competition.

COMPETITIVE INTERACTIONS FOR LIGHT

An overview of current research (Holt 1995, 143 citations) of light effects on plants emphasizes the advantages of better understanding of "plant responses to light quality, transient light, and fluctuating light environments" as a means to manipulate the light environment of crop canopies to improve weed management. Holt points out the many advances made in the ability to measure light that have implications for weed-crop competition studies and for weed management. Readers are referred to Holt's (1995) review for details on light quantity, light quality, the effects of changing light environments, and the role of transient light.

Aldrich and Kremer (1997) list the several characteristics that control plant competition for light in what they define as the horizontal dimension, which is controlled by leaf traits, and the vertical dimension, a function of plant height. Advantageous leaf traits include leaf area, leaf angle and arrangement, canopy effects (i.e., how deep and effectively light penetrates the canopy), and light effects within the plant community (i.e., shading and competition for light).

The latter point is illustrated in the work of McLachlan et al. (1993b). They asserted that a fundamental component of modeling crop-weed interference is the effect of understory photosynthetic photon flux (PPF) on weed (and crop) growth. In other words, it is a measure of how effective shading is. As PPF declined, dry matter accumulation and relative dry matter distribution in redroot pigweed was greater in the main stem components than in branch components. The result was that the proportion of leaf area and dry matter in the upper parts of redroot pigweed increased as PPF decreased with increasing corn density (McLachlan et al. 1993b). Stoller and Meyers (1989b) found that four weeds and soybeans adjusted to decreased light by decreasing light-saturated photosynthesis, leaf respiration rates, root:shoot ratio, and leaf density. However, as irradiance was reduced from a maximum of 850 µmol $m^{-2}s^{-1}$, support tissues (roots, stems, and petioles) and leaf area ratios did not change for common lambsquarters and velvetleaf. These measurements increased for soybean and decreased for eastern black nightshade and tumble pigweed. Thus, the latter species demonstrated superior adaptation for efficient light harvesting in reduced light (Stoller and Meyers 1989b). The results suggest that changing plant architecture and the influence of canopy transmitted PPF may be as important as total dry matter and leaf area when one tries to describe or predict the effects of crop-weed interference. The effect of light deprivation for weed management is shown by work with eastern black nightshade (Stoller and Myers 1989a). When grown in full sunlight without interference the weed produced 243 g of shoots and 5,957 berries in 20 weeks. Plants grown in 94 percent shade produced only 3 g of shoots and 23 berries in 20 weeks and 1 g and 1 berry in 11 weeks. Soybeans effectively, although not completely, controlled the weed. The weed produced nearly 50,000 seeds per plant in full sunlight but less than 20,000 when grown with soybeans (Stoller and Meyers 1989a). The closer eastern black nightshade grew to the soybean row, the lower was its productivity and competitiveness.

Walker et al. (1988) developed a technique to measure the vertical distribution of leaf area and thus of light interception within monocultures and mixtures of rapeseed, wild mustard, and common lambsquarters. Light measurements were made at several levels of the plant canopy and when the information was combined with species height (the vertical component), canopy leaf area index could be separated and the contribution of each species could be estimated from the sunlit leaf area index of each species.

It is common, but incorrect, to assume that greater leaf area will automatically be advantageous for any species. Common lambsquarters has been shown to be a competitive weed in sugarbeets regardless of where the work was done. When its competitive effects were compared to those of common chickweed and sugarbeet, common lambsquarters, the worst weed, had the lowest leaf area index (Joenje and Kropff 1987). Its competitiveness is, of course, related to its leaf area but its height, and subsequent competition for light, are more important. If common lambsquarters emerged up to 21 days after sugarbeet, the crop's yield was still reduced. If the weed emerged 30 or more days after the crop, it was unable to develop a canopy above the crop and sugarbeet yield was not reduced (Joenje and Kropff 1987).

The importance of the horizontal determinants cited by Aldrich and Kremer (1997) is affirmed by the work of Barnes et al. (1990). Competition for light between wheat and wild oat is strongly affected by canopy structure as it influences light interception and carbon dioxide gain in mixed and pure stands. It is good when a plant intercepts as much light as possible, but to be beneficial the light capture must be translated into carbon fixation and a net carbon gain. Changes in leaf area and leaf inclination affected canopy carbon gain differently in mixtures of the two plants and in monocultures. Competition for light was most influenced by different positioning of the leaf area in upper canopy layers (Barnes et al. 1989). Leaf position in the upper canopy layers was the prime determinant of the amount of light intercepted.

The importance of light capture to competitive success is illustrated in several reports. Jones et al. (1981) found that an "okra-leaf" cotton cultivar was less competitive because it had reduced leaf area compared to cultivars with normal size leaves. The fact that redroot pigweed is usually an effective competitor was affirmed by growth chamber studies (McLachlan et al. 1993b) that showed a linear increase in redroot pigweed's relative leaf area with temperature over normal growth ranges. The studies also showed that the weed's relative leaf area was significantly reduced by canopy induced shading.

Light interference in soybeans has been studied more than in any other crop. Interference between common cocklebur and soybeans was primarily due to shoot interaction and competition for light (Regnier et al. 1989). When the interference of common cocklebur was compared with that of velvetleaf and jimsonweed in soybeans, common cocklebur was a more effective competitor because at the end of the growing season it had more leaves in the soybean canopy, its leaf area was more evenly distributed above and below the soybean canopy, whereas the other weeds were dominantly above the soybeans, and common cocklebur had more shade tolerance, especially in its lower branches (Regnier and Stoller 1989). Soybean is an effective competitor for light. Maximum shading from the soybean leaf canopy occurred 11 weeks after planting and declined 3 weeks later due to soybean leaf drop (Murphy and Gossett 1981). Light in the soybean row, three and five weeks after planting averaged 55 and 40 percent of available light, respectively. This finding was confirmed in work that showed that shading 30 cm from the soybean row was similar for all row spacings but the shade inflection point was 15 cm from the row and it occurred more rapidly in 30 as opposed to 61 or 90 cm rows (Murdock et al. 1986).

The study by Jones and Walker (1993) showed a linear relationship between light intensity and water uptake per unit leaf area over two years. Water uptake was proportional to light intensity. Once again we see that while the elements of competition can be divided by the reductionistic science, plants integrate all things, as they must.

The vigor of competition for light by smooth pigweed compared to johnsongrass in soybeans was demonstrated by Toler et al. (1996) who showed that smooth pigweed intercepted 2.5 times more light than johnsongrass in one year and 1.8 times more in a second year. In multispecies populations, with 4 or 8 smooth pigweed 4.6 m^{-1} of row, light interception by johnsongrass was negligible. Competition for light was the primary reason for soybean yield decrease caused by hemp sesbania (King and Purcell 1997).

Growth of the vigorous perennial silverleaf nightshade is also affected by light. Taproots of plants grown in full sunlight had 16 percent greater structural carbohydrates g^{-1} dry weight than taproots of plants grown in 92 percent shade. The weed's leaf area increased in shade but the leaves were thinner as indicated by the reduced leaf weight per unit area (Boyd and Murray 1982). Plants grown in 92 percent shade had 35 percent less chlorophyll per unit leaf area than unshaded plants but plants grown in medium shade (47 percent) had more chlorophyll than plants grown in full sunlight.

Sicklepod, a common weed in soybeans, grew slightly taller in partial shade, but its dry weight was reduced (Nice et al. 2001). When soybean row width was decreased from 76 to 38 cm and soybean population per acre was increased, sicklepod population declined 80 percent, primarily due to light competition.

Light has been identified as limiting or, at least, an important component in the interaction between several crops and competing weeds. For example, wild oats limited light penetration and growth of dwarf hard red spring wheat when water and nitrogen were nonlimiting (Cudney et al. 1991). The opposite crop-weed relationship was identified when round-leaved mallow invaded spring wheat in Alberta. Round-leaved mallow produced less than 1 percent of the seed of plants growing alone because wheat reduced photosynthetically active radiation (PAR) that penetrated to the decumbent weed by 80 to 90 percent, beginning four weeks after crop emergence (Friesen et al. 1992). Manipulation of light has potential to improve wheat yield in fields infested with Italian ryegrass (Ghersa et al. 1994). If total radiation reaching the soil surface was reduced to about 10 percent of full sunlight but the red (600 nm)**:**far red (730 nm) ratio was maintained at the normal ratio of 1.0, wheat grain production declined 40 percent. When radiation was reduced to 3 percent of full sun, and the red:far red ratio was 0.2, wheat grain production was 35 percent of that in the control. Under all conditions, Italian ryegrass interference reduced wheat yield. In full sunlight, the weed reduced wheat yield up to 75 percent. Therefore, shading improved wheat yield in mixed stands and reduced interference from Italian ryegrass. Ghersa et al. (1994) suggested manipulation of the shade environment could be accomplished by intercropping or by strip- or relay-cropping patterns. Similar results were obtained in other work. Italian ryegrass had a leaf area index 6.6 times greater than wheat 200 days after emergence, and PAR was reduced up to 68 percent at wheat's boot stage (Hashem et al. 1998). Winter rye effectively reduced light to downy brome by 40 to 90 percent, although the weed still reduced rye biomass and yield (Blackshaw 1993).

Junglerice, goosegrass, and itchgrass had higher net CO_2 exchange rates at 150, 250, and 400 μmol $m^{-2}s^{-1}$ than rice. Gas exchange rates response to light intensity was greatest during early vegetative stages and declined with age. Effects were more evident in rice than in the weeds (Ampong-Naryko et al. 1992). Itchgrass had superior growth and carbon dioxide assimilation than rice, while junglerice and goosegrass were more susceptible to shading. The major effects of redstem on rice occurred only after the weed grew above the rice canopy, and they were attributed to shading that decreased shoot and grain production and increased tiller mortality (Caton et al. 1997). Caton et al. (2001) acknowledged that "the effects of weed shoot morphology on competitiveness for light in rice have not been well described quantitatively and are difficult to study empirically." Their point lends support to the claim made at the beginning of this chapter that while there have been many studies that state an effect of competition due to one or more of the elements of competition, mechanistic explanations have been elusive. A rice:weed model was developed to evaluate the effects of weed leaf area density, leaf angle (as leaf light extinction coefficients), and height on growth and competition of weeds with rice (Caton et al. 2001). Short weeds and weeds with conical leaf area densities were weakly competitive, independent of other traits. For other weed types, interference was positively correlated with height, and the tendency to have more planophile (as opposed to erectophile) leaves.

Corn hybrids with enhanced weed tolerance and greater velvetleaf suppressive ability were those with a higher leaf area index and a greater ability to capture PAR (Lindquist and Mortensen 1998). The authors suggested that optimizing corn's leaf area and, thus, PAR reception would be useful in developing integrated weed management strategies. In dry beans, competition for PAR was the principal factor in competition with common ragweed (Chikoye et al. 1996). The ability of common sunflower to intercept PAR was deemed to be an important component of interference in soybeans (Geier et al. 1996). A common sunflower density of 0.3 m^{-2} reduced PAR at the top of the soybean canopy by 24 and 18 percent over two years.

Reductions in tomato yield in Ontario, Canada, were attributed to reduction in light due to shading by weeds and to weed competition for water (Weaver and Tan 1987). Reduced light during anthesis and early fruit set did not affect tomato yield if light intensity during the rapid fruit development stage was not reduced (McGiffen et al. 1992).

Some studies have been done to demonstrate the effect of light level on weed growth independent of crop competition. Flower production in field bindweed and Russian knapweed declined with decreasing light. The leaf area of field bindweed decreased as light decreased from 520 to 325 μmol $m^{-2}s^{-1}$, but Russian knapweed's leaf area increased as light declined from 520 to 236 μmol $m^{-2}s^{-1}$. Dry matter of shoots, roots, and rhizomes of field bindweed plants grown from seed decreased as light decreased, whereas plants grown from rhizome segments did not produce rhizomes as light decreased. The dry matter of Russian knapweed grown from seed or rhizome segments decreased as light decreased. For both plants, the total PAR was more important than whether low or high light levels occurred first during the study (Dall'Armellina and Zimdahl 1988).

When lower leaves of greenhouse-grown common cocklebur and velvetleaf were shaded to 5 percent of full light for 12 days and upper leaves were in full light, lower leaf senescence and leaf area decreased but branch length and the number of second-order leaves increased. Shading of lower leaves increased the leaf area of upper leaves 3 days after shading began in common cocklebur and 6 days later for velvetleaf (Regnier and Harrison 1993). Total dry weight of velvetleaf 12 days after shading began was unaffected by shading, but that of common cocklebur was reduced 10 percent. Regnier and Harrison (1993) concluded that common cocklebur has greater shade tolerance than velvetleaf but both species have the ability to compensate for shading of lower leaves by altering upper shoot growth.

Yellow nutsedge shoots, number of tubers, height, and shoot and tuber dry weight were less affected by 20, 40, 60, or 80 percent shade than purple nutsedge (Santos et al. 1997). Shoot and tuber dry biomass of both species responded linearly to shade. In yellow nutsedge, 80 percent shade reduced dry matter partitioning to tubers and increased partitioning to shoots. In contrast, partitioning to tubers decreased with 80 percent shade without an increase in partitioning to shoots. Yellow nutsedge has a lower light compensation point that purple nutsedge. The authors suggest this may explain the greater worldwide distribution of yellow nutsedge. Yellow occurs more frequently in regions of low light intensity, whereas purple is more common in tropical areas with high light intensity.

Artificial shading reduced seed and rhizome production of yarrow, and seed production was totally eliminated at 6.4 percent of full sunlight (Kannangara and Field 1983). The weed's seed production was stopped and rhizome production was diminished significantly due to crop interference from barley or peas.

Bookman and Mack (1983) noted that downy brome dominates sites of large-scale disturbance while Kentucky bluegrass dominates sites of small-scale disturbance in the *Festuca* (fescue)/*Symphoricarpos* (snowberry) habitat of eastern Washington (US). In contrast to many studies in the weed science literature, Bookman and Mack (1983) examined the role of light in the relationship and proposed a mechanistic explanation. Their work showed that light utilization efficiency of bluegrass was greater although its light compensation point was lower than for downy brome. The plant's respective photosynthetic characteristics (maximum net photosynthesis was higher for downy brome: 14.9 versus 11.5 mg CO_2 $dm^{-2}h^{-1}$) and the seasonal pattern of light transmission in the meadow steppe canopy largely accounted for the successful establishment of Kentucky bluegrass on sites with small disturbance and little light and the restriction (dominance) of downy brome to sites with more light.

Light played an important role in the dominance of triazine-resistant and triazine-susceptible smooth pigweed. When sunlight was 10 percent of full sunlight, there was no difference in the growth rate of triazine-resistant and triazine-susceptible plants (Ahrens and Stoller 1983). However, with either 100 percent or 40 percent of full sunlight, dry matter accumulation 11 weeks after planting was about 40 percent less in triazine-resistant plants, which may account for their lack of competitive success in the field.

COMPETITIVE INTERACTIONS FOR WATER

All studies acknowledge the central role of water in weed-crop interactions. An interesting but apparently ignored approach was recommended by Norris (1996) who advocated that water use efficiency be used to measure the detrimental effects of weeds and as a way to estimate the cost of weeds. Norris (1996) constructed a graph (fig. 7.1) that compared weed biomass in kg dry weight ha^{-1} and water use in mm ha^{-1}. This method will aid modelers who must consider water use and managers who must decide if and when to control. Because irrigated land produces much of what we consume and water is a finite and increasing cost resource, it should not be wasted. Knowing the losses due to weeds and the cost of water should allow managers to estimate better the need for and benefits of weed control.

It is clear that water does not have a role of equal magnitude in all crop-weed interactions. For example, Kropff et al. (1992) showed with a simulation model that water shortage only influences the competitive strength of common lambsquarters when the weed grows above sugarbeets. Otherwise the contribution of water shortage to competitive interactions were negligible. The number of days between crop and weed emergence and the temperature in the time between crop and weed emergence were the most important factors affecting competition between common lambsquarters and sugarbeet. In contrast, root interference dominated the interactions between mayweed chamomile and peas, and soil water was more important than nitrogen (Ogg et al. 1994). Decreasing soil water potential (-33 to -175 kPa) reduced several aspects of pea growth and

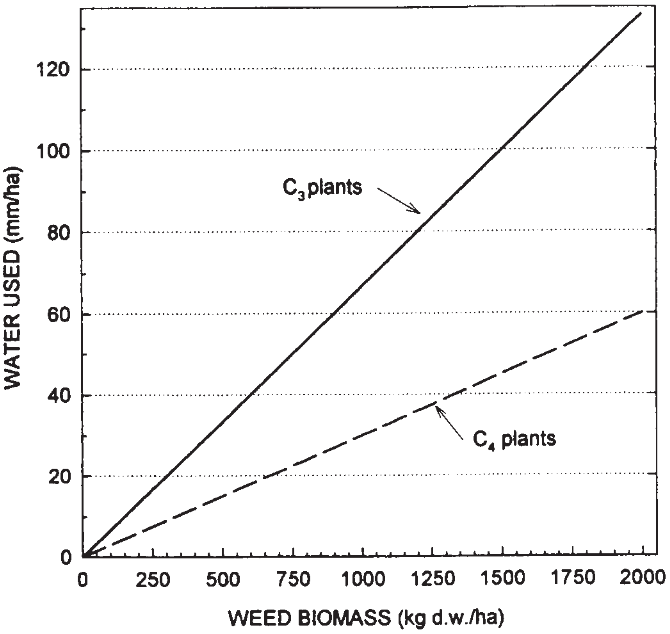

Fig. 7.1. Relationship between water used and weed biomass production. The equation is mm ha^{-1} = coeff* x/1000, where coeff is the transpiration-coefficient for either C_3 (666) or C_4 (300) plants, and x is the plant biomass in kg dw ha^{-1}. (Reprinted with permission of the Editor, *Weed Technology* [Norris 1996])

increased the aggressiveness of mayweed chamomile toward pea.

Similarly, well-watered and drought-stressed common cocklebur reduced soybean yield 29 versus 12 percent (Mortensen and Coble 1989). Drought-stressed common cocklebur interfered with soybean over a shorter distance and the magnitude of the effect at any distance was reduced. Soybean's yield potential was reduced by water stress and drought caused a reduction in common cocklebur growth. Interference between soybean and common cocklebur was not stable across all soil-moisture conditions, which has implications for modeling efforts.

Midday xylem potentials of soybeans and common cocklebur decreased as the growing season progressed and were lower in common cocklebur during the soybeans' vegetative and reproductive phases. The differences in xylem potential between soybeans and common cocklebur on a given day were small (Scott and Geddes 1979). Greater diffusive resistance was more common in soybeans than in common cocklebur and, for each species, under the stress of competition. Canopy interference and canopy and root interference of common cocklebur with soybeans increased water uptake per plant and per unit leaf area (Jones and Walker 1993), but the effects were not identical for common cocklebur and sicklepod. Canopy interference by soybeans with sicklepod increased the soybeans' water uptake per unit leaf area. Root interference by soybeans decreased water uptake per plant by common cocklebur and root and canopy interference by soybeans decreased water uptake by sicklepod (Jones and Walker 1993). The leaf area and shoot weight of all three species decreased as a result of root interference from any other species. Common cocklebur's water uptake was twice that of soybeans or sicklepod

Soybean leaf area and aboveground biomass were greater than those of Florida beggarweed under optimum soil moisture conditions, but they were equal to or less than the weed under water stress (Griffin et al. 1989). Soybeans were more competitive with adequate soil moisture but less so with drought stress. As water stress increased, stomatal conductance, photosynthetic rate, and transpiration of velvetleaf declined more rapidly than they did in soybeans (Munger et al. 1987). It is clear, perhaps the only clarity, that water stress does not have an equal effect on crops and weeds.

Among seven weeds that compete with soybeans, the net photosynthetic rate, net assimilation rate, and water use efficiency on a whole plant or a single leaf basis were greatest in C_4 smooth pigweed (Patterson and Flint 1983). Smooth pigweed affected cotton water relations by reducing plant water stress early in the season and by shading late in the season (Stuart et al. 1984). Smooth pigweed has the capacity to extract water from lower in the soil profile, it also had higher diffusive resistance and reduced transpirational losses.

Growth reduction associated with water stress was greater in soybeans than in sicklepod (Patterson 1986). With adequate water, competition from sicklepod decreased the soybeans' leaf area duration, but competition from soybeans decreased the weed's leaf area duration and net assimilation rate. Thus, the effects were similar but the magnitude of the effect was greater on soybeans (Patterson 1986).

No competition for water or light was detected in a study of ivyleaf morningglory and soybeans (Cordes and Bauman 1984). On the other hand, the yield of quackgrass infested soybeans was increased by irrigation, although irrigation did not eliminate all effects of quackgrass interference (Young et al. 1983).

Patterson and Highsmith (1989) showed that water stress reduced cotton's height, total dry weight, and leaf area in competition with velvetleaf or spurred anoda when compared to well-watered controls. Drought did not affect the relative competitive abilities of the three species or the weed's effects on cotton. The weed's effects were apparent as early as 11 days after the onset of competition.

Bermudagrass significantly reduced soil-water content 15 cm deep, but soil water was not affected 30, 45, or 60 cm in the soil profile in competition with cotton (Vencill et al. 1993).

Volumetric water content up to 180 cm deep in the soil profile did not differ in competition between cotton, and devil's-claw did not differ until the fifth or sixth week after emergence (Riffle et al. 1990). The greatest water depletion occurred early in the season in plots with devil's-claw, which corresponded to the time of most rapid weed growth. In plots with just cotton, the largest reduction in soil water occurred late in the season during peak bloom and early boll formation. Similarly, the perennial, leguminous weed hogpotato was able to extract water from up to 120 cm deep while cotton used water only from the upper 75 cm of the soil profile (Castner et al. 1989).

Wheat yield decreased more from Canada thistle competition in years with higher rainfall (Donald and Khan 1992). Jointed goatgrass seed production was lower in a wet than in a dry year (Ogg and Seefeldt 1999). The number of wheat heads per plant, wheat's rate of water use, and its weight gain were positively correlated with maintaining yield in a wet versus a dry year, but no firm relationships were established between the growth of wheat and jointed goatgrass and moisture supply.

The predicted yield loss was similar under normal water conditions when common cocklebur competed with peanut (Royal et al. 1997). When the water supply was above normal, peanut yield was 9 to 24 percent lower under competition.

Reductions in tomato yield due to weed interference were attributed to shading by the weeds (as mentioned above) and to competition for water, which resulted in stomatal closure (Weaver and Tan 1987).

COMPETITION FOR OTHER ENVIRONMENTAL FACTORS

Clements et al. (1929) limited competition primarily to nutrients, water, light, and perhaps space. However, plants require other factors for growth, but competition for these has not received extensive study. Isolating specific affects is difficult, plus the primary factors are so dominant in the environment and relatively easy to isolate for study. The first edition of this book (Zimdahl 1980) cited only 11 studies that dealt with factors other than nutrients, light, or water, and four were about temperature, which is covered above. No additional studies that carefully defined the actual or potential role of other environmental factors (e.g., soil microsite difference, soil pH, soil atmosphere, and carbon dioxide) were found in the weed science literature.

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Weed-Crop Competition: A Review, Second Edition
Robert L. Zimdahl

8
Weed Management Using the Principles of Competition

Perhaps, to use the current vernacular, this chapter is where the rubber meets the road. We must ask, has all the work that has been done to establish that weeds affect crop yield changed weed management? Has the abundant information improved weed management? One view (Norris 1992, 1999), based on an extensive survey (Norris 1997), concluded that in spite of the abundant literature on the effects of weed density and duration on competition, improved computer technology, and 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. The evidence in this review is that his plea has not resulted in a significant change in the research weed scientists do.

It is not that the dominant control orientation has failed to fulfill its goal—to control weeds in a crop and prevent yield loss. It is that the science has not moved beyond the ability to control nearly all weeds selectively in nearly all crops. That ability is not a trivial achievement. It is an achievement that took the combined efforts of university research scientists, cooperative extension specialists, and chemical industry scientists. They are rightfully proud of the progress that has been made from the days of the hoe and horse to the present era of selective, economical, relatively safe, efficient weed control.

However, as successful as these methods are, they have also created problems that have been ignored or dismissed as externalities[1] for too long. These serious problems include harm to nontarget species, harm to humans, environmental harm, ground and surface water pollution, soil pollution, and often high cost. The undeniable success of modern, chemically, energy, and capital intensive agriculture has also discouraged investigation of other options. Liebman and Dyck (1993b) acknowledged the "serious problems with conventional weed management strategies" and proposed that ecologically based alternatives ought to be "examined and tested." I have expressed similar concerns (Zimdahl 1998a, b, 1999, 2002; Zimdahl and Speer 2001). Liebman and Dyck (1993b) offered five reasons in support of the need to develop ecologically based weed management systems:

1. Herbicides have undesirable effects on the quality of surface and groundwater.
2. Many herbicides are becoming less effective due to development of herbicide-resistant biotypes (Heap 2003).
3. Many herbicides are being removed from the market due to declining sales, increasing regulatory requirements, or herbicide resistance.
4. Herbicides may not be a viable option for farmers in developing countries and are not an option for those who wish to farm organically.
5. Ecologically based weed management "can be part of agronomically productive, economically viable farming systems."

No one has demonstrated that the reasons offered by Liebman and Dyck (1993b) are bad or that development of ecologically based weed management systems is a bad idea. Little research has been done to develop such systems in comparison to the great emphasis on work to preserve the present production system. Little of the work that has been done to describe the consequences of weed-crop competition has led to development of the required principles to develop ecologically based weed management systems. The challenge remains.

The remainder of this chapter is divided into eight parts that reflect the research done since 1980: (1)

plant arrangement in the community, (2) monoculture versus polyculture, (3) tillage, (4) rotation or crop sequence, (5) shade, (6) the role of crop genotype, (7) fertility, and (8) the importance of weed biology and ecology.

PLANT ARRANGEMENT IN THE COMMUNITY

As first reported in chapter 5, Mohler (2001) claimed that "the density, arrangement, cultivar, and planting date of the crop that maximizes the rate at which the crop occupies space early in the growing season usually minimize competitive pressure of weeds." Mohler reviewed 91 papers that dealt with 29 crops and only found 6 papers that failed to verify that increasing crop density resulted in decreasing weediness. Mohler's (2001) review also found that "at any given crop density, the slope of the weed biomass curve is greater when density of the weed is high." He concluded and provided data to verify that "suppression of weeds and increase in crop yield from an incremental increase in crop density increases with the density of weeds."

Most of the work reported in this section deals with the effects of row spacing on weeds and most (nine reports) was done in soybeans and nearly all of those studies and those on other crops show that weed populations and their effects were reduced as row width decreased. In view of the early agronomic work on optimum seeding rates (e.g., see Martin et al. 1976) and on the effects of row spacing on crop yield, the effects of row width on weeds is not surprising, although narrow rows do not always result in reducing the effects of weeds. With crops, narrower rows tend to optimize yield until intraspecific interference increases and crop yield decreases. When crops and weeds interfere, one may strive to optimize crop yield by employing narrow rows to minimize the weed's detrimental effects. The effects of higher crop populations (narrower row widths) usually can be expected to reduce weed competition. But that is not always true. In cabbage and cucumbers, narrowing row width resulted in smaller crop plants and a shorter time during which the crops could remain weed infested without diminishing yield (Weaver 1984). A point confirmed by Mohler's (2001) observation is that the "effects of intraspecific competition frequently depress harvest index when the crop is grown at high densities." This effect will, of course, vary with the biology of the crop and the interfering weed(s) (Mohler 2001).

For four soybean cultivars, there was little effect of changing row widths on soybean yield if the crop was planted on what Parker et al. (1981) called normal dates. If planting was later than June, soybean yield decreased as row width increased. In other work, Costa et al. (1980) found that among several soybean cultivars, early-maturing cultivars had a greater yield response (+27 percent) to narrow (27 cm) rows than did cultivars in maturity groups I and II (+19 percent). Soybean cultivars grown in 27 cm rows versus the more conventional 76 cm rows produced an average seed yield 21 percent higher over all years, populations, and cultivars (Costa et al. 1980). Late-maturing cultivars produced the highest yields over all row spacings, plant populations, and years. Van Acker et al. (1993) advocated narrow rows or early-branching soybean cultivars to reduce weed competition.

Over two years, as row spacing increased, weed resurgence (growth after initial control) increased (Yelverton and Coble 1991), and the growth was directly correlated with the amount of light penetrating through the soybean canopy to the soil surface. In one experiment (Esbenshade et al. 2001), row spacing (38 versus 76 cm) had no effect on burcucumber emergence or biomass production.

Sicklepod growth was less in narrow (25 cm) than in wide (102 cm) rows (McWhorter and Sciumbato 1988). Reducing soybean rows from 76 to 38 or 19 cm while increasing soybean population reduced sicklepod population up to 80 percent. Smith and Jordan (1993) showed that sicklepod growth and morphology responded to its distance from the soybean row and its time of emergence relative to the crop. Virtually all sicklepod plants were taller than soybeans, but if the weed grew close to the soybean row, its height, number of main stem nodes, number of primary branches, and shoot dry weight all were lower. Sicklepod's shoot dry weight could be reduced up to 60 percent if it grew close to the soybean row (Smith and Jordan 1993). In most cases, proximity to the soybean row also reduced sicklepod seed production (Nice et al. 2001). In competition with sicklepod, it was only under optimal growing conditions (in one year) with conventional cultivars and sequential herbicide application that 19 cm rows produced more yield (21 percent) than 38 cm rows with medium soybean populations (455,375 plants ha^{-1}) in Mississippi (Buehring et al. 2002). Further illustrating the interaction of row width and plant population, Buehring et al. (2002) showed that with a low soybean population (241,000 plants ha^{-1})

19 cm rows yielded 64 percent more than 76 cm rows. However, in a second year, with similar sicklepod control, there was no difference in yield between 19 cm and 38 cm rows. However, in 19 cm rows, soybean yield was 15 percent higher and in 38 cm rows it was 24 percent higher than yield in 76 cm rows (Buehring et al. 2002). Although row spacing did not affect soybean height or seed size, the number of pods was higher in 80 cm versus 40 cm rows (Walker et al. 1984). Soybean in 20 cm rows yielded more than in 40 cm or 80 cm rows when sicklepod was not controlled (Walker et al. 1984). Redroot pigweed was 29 percent of total leaf area in wide (76 cm) rows and only 15 percent in narrow (25 cm) rows (Légère and Schreiber 1989). The leaf area distribution of soybean and redroot pigweed suggested light competition was important. With cultivation, 38 cm rows resulted in less growth of redroot pigweed and robust foxtail than 76 cm rows, but without cultivation, the reverse was true (Orwick and Schrieber 1979).

In Ontario, Canada, the decrease in biomass production by transplanted and naturally occurring weeds was greater due to narrow row spacing than to higher corn-population density. The combination of narrow rows (38 cm versus 76 cm) and high corn population increased corn canopy light interception 3 to 5 percent (Begna et al. 2001). Weed biomass was five to eight times lower under the corn canopy than in a weed monoculture. When corn density was increased from seven to ten plants m^{-1} of row and row width was decreased from 75 cm to 50 cm, there was significant increase in corn's leaf area index and a reduction in the photosynthetic photon flux available below the corn canopy (Murphy et al. 1996). In all cases, narrow corn rows and increased corn-population density significantly reduced the biomass of late-emerging weeds. Corn yield increased 10 to 15 percent in narrow (50-cm) rows, but intraspecific corn competition in the higher density plantings significantly reduced early corn growth and that offset the gain in yield from reduced weed competition (Murphy et al. 1996).

Decreasing wheat row spacing from 23 cm to 8 cm increased wheat yield at two of three locations and increased cheat infestation at six of ten locations (Koscelny et al. 1990). Increasing wheat planting rate from 265 to 530 seeds m^{-2} increased wheat yield.

Additional experiments in Oklahoma (Roberts et al. 2001) showed that wheat row spacing did not affect rye seed production. Averaged over all row spacings, increasing wheat planting rate from 67 kg to 134 kg ha^{-1} reduced rye seed production 21 and 25 percent in two experiments. At one site, doubling wheat seeding rate in 10 cm and 20 cm rows increased the yield of rye infested wheat 23 to 27 percent, but there was no benefit in 30 cm rows (Roberts et al. 2001). Increasing wheat density up to 800 plants m^{-2} reduced Italian ryegrass seed yield 87 percent but increased its harvest index 42 percent compared to its monoculture yield (Hashem et al. 2000).

Grain yield of the rice cultivar Lemont was reduced 21 percent when plants were within 25 cm of a barnyardgrass plant group (four plants in 140 cm^2 (Stauber et al. 1991). Rice yield was not affected when the barnyardgrass plant group was 25–50 or 50–100 cm from the rice. The optimum equidistant rice plant spacing for optimal rice yield was 53 mm to 71 mm (Counce et al. 1989). An increasing coefficient of variation in plant yield at closer spacings is consistent with a large body of research that indicates that plant communities become more hierarchical and variable as plant population densities increase.

Final cotton emergence was not affected by cotton's planting pattern. At layby, there were more weeds when herbicide was not used in 51 cm compared to 102 cm rows, but at harvest the number of weeds was not different in the two row widths (Miller et al. 1983). There was no cotton yield advantage for narrow rows.

With row spacings of 15, 25, 36, 46, and 91 cm, a constant density of 43 snap beans m^{-2}, and weed emergence with the beans, only row spacings of 15 cm, 25 cm, and 36 cm suppressed weed growth (18 percent) compared to standard 91 cm rows (Teasdale and Frank 1983). When weeds were controlled for the first half of the growing season, 15 cm, 25 cm, and 36 cm rows suppressed weed growth 82 percent compared to 91-cm rows. Narrow rows suppressed weed growth by increasing the speed of canopy closure of snap bean rows. Snap beans in 15 cm to 46 cm rows produced similar yields that were higher by an average of 23 percent than the yield in 91 cm rows. With increasing distance of horsenettle from snap bean rows, the weed's effect was reduced (Frank 1990).

Tomato density (0, 5, 10, or 20 plants m^{-1} of row) and barnyardgrass density (0, 0.25, 0.5, 1, 2, 5, and more than 50 plants m^{-1} of tomato crop row) had little effect on phenological development of barnyardgrass (Norris et al. 2001).

With a constant in-row seeding rate, peanut yield increased as row width decreased from 81.2 cm (the standard) to 40.6 cm and 20.3 cm. Weed growth was always less with narrower peanut rows. Without weeds, peanut yields were 6 to 20 percent higher in 20.3 cm than in 81.2 cm rows (Buchanan and Hauser 1980).

It is apparent, although not mentioned often, that the crop's competitiveness increases with the percentage of the field surface that it occupies. This percentage is maximized as the crop's planting pattern achieves the greatest degree of rectangularity (the crop row spacing divided by the crop's in-row spacing) (Mohler 2001). In spite of the strong intuitive and theoretical basis (Fischer and Miles 1973 as cited by Mohler (2001) for an inverse relationship between crop row spacing and weed growth, Mohler (2001) found only 27 of 49 studies, in 19 crops growing with weeds, in which narrowing row spacing actually increased crop yield. The difference (Mohler 2001) may be due to the effect of weed and crop height rather than just the area of ground covered.

MONOCULTURE VERSUS POLYCULTURE

The applicable principles in polyculture and inter- or companion cropping are:

1. Plant diversity is good and often diminishes harmful interference.
2. Filling all ecological niches diminishes competition.
3. A greater crop yield and less weed growth may be achieved if intercrops are more effective than sole crops in usurping resources from weeds or suppressing weed growth through allelopathy (Liebman and Dyck 1993a).

These principles have not been explored much in weed science research. Weed scientists have, in a very real sense, been bound by the dictum that the only good plant in a field is the one that is planted and all others are to be regarded as weeds and, if possible, eliminated. It is part of weed science's operative paradigm. Weed science research has made enormous progress toward achieving the goal of clean monocultural fields—fields without weeds. The fact that research and the resultant technology have allowed this to be achieved in so many crops in so many environments is laudable. On the other hand, our paradigm has not urged us to explore the possibility that some plants may grow cooperatively or, at least, not competitively with crops.

Only one paper reviewed for this book was on mixed or polyculture of plants. Ayeni et al. (1984a) showed that in early season, weed interference accounted more for yield reductions in monocultural crops of maize and cowpea than it did in the mixed culture of maize and cowpea.

Related work that has not focused on crop-weed competition has emphasized cover crops or living mulches that can be used as intercrops or companion plants to suppress weeds. A review (Hartwig and Ammon 2002) includes 93 references on the use of cover crops and living mulches for weed management. Hartwig and Ammon (2002) report that work with perennial living mulches such as crownvetch, flatpea, birdsfoot trefoil, and white clover has shown that the living mulch does not have to be reseeded annually. These plants, used as living mulches, conserve nitrogen, reduce soil erosion, and increase soil organic matter while reducing weed populations and losses due to weeds.

Appropriate weed control practices in farming systems must consider the need to maintain soil fertility and prevent erosion, and open row crops are inimical to these needs. Akobundu (1980) developed integrated low or no-tillage weed management systems, compatible with more than one crop plant in a field, which reduced herbicide use, fertilizer requirements, and soil erosion. Studies of a combination of a legume or Eugusi melon and sweet potato with corn, showed that these companion crops or living mulches maintained corn yield, contributed to nitrogen supply, suppressed weed growth, and reduced soil erosion. In unweeded no-till plots, corn grain yield was 1.6 T ha^{-1}, whereas with conventional tillage it was 2.3 T ha^{-1}. Corn yield in unweeded, live mulch plots averaged 2.7 T ha^{-1}. Yields were not different, and the presence of live mulch plants did not reduce yield; they were complementary, not competitive.

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).

Companion cropping (i.e., polyculture) can be a 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). When spring soil moisture is limiting, cover or companion crops can deplete moisture and be detrimental to crops in spite of weed control advantages.

In Pennsylvania, a polyculture of crownvetch, a legume, was successful as a living mulch in no-tillage corn (Cardina and Hartwig 1980; Hartwig 1987). Crownvetch is difficult to establish, but once established it provides soil erosion control, improves fertility by reducing nutrient loss via erosion, and contributes 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. Unsuppressed hairy vetch reduced weed biomass in corn 96 percent in one year and 58 percent 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 percent. 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.

In Wisconsin, spring-planted winter rye has been a successful living mulch for weed control in soybeans (Ateh and Doll 1996**).** A system employing just rye for weed control reduced weed shoot biomass from 60 to 90 percent over three 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 soybeans was minimal if rye was killed within 45 days after soybean planting.

The concept of smother plants for weed control is well known but not widely practiced. DeHaan et al. 1994) proposed the novel idea that it might be possible to develop spring-seeded smother plants that reduce weed biomass early in the growing season, but because they could be designed to live only for four to six weeks (the early critical weed control time), they would have only a small or no effect on corn yield. DeHaan et al. (1994) used yellow mustard selected to provide weed interference durations of 2, 4, 6, or 8 weeks and to grow only 10 cm to 20 cm tall. The best result was 10-cm-tall yellow mustard seeded at 530 seeds m^{-2} that grew with corn for four weeks. Weed growth in corn was reduced 51 percent and corn yield was reduced only 4 percent compared to monocultural corn. DeHaan et al. (1994) suggested it might be possible to develop spring-seeded smother crops that reduce weed growth up to 80 percent and have only a minor effect on corn. This innovative weed control technique has not been pursued.

Another example of a weed used to gain interspecific competition in a polyculture is azolla for weed management in lowland rice. *Azolla pinnata*, a free-floating fern, has been tried 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^{-1}. A second use is for weed control due to the competitive effect of an azolla blanket over the surface of paddy water. 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 just 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.

These methods are not perfected and will not be the perfect answer to all weed problems. Polyculture is an incompletely explored weed management opportunity. Such opportunities lead to lengthy research programs and are hard work. They challenge the existing paradigm.

TILLAGE

On arable land, tillage alone or in combination with other weed management methods may be an adequate system. 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 depleting carbohydrate reserves of perennial weeds.

Other reasons for tillage include breaking up compacted soil, soil aeration, seed bed preparation, trash incorporation, and crop cultivation. All of these are important, but the main accomplishment of most tillage done in the world's crops is weed control. The advent of no-till farming and minimum-till farming have 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. Conclusions about tillage's role, may be valid only for the place and conditions of each study (Oryokot et al. 1997).

There are situations where plowing and subsequent tillage cannot prepare land for planting. These include land heavily infested with perennial sod-forming grasses, 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. Crops can be cultivated to within a few inches of the row, but not as well in the crop row except by moving soil and burying weeds. To maximize tillage benefits, uniform spacing of crop rows, straight rows achieved by precision planting, gauge wheels, and depth guides are needed. Uneven stands and driver error often lead to damage from mechanical cultivation and destruction of some crop plants.

The success of tillage for weed control 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.

Tillage's success is also determined by physical and environmental factors such as how wet soil is and whether its condition prevents tillage. A wet spring may prevent crop cultivation when weeds are small and controlled easily. Based on a model in which the density of weed seedlings emerging is related to differing seedling's ability to emergence from depth, differential survival at different depths, and the depth of seed burial with no-tillage, Mohler (1993) made several predictions. First, in the first year following seed input to soil, nontilled areas will have more emerged weed seedlings than tilled areas. In later years, no-till areas will have fewer emerged weeds unless innate or induced dormancy is high. If seed return is allowed, no-till areas will always have more seedlings. After a major seed addition, plowing followed by years of shallow tillage is the best management technique (Mohler 1993). A risk of no-tillage systems is the development of perennial weeds. Over 14 years, a greater and more diverse population of perennial weeds developed in reduced tillage systems than in moldboard plowed systems (Buhler et al. 1994).

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 goal 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 science. Such 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 implement, is always related to the timeliness of the operation. Research can determine when to do something, but knowing when on a particular farm is part of the cultural knowledge good farmers have.

There is no question that soil tillage and crop cultivation can control weeds and that tillage or reduced tillage affect future weed populations. Several studies have shown that reducing tillage affects the population dynamics of annual weeds (Buhler 1992; Buhler and Daniel 1988; Buhler and Oplinger 1990; Johnson et al. 1989). The advent of no-tillage practices to reduce soil disturbance and soil erosion have shown that tillage is not a required agricultural practice for crop growth or weed control. However, the data reveal that the effects of tillage are not consistent among crops or across years and locations.

Studies of the effects of tillage system on weeds have not produced consistent results for all weeds. It is commonly observed that the effects of tillage, if present, are less important than the effects of crop and climate (Thomas and Frick 1993). Defelice et al. (1988) found no difference in the effect of conventional or no-tillage systems on control of velvetleaf in corn. In all three years of a study in Wisconsin that compared the effect on weeds of moldboard plowing, chisel plowing, ridge tillage, and no-tillage, green foxtail density was higher in chisel plowing and no-tillage than with moldboard plowing, and ridge tillage had the lowest density (Buhler 1992). Common lambsquarters density was always highest with chisel plowing (500 m^{-2} versus 75). Redroot pigweed averaged 307 and 245 m^{-2} in no-till and chisel plow systems versus only 25 in the other systems (Buhler 1992). Oryokot et al. (1997) provide a reason for these differences: pigweed seedlings emerge only from the top 2.5 cm of soil regardless of tillage. Pigweed seedling density is usually higher with no-tillage because more seeds are nearer the soil surface. Therefore, although tillage is necessary in many weed management systems, it is less important than crop and weather for pigweed population dynamics (Oryokot et al. 1997). Without weeds, corn yield was not affected by tillage system (Buhler 1992). Both the tillage system and crop rotation altered the relationship between corn yield over two years but tillage was not a factor in soybean yield in one year (McGiffen et al. 1997). In Nigeria, with minimum or no weed interference, corn yield was better with conventional tillage (plowing followed by two harrowings) than no-tillage, but it was worse when weeds were present (Ayeni et al. 1984b).

Bararpour and Oliver (1998) found that with tillage 11 percent of the soil seedbank of common cocklebur and sicklepod emerged one year after the seed fell on the soil, but with no-tillage only 0.7 percent of common cocklebur and 1.6 percent of sicklepod seed emerged the next year. With tillage, common cocklebur became the dominant weed, but with no-tillage, sicklepod dominated. The seedbank of both species was depleted faster with tillage.

The effects of three tillage systems (no-till, chisel plow, and moldboard plow) and the presence or absence of corn on soil temperature, moisture, and the emergence and density of common lambsquarters were studied at two sites in Ontario, Canada (Roman et al. 1999). Tillage system affected the phenology of the weed's emergence in only one year when more days were required to reach 80 percent cumulative seedling emergence in no-till plots. The effect was attributed to an extended dry period. The presence or absence of corn did not affect common lambsquarters' emergence or seedling density. Tillage, as expected, reduced the weed's seedling density, but the largest variation in seedling density was attributed to varying environmental conditions as is true for pigweeds (Oryokot et al. 1997).

The variable effects of different types of tillage on different weed species are illustrated by work in Nebraska that showed that ridge tillage enhanced development of kochia and reduced density of wild proso millet and common lambsquarters. Tandem disking increased longspine sandbur and redroot pigweed density, whereas moldboard plowing increased common sunflower density (Wilson 1993). It is probable that these effects would hold across years in this location, and they may hold for these weeds in other locations, but these assumptions must be tested.

The effect of four tillage systems (varying from intensive to no tillage) on weed populations and vertical seed distribution was studied at three locations in Alberta (O'Donovan and McAndrew 2000). The winter annual weeds, field pennycress, shepherd's-purse, and flixweed and the summer annuals wild buckwheat and common lambsquarters all increased in the soil seedbank as tillage increased. Thus, the effect of increased tillage intensity on common lambsquarters was consistent across locations. In the Alberta study, increased soil seedbank populations did not always result in increased weed seedling populations with no tillage, which O'Donovan and McAndrew (2000) suggested may mean that the requirement for herbicidal weed control may be reduced with no-tillage systems. In contrast, and to illustrate the difficulty of extrapolating these results across locations and weed species, both soil seedbank and spring weed seedling populations of shepherd's-purse at two locations and of flixweed at another were highest in the zero tillage system. In contrast, the soil seedbank and spring seedling population of green foxtail decreased as tillage decreased, suggesting that it should become less of a problem as tillage decreases. The effects of tillage are confounded by crop residues. In Wisconsin, over three years with varied environmental conditions, when tillage affected giant foxtail and redroot foxtail, emergence was greater in untilled than tilled (simulated moldboard plowing by spading 20 cm deep) plots (Buhler et al. 1996). Velvetleaf emergence was greater from tilled than untilled soil in two of three years, and the effects on common lambsquarters were not consistent over three years. Maize surface residue was inconsistent on giant foxtail and common lambsquarters. Velvetleaf emergence was reduced by two or four times the base level of residue, and the effect of maize residue on redroot pigweed emergence was dependent on tillage and precipitation (Buhler et al. 1997). Reducing tillage has a greater effect on the population dynamics of the four annual weeds than surface maize residues (Buhler et al. 1997).

Esbenshade et al. (2001) found that burcucumber emergence frequency was independent of tillage system (no-till versus reduced tillage). Preplant tillage increased the number of emerged burcucumber plants by 110 percent in one year and 70 percent in another compared to no tillage. Johnsongrass produces longer rhizomes with limited tillage. These rhizomes, as opposed to those broken by tillage, will grow more rapidly and johnsongrass interference will begin earlier as tillage decreases (Lolas and Coble 1980).

A study of cultivation frequency and time of initiation showed that seed cotton yield was increased at three of nine locations when cultivation was initiated two weeks instead of one week after emergence (Colvin et al. 1992). Cultivation with a flexible tine harrow in the fall reduced density of common chickweed, catchweed bedstraw, and rape, and thinned but did not reduce the yield of wheat. Yield was maintained because 1000 grain weight increased but the number of grains did not (Wilson et al. 1993). Summer biomass of common chickweed and catchweed bedstraw was reduced more by spring than by fall harrowing, but biomass of rape was reduced only by fall harrowing. Wilson et al. (1993) concluded that weakly rooted, climbing or decumbent species are more easily controlled by spring cultivation whereas species that develop a tap root are more readily controlled by tillage at an early growth stage in the fall. It is highly probable that this conclusion may be applicable across locations and species.

Mulugeta and Boerboom (2000) showed that there was variation in the onset of the critical time of weed removal in soybeans between a reduced tillage and no-tillage system between years and within tillage systems across years. Therefore, based on several studies, one must conclude that tillage has an effect but it is not consistent among weed species. For example, in Wisconsin, a two-year study (Buhler and Oplinger 1990) showed that common lambsquarters density was not greatly influenced by tillage system (moldboard plow, chisel plow, and no-till), whereas redroot pigweed density was usually higher in the chisel plow system. Moldboard plowing always had greater velvetleaf density than no-till, and the latter always had greater giant foxtail density. Giant foxtail and redroot pigweed became more difficult to control when tillage was reduced, but velvetleaf became easier to control (Buhler and Oplinger 1990). Another example is work in Ontario that showed that the response of annual dicots and monocots to tillage was inconsistent in oats, barley, and wheat (Légère and Bai 1999). Perennial dicots dominated in no-till systems in the three small grains, whereas perennial monocots were more abundant in tilled systems in all three cereals (Légère and Bai 1999). One must also conclude that the effects of tillage are not consistent between crops. For example, oat and barley populations were not affected by no-tillage but wheat population was reduced 16 to 20 percent in no-till systems (Légère and Bai 1999). The effects of tillage may be consistent for a weed species across locations.

A final point about the effects of tillage concerns sampling to measure the effect. Mulugeta et al. (2001) point out that the relationship between species richness and sample area has been shown in many natural communities but has rarely been considered in crop-weed communities. Using sampling areas ranging from 0.0625 to 512 m^2 in 14 nested sample areas, they determined the influence of sample area on species richness. The functional minimum area required to represent 75 percent of the total weed species in tilled and short-term no-till fields was 32 m^2. No functional minimum area was determined in long-term, no-till fields because species richness continued to increase over the range of sample areas. Regression analysis indicated that sample areas of less than 1 m^2 would contain less than 50 percent of the observed maximum species richness in a field. Sample areas of 36 m^2 in tilled and short-term, no-till fields and 185 m^2 in long-term, no-till fields would measure 75 percent of the observed maximum species richness. Therefore, as chapter 9 proposes, how one does the work is a major determinant of what one can conclude from what was done. It is as important in determining the effect of tillage on weed species as it is in all other areas of weed management decision making.

ROTATION OR CROP SEQUENCE

The first edition of this book included only five papers that reported effects of crop rotation on weed management (Zimdahl 1980). In spite of evidence of the utility of crop rotation for weed management, little additional research has been done since 1979. The literature survey by Liebman and Dyck (1993a) found that weed population density and weed biomass were reduced by crop rotation (what they called temporal diversification) and intercropping (spatial diversification). Compared to monoculture, crop rotation reduced weed density in 21 cases, increased it in only 1 case, and made no difference in 5 cases. Twelve studies reported effects on weedseed density, which was lower in nine and equal in three studies. Liebman and Dyck (1993a) report that the success of crop rotation for weed management is based on varying patterns of resource competition, allelopathy, soil disturbance, and mechanical damage to seedlings that create an unstable and frequently inhospitable environment that prevents the proliferation of a particular weed species. It is clear from Liebman and Dyck's (1993a) review that the effect of crop rotation on weeds is well known and supported theoretically, but data in support of the theory are lacking. Most of the evidence in support of the benefits and wisdom of crop rotation for weed management is observational and anecdotal rather than the result of carefully planned studies that "systematically manipulate specific components of rotational systems to isolate and improve those elements (e.g., interrow cultivation, choice of crop genotype) or combinations of elements that may be important for weed control" (Liebman and Dyck 1993a). The weed management effects of crop rotations, while generally accepted, "should be assessed through careful study of extant, complex farming systems and the design and testing of new integrated approaches" (Liebman and Dyck 1993a). It seems that although the benefits of crop rotation are accepted by farmers and researchers, there is a paucity of research data to support the benefits in modern agricultural systems. Rotation regularly changes the crop, soil preparation practices, subsequent soil tillage, and weed control techniques in a field. 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 is accepted.

If it is done, crops are rotated for economic, market, and agronomic reasons but rarely for weed management. It is known that some weeds associate with certain crops more than with others. Barnyardgrass and junglerice are common in rice. Wild oats are common in irrigated wheat and barley but almost never occur 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 as common in row crops, although without management, dandelions can increase in row crops and in pastures and hay (e.g., 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 for many years (monoculture), weeds, present in the soil seedbank, will be favored and their populations will increase. Weed-crop associations are not accidental and can be explained. Associations can be changed by changing crop, time of planting, or weed control method. Wild oats can be reduced in small grain crops by growing corn in the rotation and using herbicides selective in corn plus cultivation for control when corn is grown. The same practices cannot be used when small grain crops are grown.

A good rotation includes crops that reduce (manage) weeds that are especially troublesome in succeeding crops. Management is accomplished by competition or through use of different weed control techniques in different crops. In many places, barley is planted in spring before soil temperatures are ideal for germination of most weeds. An exception is common lambsquarters, which can be a serious weed in barley. Beans, on the other hand, are planted in late spring after tillage has destroyed many, but not all, 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. Hairy nightshade's seedbank population increased after three years of pinto beans; green foxtail increased after three years of corn; and the sugarbeet-corn sequence caused an increase in kochia. Ball and Miller (1990) 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 one weed and discourage others.

Two weeds dominated the relative dry weight of weeds in four cropping systems in the Philippines, but their relative magnitude in the cropping systems, on the same soil, was different (Pablico and Moody 1984). 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 may favor or deter species.

Growing competitive crops (e.g., hemp) in rotation may complement other means of control of yellow nutsedge, which is sensitive to competition for light. Growth and reproduction (tuber production and density in a following corn crop) of yellow nutsedge in the Netherlands was reduced in corn that followed corn grown for silage, winter rye grown for silage, winter barley, and hemp compared to corn following on land with no preceding crop (Lotz et al. 1991). After hemp, hardly any yellow nutsedge tuber production was observed. Growing a green manure crop after barley harvest reduced yellow nutsedge tuber production to 40 percent of that in winter barley followed by fallow. Competition for light was the main reason for reduction in yellow nutsedge growth and reproduction.

When corn was intercropped with cassava, corn yield decreased with time in weeded and unweeded plots except in corn plots followed by one to three years of weeded *Pueraria* fallow. Similarly, cassava tuber yield decreased with time in all unweeded plots in all treatments except when cassava followed a weeded *Pueraria* fallow (Akobundu et al. 1999). The results of this work in Nigeria suggest that rotations that included fallow years during which the soil was planted with a legume species offered more effective weed management than natural bush fallow.

Work on intercropping of pea and barley with the weed white mustard showed that nitrogen supply, water supply, soil conditions, and pea genotype (height) all interacted (Liebman 1989). To fully evaluate intercropping, the desired yield of the component crops, the priority of weed suppression (that is, consideration of potential weed benefits) can influence choice of cultivars. When the smaller Alaska pea was included, the largest yield of pea plus barley was produced with high water and low nitrogen. However, total crop yield was greatest when the large Century pea was used and nitrogen fertilizer was applied. White mustard was not a weed problem with Alaska pea but produced substantial biomass when it interfered in the Century pea plus barley intercrop (Liebman and Robichaux 1990).

Downy brome is a dominant species in much of the arid western United States and Canada and is difficult to control in winter wheat. Downy brome density increased from 24 to 970 plants m^{-2} over five years in Alberta, Canada, and density was often higher with no tillage (Blackshaw 1994). When fallow or spring canola were rotated with winter wheat, downy brome population was reduced to less than 55 or 100 plants m^{-2}, respectively, over six years. Blackshaw (1994) concluded that continuous winter wheat cropping is not a good option in areas where downy brome is prevalent, and either a fallow/wheat or fallow/canola/wheat rotation is better.

The importance of rotation for management of sicklepod was emphasized by Johnson et al. (1994). Sicklepod growing alone in fallowed areas produced more seed per plant and more seedlings than when the weed grew with a crop. Sicklepod growing in corn produced fewer seeds per plant than when it grew with peanuts or cotton.

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 seedbank from 26 to 80 percent per year. With spring barley, the soil seedbank declined 10 percent 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 percent annually. There was a great reduction in the size of the soil seedbank of winter wild oats if the cropping program was other than continuous winter cereals (Fernandez-Quintanilla et al. 1984).

SHADE

The role of shade in reducing plant vigor and growth is well known and exploited in weed management programs when possible. Silverleaf nightshade grown with 92 percent shade had 35 percent less chlorophyll per unit of leaf area and bore no fruit compared to unshaded plants, but those grown in 47 percent shade had more chlorophyll than plants grown in full sunlight (Boyd and Murray 1982). Seedling plants grown in 63 percent shade also did not bear fruit. Shading (40, 70, and 85 percent) reduced height, dry matter production, leaf area, and rhizome and tuber production of yellow and purple nutsedge (Patterson 1982). Shading reduced partitioning of plant biomass into tubers and rhizomes and increased it into leaves in both species. Partial shading increased sicklepod height and reduced dry weight, but as shading increased from 65 to 80 and

95 percent of full sunlight, height also decreased (Nice et al. 2001). A dense safflower stand closed its canopy over the soil surface early in the season and shaded green foxtail more than thin stands (Blackshaw 1993). High safflower densities (up to 192 plants m^{-2} reduced green foxtail biomass up to 72 percent and its seed yield up to 85 percent.

The role of height in competitiveness is well acknowledged, although often as an added rather than purposeful observation. The height (66 cm, 122 cm, and 168 cm) of cotton cultivars had no effect on their ability to compete with johnsongrass (Bridges and Chandler 1988). Quackgrass was nearly the same height or taller than soybeans at all stages of soybean development and offered substantial light competition (Young et al. 1983). Wild oat reduced light penetration and growth of dwarf hard red spring wheat when nitrogen and water were not limiting (Cudney et al. 1991). Wild oat grew taller than wheat and had a greater proportion of its canopy above 60 cm at maturity. In contrast, round-leaved mallow was not competitive with wheat in six of seven trials in Alberta, Canada (Friesen et al. 1992). When the weed grew in wheat, it produced less than 1 percent of the seed it produced in monoculture because of height differences. There was an 80 to 90 percent decrease in light penetration to the weed beginning four weeks after crop emergence and lasting up to six more weeks.

Velvetleaf, eastern black nightshade, common lambsquarters, and tumble pigweed were grown in a greenhouse with 850 $\mu mol\ m^{-2}s^{-1}$ of ambient radiation and 26 and 13 percent of ambient (Stoller and Myers 1989). As irradiance was reduced, the ratio of support tissues (roots, stems, and petioles) to leaves did not change for common lambsquarters or velvetleaf. The ratio increased for soybeans and decreased for Eastern black nightshade and tumble pigweed indicating a superior adaptation of the latter species for efficient light harvesting in reduced light and offering a partial explanation for the success of the latter weeds in shaded conditions. Further work (Regnier and Stoller 1989) on weeds in soybeans substantiated the role of shade tolerance in weed competition. Common cocklebur had more of its leaf area within the soybean canopy than jimsonweed or velvetleaf. By the end of the growing season, the leaf area of common cocklebur was about evenly distributed within and above the soybean leaf canopy whereas nearly all the leaf area of the other two weeds was above the soybean canopy. Therefore, Regnier and Stoller (1989) concluded that lower branching and shade tolerance made common cocklebur a better competitor than the other two weeds. Height was not an important factor because common cocklebur and soybeans were similar.

The role of light interference (or conversely, shade tolerance) and height was demonstrated in work on competition of nightshades with tomatoes in Ohio (McGiffen et al. 1992). Increasing density of black or eastern black nightshade decreased tomato fruit yield, but eastern black nightshade was more damaging because it grew taller than tomato and reduced photosynthetically active radiation at the top of the tomato canopy. Radiation at the top of the tomato canopy was positively correlated with tomato yield and negatively correlated with the density of eastern black nightshade.

THE ROLE OF CROP GENOTYPE

There are several reports in recent weed science literature on the role of crop cultivar (variety) on competitiveness. Poor emergence of two barley cultivars and the shorter stature of one contributed to their poor competitiveness with wild oat (O'Donovan et al. 2000). No differences in weed suppression were observed among 12 dry bean cultivars that differed in canopy architecture and light interception. Cooler temperatures in one year resulted in a less-dense canopy for the cultivar Mayflower and less redroot pigweed suppression. There was no difference in the ability of the 12 cultivars to compete with common lambsquarters, common purslane, and hairy nightshade (Urwin et al. 1996).

In New York, six medium-season corn hybrids differing in height, early-season vigor, leafiness, leaf angle, leaf width, leaf number, leaf area index, plant dry matter, grain yield, and stover yield differed only in that some hybrids may be more competitive when weed population density is high (Ford and Mt. Pleasant 1994). Begna et al. (2001) said that hybrid selection should be a component of an integrated weed management program because weed biomass production was lower with early-maturing hybrids in narrow rows (38 cm versus 76 cm) and high populations. In Nebraska, among four corn hybrids, those with greater velvetleaf suppressive ability had a higher leaf area index (see Ngouajio et al. 1999) and greater light interception. Lindquist and Mortensen (1998) suggested these characteristics, which may be useful measures of competitiveness, may also be useful in integrated weed management programs.

Jennings and Aquino (1968a, b) noted that tall, leafy, high-tillering tropical indica rice genotypes are more competitive under normal rice-growing conditions than small, erect, sturdy plant types. The tall cultivars become more competitive as fertility level increases and row spacing decreases. However, there was a negative association of yield and competitive ability because dwarf cultivars had a greater yield potential. Fofana and Rauber (2000) evaluated 12 rice cultivars, including the very competitive West African indigenous *O. glaberrima*, and found significant differences in weed biomass 100 days after planting. Weed biomass was negatively correlated with rice root growth at early stages and rice shoot and root growth at later stages. In Greece, the rice cultivar Thaibonnet was consistently less competitive than the cultivar Ariette (Eleftherohorinos et al. 2002). Similar results were reported by Kwon et al. (1991) from Arkansas. The total milled and head rice yield of the semidwarf cultivar, Lemont, was reduced by 10 red rice m^{-2}, but the same density did not affect the short-statured cultivar Newbonnet. The difference was due to height and thus the shading effect of red rice on the semidwarf cultivar. The effects were attributed to the difference in shoot morphology of the two cultivars and to the vigor of red rice competition (Kwon et al. 1991). Ni et al. (2000) proposed that biomass at tillering was the best predictor of a rice cultivar's competitiveness against weeds.

The competitive ability of safflower genotypes was mainly correlated with the crop's biomass at early growth stages but not to its yield potential in the absence of weeds (Paolini et al. 1998). Selecting for higher competitive ability in safflower did not appear to compromise yield potential.

Rose et al. (1984) determined that soybean cultivars differed in competitive ability because they differed in rate of emergence, seedling vigor, quickness of canopy closure, and their ability to inhibit weed growth. Allelopathy also played an undefined role. Their work did not extend to measuring the differences in cultivars. Bussan et al. (1997) found no relationship between weed competitiveness and the canopy area, height, and plant volume 30 to 45 days after planting of 16 soybean genotypes in competition with 12 weed species. They did find that the yield and competitive ranking of the 16 soybean genotypes varied with the competing weed. Grass weeds reduced yield the most and small-seeded broadleaved weeds were the least competitive. The cultivar Pioneer-9592 was more effective in reducing sicklepod shoot height than a second cultivar (Shaw et al. 1997).

Cheat seed production was consistently suppressed by one wheat cultivar in an Oklahoma study (Koscelny et al. 1990). In Nebraska, wheat tiller number, canopy diameter, and height were all negatively correlated with downy brome yield, but changes in these plant characteristics did not always result in an increase in wheat grain yield. Wheat height gave the best correlation with decreases in downy brome yield (Challaiah et al. 1986). The data in chapter 5 establish that winter wild oat presence decreases wheat yield. Wheat's dry matter and grain yield are negatively correlated with winter wild oat's dry matter (Balyan et al. 1991). Wheat's height and dry matter accumulation per unit area during early growth were more reliable predictors of a cultivar's competitive ability than tiller number. The difference in apparent competitiveness of two spring wheat cultivars with wild mustard was attributed to differences in the cultivar's canopy structure (Wright et al. 1999). The competitiveness of nine wheat cultivars against rye was compared at four sites over two years (Roberts et al. 2001). The rye-induced loss in wheat yield of one cultivar was less at 2 of the locations, and another cultivar had reduced loss at 10 of 32 locations. No particular cultivar trait was identified as consistently responsible. Drews et al. (2002) wanted to develop strategies to increase competitiveness of wheat cultivars through shading. Cultivar and row width affected ground cover and light interception and decreased weed growth. With narrow rows (12 cm, 17 cm, or 24 cm) and the same plant density (400 seeds m^{-2}), cultivars with erect leaves suppressed weeds as well as cultivars with planophile leaves. In wider rows, the planophile-leaf cultivars were more competitive because they shaded the ground better (Drews et al. 2002).

One study investigated the competitive ability of velvetleaf biotypes susceptible and resistant to atrazine (Gray et al. 1995). There was no consistent difference in the height, shoot dry biomass, or leaf area of the two biotypes. Resistance to atrazine did not reduce the noncompetitive production or the intraspecific competitive ability of the velvetleaf biotypes.

As reported by Mohler (2001), "the role of crop genotype in weed management has received growing attention over the past 30 years." The reports cited above 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 5.3 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, soybeans, and wheat), there are many reports (e.g., 14 for soybeans). 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. It is known that cultivars of a crop variety simultaneously differ in many characteristics (Mohler 2001). The most competitive cultivars combine the characteristics (height, early emergence, rapid growth, high leaf area index) that make any plant competitive. And these cultivars are able to express competitive characteristics when growing with competitive weeds. The characteristics that lead to competitiveness are well known, but it is not known which of the multiple characteristics that create competitiveness are operative in a specific crop-weed situation or which are most important in competition with specific weeds, under drought stress, in a wet spring, and so on. Thus, even though there are many studies that show that competitive differences exist between cultivars of a crop, that has not led to successful breeding programs to improve or change the competitiveness of a cultivar. In addition, changing competitiveness may also change other traits, such as yield or length of time to harvest, that one does not want to change. The extant data do not convey a message of ignorance but of insufficient knowledge.

Caton et al. (2001) suggest that the usual pattern is to compare crop varieties in competition with weeds in the field. There are two objectives:

(1) to assess differences in competitive ability between crop cultivars, and
(2) to find traits that confer competitiveness.

Caton et al. (2001) evaluate how closely studies in rice and wheat meet these objectives. The first problem they identified was that while differences in competitive ability were identified in nearly all studies, the measures (the criteria) were not consistent. The most common criteria were: crop tolerance to competition, the response of the crop to weeds, or the crop's effect on weeds equals weed suppression. In analyzing the data (25 citations), Caton et al. (2001) found that yield and competitiveness are not always negatively correlated, and crop tolerance and weed suppression responses are inseparable. When traits were identified as being associated with competitiveness, they were most often "state variables like crop drymass," which reflect competitive success rather than the possibility of success, such as "root:shoot ratio or height extension rate" (Caton et al. 2001). Forcella (1987) said that the crop traits that confer competitive ability have not been well documented and doing so will require comparing isogenic lines of crop cultivars. He suggested determining the value of leaf area expansion rate as a competitive trait as a first step. In monoculture, shoot dry matter production of two tall fescue genotypes was equal. However, when they competed with velvetleaf, the genotype with the highest leaf area expansion (LAE) rate produced 38 to 73 percent more dry matter than the genotyope with a low LAE rate. Velvetleaf growth was suppressed 14 to 24 percent when grown with the high LAE genotype. Forcella (1987) concluded that a high LAE rate confers weed tolerance and competitive ability to tall fescue. Johnson et al. (1998) showed that a rice cultivar (IG-10, an *Oryza glaberrima*) (also see Fofana and Rauber 2000) in competition with weeds accumulated more biomass, produced more tillers, had a higher leaf area index, a higher specific leaf area, and, during its early growth, partitioned more of its biomass to leaves than two *O. sativa* cultivars. These studies illustrate what Caton et al. (2001) advocated—develop a hypothesis and subject it to appropriate field testing.

The conclusion is that weed science needs better and standardized methods that go beyond observations of success and experiments designed to test hypotheses about identifiable traits. For example, the magnitude of yield advantage for particular cultivars differed between years and between locations, and there was little correlation between competitiveness at different sites in a year or in different years at a location (Cousens and Mokhtari 1998). Such variation made it difficult to know what the results of an experiment meant and to give advice to farmers. Cousens and Mokhtari (1998) advocated more attention be given to agronomic ways of making a given cultivar more competitive, which is a different way of saying that hypotheses need to be developed and tested.

FERTILITY

Fertility manipulation to manage weeds is virtually unknown even though it is widely accepted that fertility affects weeds. Walters (1991) suggests that most weeds can be controlled by manipulation of soil nutrients. His claim, supported by abundant anecdotal evidence but not by research, should not be dismissed as idle speculation. For example, high phosphorus fertility enhanced the competitive ability of lettuce with smooth pigweed. Smooth pigweed was not responsive to phosphorus but luxurious consumption by the weed reduced the nutrient's availability to lettuce. Common purslane also responded to phosphorus and increased its competitive ability in lettuce (Santos et al. 1998). Competition for phosphorus appeared to be the main mechanism of competition between common purslane and lettuce grown in low P soil. The interaction between lettuce and spiny amaranth was not due to competition for phosphorus, although banding phosphorus reduced the effect of spiny amaranth on lettuce (Shrefler et al. 1994). Over two years, time of nitrogen fertilization did not affect weed-free sugarbeet biomass, yield, or quality, but early nitrogen fertilization resulted in higher crop biomass reduction in the presence of wild mustard and lower crop biomass in the presence of common lambsquarters (Paolini et al. 1999).

Downy brome was more competitive with the rangeland weed medusahead with high soil levels of nitrogen and phosphorus. When nutrients were deficient, there was competitive equality between the species (Dakheel et al. 1993). When nitrogen was added to soil in the greenhouse at 20 mg wk^{-1}, there was no effect on pea, a strong competitor, but the size of mayweed chamomile, a weak competitor with pea, more than doubled (Ogg et al. 1994).

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 the crop a more vigorous competitor with weeds. But when weed density is high, added nutrients favor weed over crop growth. At high nitrogen application rates (above 103 kg N ha^{-1}), nitrogen uptake by weeds was higher than that by rice. Nitrogen application at levels below those required by rice reduced its competitive ability with goosegrass, itchgrass, and spiny amaranth but did not affect interference with purple nutsedge (Ampong-Nyarko and DeDatta 1993).

DiTomaso (1995) summarized much of the literature on crop-weed fertility interactions. Late watergrass had a significantly stronger response to nitrogen than rice (Gibson et al. 1999), and root competition was primary. Nitrogen is always important to plant growth, but it may or may not be a limiting factor in weed-crop relationships. It was not the main limiting factor in competition between winter wheat and Italian ryegrass (Hashem et al. 2000). 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 percent of normal (21 mm versus 62 mm), nitrogen fertilization reduced wheat yield 12 to 20 percent.

Total nitrogen uptake by wheat was three times greater than by Italian ryegrass, but the weed was twice as efficient as wheat in producing biomass per unit of N taken up. Nitrogen was a limiting factor in interactions between wild mustard, common lambsquarters, littleseed canarygrass, and spring wheat (Iqbal and Wright 1997). Low nitrogen (20 kg ha^{-1}) decreased net photosynthetic rate, percent leaf N, plant dry weight, and N uptake of all three weeds and of wheat. The effects of low N on net photosynthetic rate and dry weight were greater on weeds than on wheat. With high N (120 kg ha^{-1}), wild mustard was more competitive than wheat, littleseed canarygrass was less competitive, and common lambsquarters was more competitive, regardless of N level (Iqbal and Wright 1997). Similarly, in winter wheat and spring barley, increased nitrogen did not enhance weed germination, tended to decrease total weed biomass, and had a differential effect on the biomass of particular weed species (Jørnsgård et al. 1996). A long-term trend toward lower nitrogen application will favor the weed species (common lambsquarters, common chickweed, speedwells, deadnettles, and burning nettle) in this study and change the composition of the weed flora.

In Greece, Dhima and Eleftherohorinos (2001) showed that nitrogen fertility (150 kg N ha^{-1}) increased sterile oat's dry weight and competitiveness with wheat, barley, and triticale. Split application, 50 kg ha^{-1} before planting and 100 kg ha^{-1} in early March, increased sterile oat's dry weight. Barley significantly reduced sterile oat's interference.

Ammonium nitrate (0 g, 10 g, 25 g, 50 g, or 100 g per pot) or ammonium sulphate (0 g, 20 g, 40 g, 60 g, or 80 g per pot) reduced branched broomrape infestation in tobacco and tomato at the higher levels in a greenhouse study (Abu-Irmaileh 1981). However, the dry weight of shoots and roots of both crops and tomato fruit yield declined when more than 50 g of ammonium nitrate or more than 60 g of ammonium sulphate were applied to a pot. In the field, branched broomrape infestation in tomato decreased and shoot dry weight and yield increased when ammonium sulphate was applied in two doses of the 20 g per pot greenhouse rate, ten days apart.

An important, long-term illustration of the potential of fertility manipulation as an instrument for changing 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 1865 by Sir John Lawes, the son of the manor and founder of Rothamstead as an agricultural research center. In most ways, the experiment continues in its original form.

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 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 above. If potassium is absent, dandelions are absent because they flourish only with potassium and a pH above 5.6.

Competition for nutrients is not independent of competition for light and water. The complexity and opportunity of fertility manipulation is well illustrated in work by Liebman (1989). He demonstrated improved weed control because of differing nitrogen-use efficiency of crops and weeds. 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 percent 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 (Liebman and Robichaux 1990).

The preceding presentation and discussion of seven of the eight points mentioned at the beginning of this chapter has shown that each of the seven factors affects weed populations and plays a role in weed management. The studies lead to Mohler's (2001) conclusions. His first conclusion was that "the presence of weeds changes the cultural conditions that result in maximum crop yield." It is doubtful that anyone will disagree. Second, Mohler (2001) said, "crop yield in the presence of weeds increases with the differences in the height, biomass, and leaf area of the crop relative to that of the weeds at the onset of competition." Again, agreement will be universal. After each conclusion, Mohler (2001) presents an informed description of the complexity of the weed-crop relationship that leads to the primary conclusion of his work: "To the extent the crop is in a better position to shade the weeds and deplete the water and nutrients in the rhizosphere of the weeds at the onset of competition, the less it will suffer yield loss from competition with weeds." All of Mohler's (2001) conclusions are correct and affirmed by his review and by this review. The problem remaining is to know how to apply the knowledge about plant arrangement, monoculture and polyculture, tillage, rotation, shade, genotype, and fertility to a crop in a field, in a year. The general principles (plant early, use a vigorous, competitive genotype, take advantage of early shading, fertilize to give the crop an advantage, use narrow crop rows in a polyculture, rotate crops, etc.) are well known and understood. We know—to use Mohler's (2001) term—how to enhance the competitive ability of crops. How to apply that knowledge, in full consideration of highly variable agricultural environments and the farmer's economic realities, to each cropped field remains a problem. The task is development of weed management systems that incorporate the well-known principles across regions, years, and environments. The survey by Norris (1997) suggests that population dynamics and competition are the areas that weed scientists most want to study because they think they will have the greatest effect on development of desirable weed management systems.

THE IMPORTANCE OF WEED BIOLOGY AND ECOLOGY

This chapter began with the question posed by Norris (1992, 1999): Have ecological and biological studies improved weed management strategies? Has the abundant information on how various factors affect weeds and crops improved weed management? Norris (1999) concluded that in spite of the abundant literature on the effects of weed density and duration on competition, improved computer technology, and decision-aid models, the information on weed crop competition has had almost no effect on weed management practice. As claimed above, the task is to apply what is known. However, Norris (1999) also strongly argued for greater emphasis on weed biology and research to understand the mechanisms of competition. What we know is how to control, but we do not know enough about the organisms to be controlled or their ecological relationships. The evidence in this review is that Norris's (1992, 1999) plea has not resulted in a significant change in the research weed scientists do, but perhaps that judgment is too quick. Science and scientists do not (perhaps cannot) change direction quickly. If we are to reduce the chemical load on the environment, maintain crop yields, and develop improved weed management systems, a much better understanding of weed ecology (Forcella et al. 1993) and weed biology (morphology, phenology, seed dormancy and germination, growth physiology, reproductive biology, seedbank dynamics, longevity of vegetative propagules, etc.) (Bhowmik 1997) will be required. Moreover, the requirement is not only for the knowledge, it is for its integration into new weed management systems. The requirement for more knowledge of weed biology and ecology has been common in many of the papers reviewed here.

However, it is clear from the literature reviewed that as Radosevich and Roush (1990) point out, weed scientists have not been overly concerned with understanding ecological processes especially because empirical results are reasonably definitive. Reliance on empirical research has allowed, and agriculture has benefited from, what Radosevich and Roush (1990) call "a narrow perspective on competition in agriculture." One wonders if the frequent plea for more knowledge of weed biology and ecology will change what weed scientists do, or if it will be subsumed under the strong desire (need) to solve weed problems now.

Forcella (1997) argues that the situation is not as bleak as presented above. There is abundant weed biology information about, but it is unknown or unused (or both) because weed biologists who develop and publish the data leave it to others, who may not even know they exist, to decide what they mean and how to apply them. Those who study weed biology have failed to demonstrate its application to weed control and agricultural profit, but in Forcella's (1997) view, there are some useful (but unused) data available. For example, a great deal is known about weed seedbank dynamics (Buhler et al. 1997), but what is known has not been well integrated with weed management strategies.

It was a conscious choice to omit the many papers on weed biology and ecology from this review. The primary reason is that the task as defined was large enough and inclusion of the literature on weed biology and ecology would have made it impossible.

NOTE

1. In economics, an externality is a cost that is not reflected in price, or a cost or benefit for which no market mechanism is available. In accounting, it is a cost that decision makers do not have to bear.

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Weed-Crop Competition: A Review, Second Edition
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9

Methods Used to Study Weed-Crop Competition

People are, or at least think they are, too busy. Some people take great delight in telling you how overworked and underpaid they are. Work and sometimes life itself, in the view of many, are "just crazy," everything is going too fast, and there is not enough time to do all that one must do and even less time to do what one wants to do.

For scientists, being too busy often leads to avoiding careful study of the literature. When the busy scientist does read a journal, the order usually is: title, authors, and the abstract or at least some of the abstract. If reading goes beyond the abstract, methods are often skipped and one goes right to results—the important part. However, scientists all learned that in science it is important to understand the relationship between the experimental methods and the results and conclusions. Results and conclusions are, of course, important, but the experimental method is one of the things that determines the conclusion's validity. How the work was done determines if the results are true and if the conclusions are justified. Competition studies are no exception to this generalization.

Harper (1961) said that agronomists are concerned with the description of factors that determine crop yield and an analysis of causes that relate effects to environmental changes. The literature reviewed for the first edition (Zimdahl 1980) of this book and the literature reviewed for this edition support the proposition that the majority of weed-crop competition studies have been descriptive but not very analytical (see chapter 6). That is, the results of weed-crop competition have been described many times, but researchers have not been equally attentive to analyzing why observed effects occur in specific crop-weed interactions or how and why environmental changes influence results. It is not uncommon to read in the weed science literature that differences between years were due to environmental differences. But that frequently is as far as the analysis goes.

However, one should not assume that weed science studies have all been for naught or that the failure to consider mechanism is tantamount to the studies' being worthless. Radosevich and Roush (1990) note that agricultural research "often differs from that performed in natural systems in objectives, method of study, and, therefore, the interpretation of experimental results." Agricultural studies, particularly those in weed science, are done to show how weed presence, density, duration, and so on influence crop growth or yield. It is clear from the literature reviewed that as Radosevich and Roush (1990) point out, "agricultural scientists are not necessarily concerned with understanding ecological processes especially when empirical results of their studies are reasonably definitive" (Snaydon 1980; Radosevich and Holt 1984). Reliance on empirical research has allowed, and agriculture has benefited from, what Radosevich and Roush (1990) call "a narrow perspective on competition in agriculture."

Dawson (1971) enumerated three things that most weed-crop competition studies have attempted to determine. Each is affected by the environment: (1) the time of weed emergence that causes yield reductions, (2) the time during the crop growing season when weeds are most injurious, and (3) the time during the crop growing season when weeds are relatively harmless.

Most studies have been designed to determine the extent of yield reduction by specific weeds at known density. The objective is to determine the relationship between weed density and crop yield (Pantone and Baker 1991b).

Predicting how much crop yield will be reduced from a certain density of specific weeds or a complex of weeds is nearly always close to impossible. The relationship between weed density and crop yield will vary with year, location, and environment. Aldrich (1987) said this was true for at least five reasons, which describe what is often unknown.

1. The stage of crop and weed growth when there is a shift in crop yield from a weed density-dependent to a weed density-independent relationship
2. The effect of weed density on the essential growth factor(s) competed for
3. Differences in competitiveness among weed species
4. The differential effect of environmental conditions on competitiveness of the weed(s) and crop
5. The effect of time of emergence on competition

To gain predictability and reduce variability, methods of study must be developed that consider, at a minimum, the five factors mentioned by Aldrich (1987) as determinants of the effect of weeds on crop yield.

A complication of weed-crop competition studies is the well-known fact that weed emergence times vary. If most weeds emerge within a short time, plants increase in size with time, but population size remains constant. For plants with long emergence periods (e.g., wild oats), more plants appear as the season progresses while the early-emerged plants continue to increase in size. Thus, in the latter situation, at any time there will be plants of different ages with differing competitive abilities.

Peters (1972) proposed a method that allowed consideration of growth only of weeds emerging within predetermined times. This technique, best suited for weeds with long emergence periods, would determine which fraction of a competing population proved most competitive. Peters's (1972) main point, emphasized above, is that the method employed in competition studies unavoidably creates artifacts that should be considered when results are interpreted. He indicated some of the problems associated with precise quantitative interpretation of results based on imperfect methods. In spite of the disadvantages of imperfect techniques, they have been and apparently will continue to be used for competition studies. The procedures work, in the sense that they answer the important question of what the effect of weeds on crop yield is. If the disadvantages of the method are known and artifacts recognized or controlled, the results are useful, albeit with limitations.

In the first edition of this book, most studies of weed-crop competition reviewed used the imperfect but common and adequate, for some objectives, additive design (Zimdahl 1980). The studies were designed to determine the effect of the density of a particular weed, or an assembly of weedy species, on the yield of a crop. The weed density was created at varying levels or the density of a natural stand was determined. In these studies, crop density was what was planted. It was usually not controlled but was usually known and was constant. These studies produced an abundance of data for several crops in support of the central hypothesis of weed science—weeds reduce crop yield. In retrospect, such studies have been useful to determine the effects of different weeds on the same or different crops, to determine the level of crop yield loss weeds cause, and to justify and gain financial and political support for weed science. A primary benefit of these studies was their contribution to development of weed management practices. The studies were not designed to be analytical or to explain mechanisms of competition. They were designed to ask and answer the important question of what the effect of weeds is on crop yield. The additive design has been the most common method employed by weed scientists in weed-crop competition studies (Radosevich 1987; Rejmànek et al. 1989). Stoller et al. (1987) reported that it was the most common method to establish economic and damage thresholds. These studies were not designed to ask and their design did not permit one to ask, why the observed effects occurred.

I propose that the traditional methods of limited scope began to change with publication of Harper's (1977) large and important work*, Population Biology of Plants*. Harper (1977) illustrated experimental models to study the growth of mixed populations. These were all known before Harper's book was published, but his book is the one cited most often in the weed science literature, and he is properly credited with changing how weed scientists think about and study weed-crop competition. Harper (1977) said that much of the current theory of plant ecology was built on the premise that competition is one of the main factors that determines community composition, species survival, and productivity of plants. Competition could be interspecific (with members of the same species) or intraspecific (with other species).

The additive design used in so many weed-crop competition studies is the first one mentioned by

Harper (1977, p. 249). As pointed out above, in the past, its use was common. However, Harper (1977, p. 249) correctly notes that "because the proportional composition *and* the density of the mixture are both changed, their effects are completely confounded." The design has been criticized for the same reason by others (deWit 1960; Rejmànek et al. 1989). Because the proportion among species changes simultaneously with total density (Radosevich 1987), interpretation of the effects of proportion or of density is almost impossible, but it is, nevertheless, attempted. Firbank and Watkinson (1990) note that the perceived deficiency is "only a problem if the model used to describe the effects of competition uses these two variables; if the two equivalent variables of the density of each species are used, then the problem disappears."

In spite of its faults, the additive design seems to be exactly what the weed scientist needs when the objective is to study the effect of an invading species (a weed) on a crop, precisely because it mimics what one finds in the field (Cousens 1991). With understanding of the objectives and limitations of additive experiments for study of weed-crop competition, Cousens (1991) argues that they are well suited to most agronomic objectives. This is because, as Firbank and Watkinson (1990) showed, the principal limitation of confounding proportion and density is simply irrelevant to the objectives of the experiments that use additive design. Weed scientists have been a pragmatic group, and if the objective is to determine the economic threshold for control, what the cost of weeds may be in terms of yield loss, what weed or weeds are most competitive in a particular crop, or what the effect of a management practice will be, additive designs are just fine. Criticism of additive designs is valid but is not compelling, especially when the critic neglects to consider the experiment's objective(s).

The method that avoids confounding of density and proportion is the substitutive experiment exemplified by the replacement series (deWit 1960). Cousens (1991) notes, without further citation, that the design is usually attributed to deWit, as Harper (1977) did, but it was first used by W. H. van Dobben. Substitutive designs and replacement series models allow direct comparison of two plant species (Pantone and Baker 1991b). They involve planting two species in varying proportions while maintaining overall density constant (Harper 1977, p. 250). The total density of the two species is constant but the proportion between the two species changes (Begon and Mortimer 1981; deWit 1960; Pantone and Baker 1991b). A monoculture of each species at the proper density should also be included. The competitiveness of one species compared to another is measured by the relative crowding coefficient (RCC) (deWit 1960). The RCC can measure the competitive ability of a weed relative to a crop or the reverse (Pantone and Baker 1991b). The RCC and thus the actual competitiveness of a weed or a crop may change with different densities (Connolly 1986, 1987; Firbank and Watkinson 1985; Pantone and Baker 1991b), and, therefore, the results of studies that do not use the same total density may differ. Connolly (1986) argued that "the fundamental problem with the replacement series method stems from ignoring the two-dimensional nature of mixtures, the density of both species being independently variable." Connolly (1986) showed that the relative crowding coefficients (one for each species), the product of the RCCs, the aggressivity index, the competitive ratio, and the relative total yield all are "widely unstable" and dependent on experimental design. Much of the problem can be attributed to the fact that the replacement series is a one-dimensional representation of what is at least a two-dimensional phenomenon. Connolly (1986, 1988) proposed that additive and replacement designs share some inadequacies and both may be biased in favor of the larger species in a mixture. He proposed using response models that relate the yield per individual to the density of the species in the mixture. Connolly (1988) suggested use of response models to do three things:

1. Measure the effect of weed species on yield per individual and yield per unit area for the crop and weed.
2. Develop methods of weed control based on interference between crop and weeds and the population biology of the weed species.
3. Establish a cost-benefit analysis of weed control programs.

Response models also have the advantage that the effect of relative emergence time and crop and weed management practices can be included.

All who have considered experimental designs agree that the purpose of the substitutive design is to determine the yield of mixtures (the effect of competition) by comparing that yield to the yield of a monoculture. Contrary to what one might expect, based on the primary criticism of the additive design, replacement series are not used to determine the effect of proportion. The objective is usually to determine which of two species is the best competitor or to study how species interact in competition (Cousens 1991). Joliffe et al. (1984) agree with all that has been said above about replacement series experiments: their primary use has been to study interactions between species in a mixture. However, Joliffe et al. (1984) point out that comparisons with expected yields are of limited value, since they do not assess the contributions of intraspecific and interspecific interference to the determination of mixture yields. They use the analogy of competitive enzyme inhibition to illustrate that expected yields of any mixture represent one state (created by the environment, time of planting and emergence, plant density, and all other factors affecting plant growth) in a continuum of possible yields that could result as the intensity of competition changes in a mixture. Joliffe et al. (1984) propose that the difference between a monoculture yield and the yield of a mixed culture is the combined result of interspecific interference and any (inevitably) altered intraspecific interference that may occur in the mixture. Joliffe et al. (1984) proposed using the relative monoculture response and the relative mixture response as measures of plant interference in monocultures and mixtures. They argue that this approach will separate the effects of intraspecific and interspecific interference and can be used for all species, proportions, and densities. This contrasts with deWit's (1960) relative crowding coefficient, which determines the effects of interference over several generations or growing periods. In their work, the total yield projected from monoculture yield:density relationships often greatly exceeded mixture yields. They concluded that there may be adequate scope for developing mixtures that give greater yields than monocultures, which, in their view, may have particular relevance to pastures and agricultural intercropping systems.

Regardless of the design chosen, the experimenter must decide what densities to use. Weed scientists tend to choose densities that are likely to be found in the field and exclude low densities because they have no practical interest or application. Density must be chosen carefully to achieve the experiment's objective, but no design allows extrapolation outside the bounds of the densities included in the study.

The results of replacement series experiments can, in theory, take one of four basic forms (Harper 1977, p. 255). These graphs show which species is the dominant competitor and the degree of niche differentiation (deWit 1960; Harper 1977; Pantone and Baker 1991b) (fig. 9.1). Interested readers are referred to Harper (1977, pp. 255–257) or Radosevich (1987) for a complete discussion and explanation of these graphs.

Radosevich (1987) discusses diallel experiments (a combination of individuals of two or more species into all possible pairs to examine the complexity of interactions) and Nelder experiments, which have been used to study interference among individuals of a single species. Neighborhood experiments

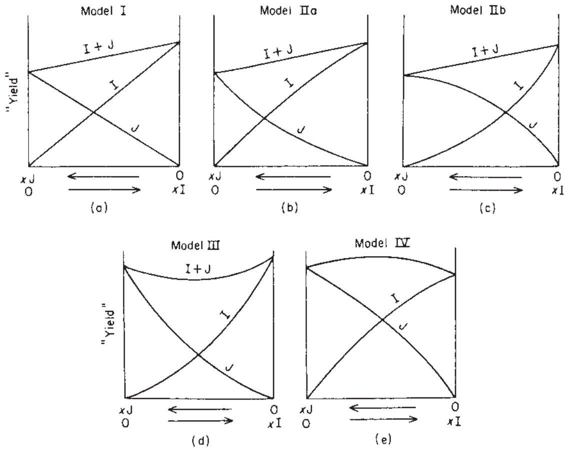

Fig. 9.1. A variety of results from "replacement series" experiments.

(Radosevich 1987) measure the performance of a target plant (an individual) as a function of "the number, biomass, cover, aggregation, or distance of its neighbors." Neighborhood experiments are studies of the effect of proximity.

Firbank and Watkinson (1990) advocate the addition series as the best way to describe the complete range of outcomes of competition between two species. The results of an addition series experiment form a response surface whereas the additive and replacement series designs "merely take slices through that surface." The addition series is replication of a replacement series design at several densities. The costs of such work are high and the results may not be worth the cost given the objectives of the weed scientist.

A two-species model was used for describing the results of a greenhouse study of the competition between barley or peas and common lambsquarters or white mustard. The model was not always able to describe the relationship between a species yield and its density or the density of a competing weed. When the model failed, it always did so for the least-competitive species. The authors (Vleeshouwers et al. 1989) concluded that the model to quantify competition and describe niche differentiation was too general because competition between the species was not independent of species density.

Despite criticism of the approaches, partial additive and replacement series designs remain the most popular and most frequently employed by weed scientists. Population biologists and some weed scientists have questioned their utility (Connolly 1987; Pantone and Baker 1991b; Rejmànek et al. 1989). The reciprocal yield (inverse linear) has been proposed to overcome the limitations of other methods of analysis of weed-crop competition experiments (Pantone and Baker 1991b). This model allows evaluation of the influence of the weed on the crop and the crop on the weed, as well as partitioning of net competitive effects into intra- and interspecific components (Rejmànek et al. 1989). The model uses multiple linear regression where the densities of the competing species are the independent variable and the reciprocals of the average yield per plant are dependent variables (Ogawa 1961; Pantone et al. 1989; Pantone and Baker 1991b; Rejmànek et al. 1989; Roush et al. 1989; Spitters 1983). Roush et al. (1989) showed this was the most effective analytical technique for the competitive interactions of wheat and Italian ryegrass, and Pantone and Baker (1991a) showed it was the most effective technique for interference between rice and red rice. Reciprocal yield analysis is the simplest and most sensitive technique to analyze the joint influences of density and proportion. It is also the most quantitative analysis of the influence of density on species interaction (Roush et al. 1989).

Cousens (1991) challenged the most common methods used to analyze data from weed-crop competition studies. He discussed response surface designs, which have not been used extensively by weed scientists; a full explanation is beyond the scope of this book. The response surface model was developed by Firbank and Watkinson (1985). It uses biologically meaningful parameters and is a further development of the reciprocal yield model. It differs from the reciprocal yield model because it does not assume that total stand yield is constant at higher plant density (Pantone and Baker 1991b). In principle, Pantone and Baker (1991b) suggest that the response surface model should permit the yield of crop and weed to be estimated at any crop and weed density. If this is possible, then optimum crop density (the density to maximize competition) and the weed threshold (the weed density at which yield begins to decline) should be predictable.

One hopes that weed scientists and plant ecologists will come closer together in the future. The broad aim of weed science research on weed-crop competition has been to provide quantitative data to illustrate how much particular weeds at specific densities reduce the yield of particular crops in one or over several growing seasons. The broad aim of the plant ecologist studying population or community ecology has been to understand the way different kinds of interactions affect the dynamics of and structure of a particular system or systems (Silander and Pacala 1990). The objectives of the ecological approach are illustrated well in the chapters by Silander and Pacala (1990) and Firbank and Watkinson (1990) in the book edited by Grace and Tilman (1990).

One suspects weed scientists will continue to do experiments to demonstrate crop losses due to weeds. These will be done because it will continue to be important to know what happens and to have data to convert what happens to monetary terms. They will also be done because the experimental methods and data analysis are fairly easy and straightforward. Combining the objectives will enable weed scientists to continue to move toward understanding of why things happen as they do and will enable plant ecologists to apply theory to practical problems.

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Weed-Crop Competition: A Review, Second Edition
Robert L. Zimdahl

10
Models and Modeling

The first edition of this book in 1980 established that many experiments had been done to determine the weed density, often of specific weed species, that caused a yield loss in several different crops. Only a few experiments used a simple mathematical model to describe the data. This review confirms that weed scientists have continued to do experiments to describe the relationship between weed density and crop yield. The primary purpose of this chapter is to provide a nonmathematical review of the studies that have been done since 1980 to develop, test, and validate mathematical models of weed-crop competition. This chapter is neither an analysis of all models nor an evaluation of their worth; it is a review of what has been done.

The chapter includes sections on conceptual, simulation or analytical, empirical, mechanistic, or ecophysiological models, decision-aid models, and thresholds. The sections on decision-aid models and thresholds are included because these seem to be the logical purpose of the work on yield loss models. That is, the intent often seems to be to determine if competition can be modeled well enough to help growers make decisions about weed management using decision-aid models that are based on yield loss models.

The techniques of mathematical modeling and simulation are fairly recent additions to weed science research (Cousens and Mortimer 1995; Kropff and van Laar 1993). Cousens et al. (1987) thought the slow development of modeling in weed science was due to several factors: the early lack of scientists familiar with the methods, limited demand for investigation of models and simulation studies, and a high demand for pragmatic, results-oriented, herbicide evaluation that provided solutions to immediate weed management problems.

Weed-crop competition was the first process of weed biology that weed scientists modeled, and research continues because 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 (Swinton and King 1994). Lundkvist (1997) categorized models of weed competition as research models (to develop an understanding of processes) or practical models (decision-aid or weed management tools) in a nonmathematical review of available models. These can be described as:

1. Research models that 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 that 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. However, several weed management models are available and are beginning to be used to help choose weed management methods.

Wiles (personal communication) claims 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).

CONCEPTUAL MODELS

The first models developed and adopted by weed scientists were conceptual research models. A classic conceptual model, taught in many basic weed science classes, is the replacement series that regards competition as an interaction between two species and assesses the degree of competitiveness (Harper 1977 following deWit 1960). Early attempts to model plant interactions used a diallel arrangement for analyzing competition and employed the essential features of the deWit (1960) density replacement series. Thomas (1970) used a mathematical approach to fit parameters to deWit's (1960) model to test the hypothesis that species compete for space, or what space contains.

The foundation of these models is the law of final constant yield and the hypothesis that yield in a mixture of two species can be determined from the yield of each species when grown separately (Radosevich and Holt 1984). The total density of mixtures must be constant with the two species grown in various proportions ranging from 0 to 1. Hill (1973) developed a theoretical model to identify conditions under which a 50:50 mixture could be expected to exceed the average of component monocultures or surpass the better monoculture. Hill (1974) also proposed a model for competing pairs of individuals in binary mixtures. Firbank and Watkinson (1985) developed a model to describe competition in a two-species mixture of any combination of frequency and total density. They reported that their model is more succinct and easier to interpret than the replacement series analysis of deWit (1960).

Space capture has been an important conceptual model for intraspecific competition of weeds and the resulting hierarchy of weed sizes in a population. The basis of the model is that the sequence of seedling emergence affects the capture of space and the resources in the space. The space each seedling preempts is proportional to its weight (Radosevich and Holt 1984). Late-emerging seedlings do not grow because other seedlings have already captured the resources in the space. Fischer and Miles (1973) developed a similar conceptual model to analyze the role of spatial pattern in competition between weeds and crop plants. The basic assumption regarding competition of a weed or crop plant is that the zone of exploitation of environmental resources is an expanding circle in a horizontal plane centered on the point of emergence. The zone expands until it intersects with the zone of other plants. It is also assumed that final dry matter yield of each plant is directly proportional to the area of its zone. With this analysis, they determined that arranging crop plants in a square produced maximum competitiveness.

Based on deWit and Baeumer (1967) and deWit et al. (1966), Hill and Shimamoto (1973) classified competition between herbage plants into three groups:

1. *Compensatory.* Gains and losses incurred by two components counterbalance leading to constant net productivity.
2. *Positive complete complementation*. The advantage gained by the stronger component is such that the mixture's performance matches that of the better monoculture.
3. *Positive over-complementation*. Yield of the better monoculture is surpassed by the mixture.

Dew (1972a) used data from studies by Bell and Nalewaja (1968a, b) and Bowden and Friesen (1967) to develop a mathematical index of competition for wild oats. Dew's index ranked competitive ability; barley had the greatest competitive ability followed by wheat and rapeseed (1972a, b; Dew and Keys 1976). Using weed density data and expected weed-free yield of the crop, Dew verified mathematically that competition for each of the crop-weed combinations was unique and independent of the estimated weed-free yield and cultural practices. Where potential weed-free conditions generated high yields, extensive losses occurred for a given density of wild oats. Regression methods predicted yield losses associated with varying densities. For Dew's (1972a) theory, the ratio of the regression coefficient over the intercept (b/a) equaled the competitive index.

The first edition of this book (Zimdahl 1980) found only a few studies of weed-crop competition that employed mathematical analysis. Weed competition studies had been conducted in a wide range of crops by agronomists, horticulturists, and weed scientists, but mathematical models or mathematical description were not regularly used. Clearly, this is no longer true.

SIMULATION (ANALYTICAL) MODELS

Kropff et al. (1992b) and Withrow[1] proposed reasons for the development of simulation models and justified the quest for better models. When a model successfully depicts reality there is improved predictive capability. However, even when a model fails, it provides insight about the areas where scientific understanding and inaccurate interpretations exist. That is, a failed model tells us what is not known and serves as a guide to further research. Successful simulation models, in Withrow's view, guide weed science research in three ways:

1. Improved ability to know the long-term effects (e.g., population shifts, reduced control efficacy) of weed management methods, that is, herbicide use, crop rotations, tillage methods, time of planting, and so on
2. More precise use of available weed management techniques. (This is often called precision agriculture but can also be seen as a quest for more certain efficacy of the methods employed.)
3. Prior, accurate evaluation of the efficacy of a wide range of available methods that could be used in a weed management plan

Simulation is used when a system is too complex to be handled by simple straightforward analysis of its components. The dictionary reveals that a simulation is a pretense; it is feigning. Although all know it is representational and may be wrong, it allows, as Withrow noted, testing of hypotheses and their improvement so future models will reflect reality more accurately.

Model terminology is not precise. Mechanistic models can also be simulation or analytical. Wiles (personal communication) argues that most mechanistic models are also simulations of the complex, incompletely understood processes involved in weed-crop competition.

Weed scientists also have developed what are called ecophysiological models to understand competitive capture of individual resources and the effect of factors that influence the ability of weeds to compete. These models attempt to simulate the mechanisms of plant growth and capture of individual resources (light, water, fertility—primarily nitrogen) and, consequently, how weed-crop competition may respond to weather, ecophysiological attributes of weeds and crops, and some management practices. Experiments have been conducted with these models to understand better the nature of competition and to develop strategies to minimize crop yield loss from weed competition (Weaver 1996).

Ecophysiological simulation models have been developed for several crops: alfalfa, corn, rice, soybeans, sugarbeet, and wheat (see Weaver 1996). Models include ALMANAC, INTERCOM, SOYWEED, an unnamed model for rice developed by Graf et al. (1990a, b), and DSRICE1 (Caton et al. 1999). ALMANAC is a process-oriented simulator of interplant competition. It is a dynamic model of intermediate complexity Debaeke et al. (1997) developed for use with weeds in wheat. It simulates plant growth, water balance, light, and soil nitrogen dynamics on a daily basis for two or more competing species. The ALMANAC model was judged capable of distinguishing between environmental conditions that encourage large yield losses and those that allow corn to outcompete velvetleaf (McDonald and Riha 1999a, b). SOYWEED (Wilkerson et al. 1990) is a dynamic soybean-weed competition model based on SOYGRO (Wilkerson et al. 1983), a crop growth model. SOYWEED has been validated for competition of cocklebur with soybeans (Wilkerson et al. 1990). INTERCOM is perhaps the most comprehensive and well-documented model of crop-weed competition (Kropff and Spitters 1992; Kropff and van Laar 1993; Weaver 1996). It is based on work by Spitters and Aerts (1983) and Spitters (1989) and on earlier monocultural simulation models of Spitters et al. (1989). The model describes light interception and distribution among competing species and competition for water (Weaver 1996). The model has been parameterized for at least five crops and several weeds in different locations and environments (Weaver 1996). Lindquist (2001) and Lindquist et al. (1996, 1999) developed INTERCOM for corn. Caton et al. (1999) developed DSRICE1 to analyze integrated weed management strategies for interspecific competition for light in direct-seeded rice in competition with two weeds.

Because simulation models are complex and require detailed information about ecophysiological traits of weeds, most of which is not available, most models are presently restricted to simulation of competition with a single weed species. Exceptions are the INTERCOM-based model of Graf et al. (1990a, b) that simulates competition with six groups of weed species that are similar in leaf shape, growth form, height, and phenology, and Caton et al.'s (1999) model for rice-weed competition. However, simulations give researchers insight into the relationship between crop and weed density, relative time of emergence, and several physiological and morphological plant traits and their interaction with environmental factors and resource levels (Weaver

1996). Simulation models enable conduct of experiments under a range of simulated weather conditions to generate predictions of yield effects and hypotheses for testing (Kiniry et al. 1992, Weaver et al. 1992, Weaver 1996). They are useful for analysis of experimental data to provide insight into the competitive processes. As noted above, Kropff et al. (1992b) point out that simulations are most helpful when they fail to simulate what actually happens because they reveal what data and research are still required (Weaver et al. 1992).

MECHANISTIC OR EMPIRICAL MODELS

The development, mathematical derivation, and theoretical support for the models discussed here are described well in Kropff and Van Laar (1993), and readers are referred to their book and its references for more detail. These models are usually based on the Law of Constant Final Yield in which plant yield is described as a nonlinear function of plant density (Ogawa and Shinozaki 1953). Kropff and van Laar (1993) point out that deWit (1960) developed the first systematic, mathematical approach to competitive phenomena. It was not until the 1980s that an approach was developed to describe competition over a range of population densities (Kropff and van Laar 1993; Suehiro and Ogawa 1980; Spitters 1983; Wright 1981). Early models were based on a nonlinear hyperbolic relationship between crop yield and density (Kropff and van Laar 1993).

Kira et al. (1953) and Ogawa and Shinozaki (1953) in Japan were among the first to examine the dynamics of within-season population growth (Silander and Pacala 1990). The early studies and subsequent work especially by Firbank and Watkinson (1985, 1986, 1987) have led to general understanding of intraspecific competition within a growing season; the realm of immediate interest to weed science. The models have been empirical and not always supported by appropriate theory of plant population and community dynamics (Silander and Pacala 1990). Spitters (1983) argued that the accepted fact that plants compete for growth factors (light, water, and nutrients) mandated certain kinds of models. Spitters and Aerts (1983) introduced a deterministic, ecophysiological model (WEEDCROP) to simulate the competition between a crop and weeds for water and light. Because biomass production is approximately linear with the supply of the resource that limits growth, distribution of the limiting resource is reflected in plant biomass. Spitters's early work provided much of the theoretical foundation for later studies, and in 1983 Spitters introduced a simple model to estimate the degree of intraspecific, interspecific competition and niche differentiation from biomass data. His work (1983) assumed the following points.

- The density response of a species biomass could be described by the rectangular hyperbola.
- Interspecific competition can be incorporated in the hyperbolic equation similarly to intraspecific competition.
- The additivity of the effects implies that competition effects, measured by regression coefficients, are independent of plant number. That is to say that competition effects are independent of mutual frequencies of the species in a population and of total population density.
- The model does not account for the effects of spatial arrangement of plants on competitive relations, that is, fields are homogenous.

It is generally believed that mechanistic models predict crop yield loss well, but the paucity of extensive and difficult-to-obtain weed and crop ecophysiological parameters limits their use for practical management (Wiles et al. 1992; Wilkerson et al. 2002). Deen et al. (2003) evaluated four crop:weed competition models for predicting crop yield loss from rigid ryegrass in wheat. They concluded that relatively simple algorithms were capable of accounting for the majority of the effects of competition. Increasing model complexity seems to be inevitable, but, in this case, it did not improve the model's accuracy.

Mechanistic models are particularly useful because weed-crop interactions can be quantified (Caton et al. 2001), and it may be possible to quantify the long-term behavior of specific weed-crop combinations (McDonald and Riha 1999b). Kropff and Van Laar (1993) make the debatable claim that mechanistic models have been used primarily to predict yield losses. This may be true, but it may also be true (Wiles, personal communication) that a primary use has been to evaluate whether a model is accurate enough to be used for real management decisions and to determine how to make a model more accurate, that is, more reflective of the real world of weed-crop competition. A few of the several examples of studies designed to develop and evaluate models include Caton et al. (1999), Graf et al. (1990b), Kiniry et al. (1992), Kropff, et al. (1984), Lindquist (2001), McDonald and Riha (1999a, b), Weaver et al. (1992), and Wilkerson et al. (1990).

Other evaluations include Dunan et al. (1999), who built a relatively uncomplicated mechanistic model for weed management decision making in onion based on competition for light. McDonald and Riha (1999b) tried to explain year-to-year variability by distinguishing between environmental conditions that facilitated large yield losses and those that permitted corn to dominate velvetleaf. They (McDonald and Riha 1999a) also asked if climate-based economic thresholds might be more accurate. Weaver et al. (1992) evaluated the influence of weed density, weed height, and weather on the timing of the critical period of weed interference. Caton et al. (2001) in rice and Cavero et al. (2000) for jimsonweed in corn evaluated the effect of weed's morphological traits on competitive ability for light. The complexity of modeling and the risks involved in poor weed management decisions are illustrated in WEEDING, a process-level program that permits the user to make weed management decisions for a simulated soybean crop during a simulated season and to calculate the effect(s) of those decisions (Wiles et al. 1991). A few models include competition for light (see Weaver 1996).

The basis of most common models used to describe the effect of weeds on crop yield is the rectangular hyperbola (Cousens et al. 1984; Cousens 1985a; Kropff and van Laar 1993). Most commonly it is a manipulation of the equation below in one of two different ways. The first explores the reciprocal per-plant crop yield (Spitters et al. 1989).

$$N_c / Y_{cm} = b_o + b_c N_c$$

where, Y_{cm} = the yield of the crop in monoculture in g cm^{-2}, N_c = the crop density in number m^{-2}, b_o = the intercept, and b_c = the slope.

In contrast, the same equation can be expressed as

$$Y_{cm} = \frac{1}{b_c} \frac{N_c}{\frac{b_o}{b_c} + N_c}$$

This defines $1/b_c$ = the maximum yield per unit area with high crop density and b_o/b_c = the crop density at which yield is one-half the maximum.

Cousens et al. (1984) proposed a simple hyperbolic model of weed-crop competition and compared it to five other models with consequent firm rejection of the sigmoidal hypothesis because it represented a threshold density below which yield loss is not observed. Cousens (1985b) compared models of yield predicted from weed and crop density and the best was a simple function of crop and weed density. Cousens (1985b) proposed a single species model and recommended its use to predict crop yield (which can be measured) or yield loss (which is estimated from crop yield comparisons) as a function of weed density. This method allows separate determination of the effects of inter- and intraspecific competition and gives a simple, accurate description of data from experiments in which only plant density varies. Cousens (1985b), after review of 18 different mathematical equations to describe crop yield loss as a function of weed density, concluded that of the two-parameter models, the simple hyperbolic crop yield loss–weed density relationship was the best descriptor. This was confirmed in a later paper (Cousens et al. 1987a) that examined the relationship between population density and established the importance of the relative time of seedling emergence of wild oat and yield of barley and wheat. Cousens (1985b) and Cousens et al. (1987a) introduced a parameter that does not permit maximum yield loss to exceed 100 percent.

$$Y = Y_{wf} [1 - Id / 100 (1 + Id / A)]$$

where Y = yield, Id/100 (1 + Id/A) = percentage yield lost due to weed competition, I = percentage yield loss per unit weed density as $d \rightarrow 0$, d = weed density, and A = total yield loss per unit weed density as $d \rightarrow \infty$.

It is assumed in derivation of the equation that weeds are distributed randomly and that all other factors, including crop density, are held constant (Cousens 1985b). Models also tend to assume that all weeds emerge at the same time, which everyone knows is not true. Cousens (1985b) demonstrated the superiority of the modified hyperbolic model via statistical analysis of extant data. The model has two regions of virtual linearity. The first is that at low density the yield loss curve is constrained to pass through the origin and the effects in this portion of the curve are additive. The second linear region occurs at high density where the curve is constrained to asymptotically approach a finite value such that yield loss cannot exceed 100 percent. Thus, as weed density increases and the area of influence of each weed or of weeds and crops overlaps, effects are no longer additive. Therefore, the rate of yield loss per unit of weed density decreases. Each weed unit has a greater effect at low than at high densities. The parameters I and A represent the competitiveness of the weed species (I) and the crop (A).

Subsequently, most studies have used the hyperbolic model described by Spitters (1983) and Spitters et al. (1989) and advocated by Cousens (1985b). Spitters et al. (1989) found that competitive relations between maize and barnyardgrass and common lambsquarters "were described accurately by a model based on a hyperbolic relation between yield and plant density." Those who have used the hyperbolic model have combined mechanistic and empirical elements to describe weed and crop growth in response to environmental variation. The model is presently based on incomplete understanding of the underlying plant physiological processes and their interaction with the physical processes of the environment. Thus, for now, mechanistic models are compelled to become empirical at some level. That apparent disadvantage is required for research to progress toward improved models.

Those who have subsequently accepted the hyperbolic model cover several crops and weeds and include the following partial list:

Askew and Wilcut for ladysthumb (2002a), pale smartweed (2002b), and Pennsylvania smartweed (2002c)
Askew and Wilcut (2001) for tropic croton interference in cotton.
Cardina et al. (1995) for velvetleaf in corn
Kim et al. (2002) used a combined model that incorporated the standard herbicide dose-response curve into the rectangular hyperbola model to describe the effects of plant density of rape, as a model weed, in wheat and the effects of a herbicide on wheat yield and weed seed production.
Kwon et al. (1998) developed PALWEED:WHEAT II to replace PALWEED:WHEAT, which used a linear function, for annual weeds in winter wheat.
Lindquist et al. (1999) for corn and foxtail species
Lindquist (2001) developed INTERCOM for predicting corn-velvetleaf interference in north-central United States.
Martin et al. (1987) used a parabolic wheat yield-density component and a hyperbolic yield loss component. The parabolic component best described the effect of limiting soil water on the wheat yield-density relationship. The model showed that wheat and wild oat were nearly equally competitive.
Moyer and Schaalje (1993) for quackgrass in alfalfa
Norris (1992) for barnyardgrass in sugarbeets
O'Donovan et al. (1989) for canola and volunteer wheat. (In this study, as is true but perhaps not noted for many studies, the variability of early-season growing conditions between years affected the response of canola to weed density and weed emergence time.)
O'Donovan (1991) for quackgrass in canola
Pantone and Baker (1991) for rice
Wilkerson et al. (1990) for soybean weed growth and competition
Wilson et al. (1995) for field violet and field poppy in winter wheat
Wilson and Westra (1991) for wild proso millet in corn

Lindquist et al. (1996) showed that over a range of sites, the use of common coefficient estimates in models was not acceptable. The hyperbolic model was biologically more acceptable primarily because it included an upper limit to yield loss (it could not exceed 100 percent), but its application in bioeconomic weed management models across a geographic region was dependent on the stability of the coefficients (that were best obtained from empirical data) within a region.

There are disadvantages to mechanistic equations. Their acceptance in diverse regions depends on their adaptability to different locations, the precision of required inputs (the parameters), and the generality of a model for diverse weed(s) and crop combinations (Kiniry et al. 1992). In other words, the models will be most useful when they are appropriately parameterized and tested with local field data generated under local conditions (McDonald and Riha 1999a). The essence of the problem of universality is that not enough is known about weed biology and ecology to properly parameterize the equations. When adequate biological and ecological knowledge are available, the number of parameters will not be a major hurdle. It will then be relatively easy to validate models, whereas now there has been only limited validation (Deen et al. 2003). The desired validation depends on rigorous performance assessment in the field and more knowledge of weed biology (Deen et al. 2003).

Empirical models that one hopes will be used to assist weed management decision making must be biologically feasible and the ultimate evaluation of the model should be based on the quality of the decisions it leads to (Jasieniuk et al. 2001; Wilkerson et al. 2002). That is, the model's evaluation should not stop with determination of the accuracy with which the model predicts weed-crop competition. Part of accuracy is the assurance that parameter estimates conform to biological reality (Swinton et al. 1994). Biological nonsense must be eliminated by thorough consultation with the literature or with experts (Swinton et al. 1994).

The rectangular hyperbola has not always been the best model as illustrated by the work of Webster et al. (2000) with hemp dogbane in soybeans. They showed that the rectangular hyperbola appeared to describe the relationship between soybean yield loss and hemp dogbane density but the model appeared to be dominated by its initial linear phase. This, they concluded, may indicate a lack of high levels of intraspecific competition among hemp dogbane shoots. Their (Webster et al. 2000) work showed a strong linear relation between soybean yield and hemp dogbane shoot density. They questioned the biological basis for the use of the rectangular hyperbolic model for creeping perennial weeds.

Vitta and Satorre (1999) used a model of crop-weed competition based on parameters from the logistic biomass growth of a crop and weeds in monoculture. Their model adequately described the competition between species when the relative total yield was close to one. Final crop biomass was affected most by the relative growth of the species. However, there were many parameters for the weed and the crop, and some may be difficult to calibrate.

Jolliffe (1988) suggested a two-stage approach to describe plant's response to interference in mixtures. The first stage is a nonlinear model that defines the monoculture yield-density response. The second stage extends the model to mixtures from monoculture by defining the deviations from the monoculture caused by interspecific interference.

Time of Emergence

Spitters's (e.g., 1983, 1989) and Cousens's (e.g., 1985b) work led many model developers to use the hyperbola or a form of the hyperbola modified to incorporate the time between crop and weed emergence to predict crop yield loss (Cousens et al. 1987b; Wilkerson et al. 2002). It is the accepted standard. The importance of incorporating the relative time of emergence of crop and weed(s) was affirmed by the work of O'Donovan et al. (1985) for wild oats in wheat and barley and by Hume (1989) for weed communities in wheat that were dominated by green foxtail. Hume (1989) postulated that environmental variables (precipitation and growing degree days) could be regarded as proxies for varying time of emergence. Lotz et al. (1990) evaluated the effect of time of emergence and weed height of broadleaf weeds on winter wheat and said better knowledge of the timing of weed emergence was required so that emergence over time could be simulated. Such estimates ought to include the negative effect of herbicides or other weed control methods on weed and crop growth and development. O'Donovan (1985) and Dieleman et al. (1995) demonstrated that when the relative time of emergence was taken into account, it led to a better model fit. Cousens et al. (1987a) had suggested that the more biologically plausible models would include competitiveness as a function of time. Chikoye and Swanton (1995), in their evaluation of three empirical models, tried to use thermal time in lieu of calendar time, but the difference did not matter much in their study.

Dieleman et al. (1995) tested four empirical models of the interference of redroot pigweed and Powell amaranth in soybeans and determined that the model that used weed density and time of emergence (for confirmation of the importance of time, see O'Donovan et al. 1985; Hume 1989) gave the best description of soybean yield loss in comparison to relative leaf area models.

Leaf Area Models

Kropff and Spitters (1991), building on the early work of Spitters and Aerts (1983), Spitters (1983), and Spitters et al. (1989) provided an alternative approach with the relative leaf area model derived from the hyperbolic crop yield loss–weed density model. The model is based on simulation studies that showed a close relationship between yield loss and relative leaf area of the weeds determined shortly after crop emergence. Kropff and Spitters (1992) proposed an ecophysiological simulation model based on distribution of light and water and their utilization to create biomass. Absorbed radiation was calculated in relation to plant height on the basis of leaf area of the competing species and its distribution over the canopy. In a subsequent paper, Kropff et al. (1992a) used competition between sugarbeet and common lambsquarters to test the hypothetical utility of leaf area and validate the model. They concluded that morphological characteristics such as the early relative growth rate of leaf area, specific leaf area, and height largely determine a species' competitive strength. The contribution of differences in water supply were negligible, whereas the number of days between crop and weed emergence (0 to 31) was the main factor responsible for differences in yield loss between experiments (also see Kropff 1988). Because temperature during the time between crop and weed emergence was an important factor in determining competitive relationships, Kropff et al. (1992b) concluded time should be expressed as degree days rather than as days. They found that an empirical model describing the relationship between relative leaf area of weeds shortly after crop emergence for three different crop-weed combinations and yield loss had several advantages for management decisions over a mechanistic model.

Dieleman et al. (1995) found the competitiveness parameter varied when leaf area was measured, but it could be estimated from a single measurement, leading to a simpler model. Smith and Murdoch (1997) compared ground cover with leaf area and weed density as a predictor of yield loss from two weeds in wheat. Similar to Dieleman et al. (1995), they found a simple model of weed cover, irrespective of species, was best. However, the damage parameter changed with time and the best time to measure it was not determined.

Kropff et al. (1994) proposed an ecophysiological model based on leaf area for rice ecosystems based on the assumption that competitive effects were a function of time, which could be modeled from leaf area. A two-parameter model was introduced (Kropff et al. 1995) for prediction of yield loss from weed competition in rice and sugarbeet. The second parameter (maximum yield loss) was required to make the equations biologically reasonable. One-parameter models (e.g., Kropff and Spitters 1991) based on the relative leaf area of weeds shortly after crop emergence assume a maximum yield loss of 100 percent with high weed density. Several authors have noted that this is not what happens and is biologically unrealistic. Some weeds have a shorter life cycle than the crop, emerge later than the crop, or never grow above the crop canopy and do not reduce yield 100 percent. The two-parameter model includes a relative damage coefficient (q) and a parameter that describes maximum yield loss (m). The model described the data on the effect of different weed densities and the effect of different emergence times of rice, sugarbeet, and weeds "fairly well." Use of the second parameter (q) improved model performance significantly in five of nine data sets.

Kropff et al. (1995) claim that the advantage of the relative leaf area approach is that it includes consideration of the dynamics of competition as the process is affected by the "relative starting position" of the competing species. At the same time, this leads to the disadvantage of the dependence of the q parameter on the date of observation. Competition described by the relative leaf area model is more accurate than that of a density-based model but improved mechanistic understanding of the process of competition (a plant's eye view) is required to further improve such empirical approaches (Kropff et al. 1995). Use of leaf area or other models in practical weed management "will be increased when inter specific variation in weed life history, morphology and development can be accounted for by aggregating weeds to groups of problem weeds." This is a goal to be achieved.

The data presented on soybeans in chapter 5 illustrate that many weeds that compete effectively in soybeans do so by light interference. Wiles and Wilkerson (1991) developed LTCOMP, which modeled the vertical canopy structure and light interception by common cocklebur and soybeans and incorporated LTCOMP into SOYWEED (Wilkerson et al. 1991) to improve simulation of competition for light with changing cultural and environmental conditions. Daily photosynthetic rates per unit of ground area were calculated according to the interception of direct light by the weed and the crop. For each kind of plant, light interception depended on the amount and arrangement of leaf area. Preliminary testing was satisfactory but also indicated the lack of required data on the canopy structure of soybeans and the competing broadleaf weeds.

Kropff and Lotz (1992) affirmed that empirical models that describe the relationship between weed density and yield loss have been used for decades. Ecophysiological models that simulate growth and production of species in mixtures are more recent developments. These models are based on physiological processes in plants and the response of these processes to environmental changes. Kropff and Lotz (1992) proposed that ecophysiological models would be used (but were not in 1992) "to link field-level observations of weed effects to underlying physiological processes." The primary problem with the advantageous leaf area models that attempt to relate relative leaf cover of weeds shortly after crop emergence to final yield loss is "the lack of data for parameterization" of the model as suggested by Wiles and Wilkerson (1991). Kropff and Lotz

(1992) strongly advocated the value of systems approaches that encourage weed ecologists to pose challenging questions for weed technologists (those whose task it is to manage weeds in crops). They suggest research needs to be done to separate the effects of weeds in a given year and crop from their effects in future crops. These effects were separated into tactical (the current year) and strategic (future crops) weed management. Such work necessitates better knowledge of seedbank dynamics and management methods to prevent weed-seed production. Kropff and Lotz (1992) advocated development of new chemical control techniques and biological knowledge to develop technology to interfere with a plant's normal development. They suggested the novel and still untried idea (presumably because of feasibility and cost) that flowering and subsequent seed formation could be inhibited in short-day weedy plants when days become shorter by interrupting the night with bright light flashes. Lotz et al. (1996), in attempting to integrate simple yield loss models into threshold weed management systems, concluded that a model based on the relative leaf area of the weed described data better than the more-common model based on weed density. However, they also concluded that the predictive ability of the leaf area model had to be improved before it could achieve wide application. Improvement meant that more information was needed about the effect of abiotic factors on plant development and morphology and more careful definition of the time during which predictions could be made with an acceptable margin of error was required. Murphy et al. (2002) agreed and proposed that density–yield loss models that are parameterized from a particular site or in particular seasons too often rely on fixed coefficients, which were criticized by Lindquist et al. (1996). This empirical approach fails to incorporate environmental effects such as rainfall (Murphy et al. 2002), temperature (Kropff and Spitters 1992), time (Kropff et al. 1995), and abiotic factors (Lotz et al. 1996), and that failure has major biological and economic implications. Murphy et al. (2002) suggest that the value (accuracy and reliability) of yield loss predictions "will be vastly improved by making their parameter values a function of seasonal factors such as rainfall."

Vitta and Fernandez-Quintanilla (1996) found that leaf area models were at least as accurate as weed density models and visual estimates were satisfactory. The generality of leaf area models was, however, restricted by changes in the relative damage coefficient over years and with the time of year the observation was made. Ghersa and Martinez-Ghersa (1991) found, in Argentina, that to predict yield loss due to johnsongrass in corn, one should use relative leaf frequency because it determined biomass. Total biomass was constant and independent of the crop-weed ratio, and biomass and, therefore leaf frequency, are related to grain yield.

Van Acker et al. (1997) did experiments with linseed and field bean to test the usefulness of the leaf area model of Kropff and Spitters (1992). Generally, the model provided a better estimate of yield loss due to interference from barley than from common chickweed. This was because of the variability in crop yield due to common chickweed's plasticity and the minor crop response to its interference. It is also important to note their conclusion that for the two-weed species, yield loss prediction models that were parameterized using data from single-weed species experiments generally resulted in different and less-reliable estimates of yield loss than models parameterized using data from two-weed species experiments. Knezevic et al. (1995) evaluated three empirical models for crop weed competition between corn and redroot pigweed. In models based on weed density, the percentage yield loss at low weed densities was relatively stable across similar redroot pigweed emergence dates over years and locations. The estimated maximum yield loss was more variable between locations, and they suggested this was due to environmental variation among sites. Two-parameter models based on relative leaf area that used the maximum yield loss caused by weeds and the relative damage coefficient gave a better fit than a single parameter version that used only the relative damage coefficient. For both leaf area models, the value of the relative damage coefficient varied between years and locations. They (Knezevic et al. 1995) concluded that while leaf area models were often best, their practical application awaits a quick, accurate method to estimate leaf area. This need may have been satisfied by Ngouajio et al. (1999), who developed and validated an image analysis system for measuring leaf cover, defined as the vertical projection of plant canopy on the ground. Over two years, the relative leaf area of varying densities of common lambsquarters, barnyardgrass, and the two weeds together with corn was an adequate predictor of corn yield loss. The r^2 varied from 0.61 to 0.92. The precision of predictions was not influenced by whether the leaf area sampling was done at corn's four- or eight-leaf growth stage. Neither weed relative leaf area nor relative leaf cover of weeds was superior to the other to predict corn yield loss. Subsequently, Ngouajio et al. (2001) examined methods of measuring leaf area for yield loss prediction, as Lotz et al. (1994) had. Ngouajio et al. (2001) found a strong linear relationship between Italian ryegrass density and direct leaf area. Both direct leaf area measurement and canopy estimates described broccoli yield as well as or better than Italian ryegrass density. Lotz et al. (1994) noted that destructive measurements to determine leaf area are laborious. They found that weeds with different morphology showed the same linear relationship between relative leaf area measured destructively and cover, assessed by a frame (a 2.5 by 0.5 m rectangle divided into 6,000 12.5 mm square subsections) until three to four weeks after crop emergence. Differences in weed morphology at later growth stages resulted in different relationships. Visual estimates were only “roughly” reliable. Leaf reflectance was satisfactory in wheat infested with white mustard but did not work well in sugarbeet.

A study by Chikoye and Swanton (1995) reached a similar conclusion. They studied the performance of three empirical models to describe the yield loss in white bean from common ragweed competition. One model (Cousens et al. 1987) was based on weed density and relative emergence time. The other two models described yield loss as a function of weed leaf area relative to the crop. The first model best described the data sets, and using thermal time did not improve model performance over calendar time. The predicted maximum yield loss and the parameter for relative time of weed emergence varied across locations and years while the yield loss at low weed density was relatively consistent across locations and years. The two-parameter leaf area model gave a better fit to the data than the one-parameter model. The relative damage coefficient varied with time when leaf area was measured at different locations and in different years. Chikoye and Swanton (1995) concluded as Knezevic et al. (1995) had that models based on leaf area measurement have important advantages over those based on density or time of emergence because the leaf area can be measured only once, whereas density and emergence must be measured frequently. Both agree that the ability to measure leaf area rapidly and accurately may limit the practical application of leaf area models.

In other work from the same group, Chikoye et al. (1996) proposed in a simulation of competition between dry bean and common ragweed that competition for photosynthetically active radiation was the primary factor in the competitive process. Shading of the bean canopy by common ragweed accounted for 50 to 70 percent of the crop yield loss when the weed emerged with the crop.

Multispecies Competition

Swinton et al. (1994) described a multispecies modification of Cousens’s (1985b) rectangular hyperbola model to estimate a nonlinear competitive index for weed-crop interference. The competitive coefficients Swinton et al.(1994) derived were stable over years but not over locations in a year. Swinton et al. (1994) discussed the disadvantages of multispecies methods. They suggested estimation of species competition from data based on the rectangular hyperbola and included useful discussion of statistical mechanics. Jolliffe (1988) advocated defining deviations from monocultural interference when competition for resources was an important aspect of interference and in cases of multispecies interference, which is typical of most crop-weed interference relationships. Only a few models are capable of (designed to) modeling multiweed species interference (see Graf et al. 1990b; Ball and Shaffer 1993).

Van Acker et al. (1998) proposed a graphical method of analysis of two-weed species interference based on the model for study of the efficacy of herbicide mixtures. They were able to classify the interference of two-weed species as synergistic or antagonistic with regard to the effect on crop yield.

Wilson and Wright (1990) estimated competition for single species but suggested that it may be possible to estimate competitiveness for species with similar growth patterns rather than attempting to estimate a parameter for each weed. Early weeds that senesced in midsummer were less competitive than those with a growth pattern similar to the crop. Wilson and Wright (1990) reasoned that a competitive index (CI) derived from yield density relationships and expressed as the percent yield loss per weed m^{-2} is more likely to reflect the competitive ability of a species than an index obtained from the plant’s weight in the growing crop. The thought is similar to Berti and Zanin (1994) who proposed a density equivalent method to estimate a weed’s competitiveness. It is worth noting that the effect of multiple species in a crop is important, but it is also true that most crops are dominated by one or two weed species.

THE EXTRAPOLATION DOMAIN OF MODELS

A major purpose of the work by Kropff and van Laar (1993) stands in sharp contrast to most of the work reviewed here. Most studies describe the outcome of competition in a place, in an environment, and at a time but usually do not attempt to provide an explanation of the process, which is what Kropff and van Laar (1993) attempt. They point out that "the extrapolation domain of these descriptive approaches is often limited, because they only account for the effect of a small number of factors that influence the competition process." Such studies answer the question of what happens: how much crop yield is reduced by the presence of a certain density of weed X for a certain time. They do not, because they cannot, explain the mechanism of competition. The results of these studies may be widely applicable but without explanation of underlying mechanism, the likelihood of universal application is reduced and, more likely, impossible. Kropff et al. (1992b) state that although empirical models may best describe competitive relationships, mechanistic models are more suited for research because they lead to the necessary understanding of the mechanism and process of competition. In fact, as Kropff et al. (1992b) note, mechanistic models require a great deal of often unavailable, physiological information; they may be most useful when they fail because they indicate what research is needed.

Mortimer et al. (1989) pointed out that "baselines for studies of population dynamics of weeds have usually concentrated on analysis of a single species in defined habitats," albeit manipulated habitats. This has been justified for two reasons: (1) "the combined milieu of crop husbandry practices tends to lead to a definable set of habitat characteristics that is repeatable through time (cropping seasons)," and (2) "weed-crop associations are often simple species mixtures" of usually no more than about six species (Cousens and Mortimer 1995).

Mortimer et al. (1989) proposed a group of models that "explicitly evaluate the dynamics of populations over generations of growth." The models could then possess a generality that enables "them to be easily fitted to any species that displays discrete generations serially contracting to a propagule population within its life cycle." The models were also suggested to be robust because they subsumed "the effects of individual regulatory processes that may occur within generations of population growth." However, based on this review of the literature, the models proposed have not been used nor has the advice been heeded.

Variability of parameters between years and among sites is readily acknowledged but has not been studied carefully. Parameters of empirical equations may vary independently among sites and years, and one must conclude that there will be similar and undesired variability when the models are used to make weed management decisions. Most authors attribute the variation to environmental effects, but these are not usually well defined. Different variability among parameters was found in density-based models by Chikoye and Swanton (1995), Jasieniuk et al. (1999), and Lindquist et al. (1996, 1999). Variability was also found in leaf area models (Chikoye and Swanton 1995; Lotz et al. 1996; Ngouajio et al. 1999; and Smith and Murdock 1997). Variability has not always been a problem (see Dieleman et al. 1995). Some have attempted to deal with environmental variability. Chikoye and Swanton (1995) used thermal as opposed to calendar time, but it did not improve the data's fit. Hume (1989) dealt with the problem by suggesting that environmental variation is a proxy for differential times of emergence, which is a proper focus to explain variation in results. Swinton et al. (1994) present a statistical method for detecting and dealing with variability.

Studies that describe the outcome of competition do not help us understand if Grime (1979) was right when he proposed that competition was "the tendency of neighbouring plants to utilize the same quantum of light, ion of nutrient, or molecule of water, or volume of space." Nor do they help us determine if Tilman (1982) was more correct when he proposed that competition was "the utilization of shared resources in short supply by two or more species." Competitive ability is then determined by a plant's minimum resource requirement, usually designated R*. Descriptive studies also cannot tell us if Grace (1990) was correct when he proposed that Grime (1979) and Tilman (1982) offered complementary, not conflicting, definitions. Grace (1990) suggested that if a habitat is fertile, a species' competitive ability is determined by its ability to capture the required resources. But if a habitat has low fertility, competitive ability and the results of competition are determined by a species' ability to tolerate low resource availability.

DECISION-AID MODELS

Models to predict yield loss from weed competition are evaluated by how well the equation fits the data;

their statistical accuracy is important. In addition to providing information on basic ecophysiological questions and identifying research needs, these models, one hopes, will lead to the use of yield loss functions in decision-aid models for weed management. These kinds of models are, or should be, evaluated by a different criterion—the quality of decisions they lead to. However, given the frequent and presently expected large errors in weed estimates from scouting, the accuracy of the yield loss function, while important, may be the smaller source of error encountered in use of decision-aid models.

The development of models that incorporate scouting or economic thresholds and purport to be decision aids for weed management occurred later than development of mathematical models. Wilkerson et al. (2002) propose that their development awaited introduction of the economic threshold concept and the wide availability of computers. The economic threshold (Stern et al. 1959) was introduced to and rapidly accepted by entomologists (Stern 1973). Adoption of an economic threshold approach to weed management has been much slower but not irrationally so. The reasons for slow development include (1) the multispecies nature of weed populations in most crops, (2) the fact that both crop yield loss and management system efficacy are crop and weed-species dependent, (3) weeds interfere with each other as well as with the crop (Wilkerson et al. 2002), and (4) the aforementioned large errors in estimates of weed density and extent (area covered) based on human observations (scouting) of fields.

It seems intuitively obvious that threshold-based weed management strategies will be more cost effective than prophylactic control applied to whole fields in anticipation of a problem that may not occur (Munier-Jolain et al. 2002). However, long-term herbicide use frequency was insensitive to threshold values between 0.01 and 100 plants m^{-2}. The highest long-term profitability was obtained by Munier-Jolain et al. (2002) for the lowest threshold tested and profitability decreased rapidly when the threshold was above 4 to 6 plants m^{-2} for blackgrass or 10 to 20 plants m^{-2} for annual bluegrass. Munier-Jolain et al. (2002) decided that the "exact threshold value is of little importance for the long-term reliance of the system" on a herbicide, as long as the threshold is low. If a weed has low competitive ability (which, for most weeds, remains undefined), high thresholds may be useful in some cropping systems to reduce herbicide use frequency for environmental reasons (Munier-Jolain et al. 2002). Lutman et al. (1994) studied the response of spring-planted peas, barley, broad bean, and oilseed rape to competition from cultivated oat as a mimic of wild oat. Competition from oats was greatest in the year with highest rainfall. Oats had the least effect on barley and oilseed rape (yield loss per oat plant m^{-2} was 0 to 2.3 percent) and the greatest effect on peas and beans (yield loss per oat plant m^{-2} was 0.34 to 7.2 percent). Given these findings, Lutman et al. (1994) proposed that for oats and peas the high variability raised questions about the validity of predicting yield responses from estimated weed numbers. Others (e.g., Kropff and Spitters 1991) have also questioned basing thresholds on weed number or density. Lutman et al.(1994) advocate using relative crop and weed leaf area, which may be more accurate.

Better computer technology has greatly improved the speed of development but not the speed of adoption of decision-aid models. It is not clear that any of the decision-aid models that have been developed are used extensively by farmers. The first decision-aid model was published for soybeans in 1983 and used linear and log-log equations but found that nonlinear relationships were best (Marra and Carlson 1983). Mortensen and Coble (1991) reported that the number of efficacy- and population-based decision-aid models increased dramatically over eight years. The models aided decisions ranging from optimal weed control (independent of profitability) to prediction of weed populations and guidance for selection of the most profitable treatments. Subsequently, Wilkerson et al. (2002) reviewed the several decision models that have been developed and made available to weed scientists, growers, and crop consultants. Each model, independent of its mathematical basis, requires at least three kinds of information, no one of which is easy to obtain (Wilkerson et al. 2002): (1) a description of the weed problem in the field, (2) a determination of expected crop yield loss caused by weed interference before and after weed control has been done, and (3) an estimate of potential economic returns for each control option based on cost of control, control efficacy, expected yield after control, and crop value.

In addition, successful models (which, one assumes, means models that are used) must also satisfy three criteria (Wilkerson et al. 2002): (1) be able to make reasonable biological predictions, (2) assist users to make better decisions than would be made without the model (these are decisions that are more profitable, more environmentally sound, or both); and (3) be convenient and easy to use.

A qualification for success is consideration of the patchiness of weeds in a field, which most models do not consider. Wiles et al. (1992) point out that modeling weed distribution in a field is difficult and is made more difficult because of the poor correlations between distribution of a weed in a field and variation of its distribution between fields. Weed patches are well known to farmers and modelers, but postemergence (usually herbicide) management decisions are almost always made on the assumption of a uniform population (see chapter 7 in Cousens and Mortimer 1995 for a complete discussion of the influence of weed patchiness). That is, the weed management technique is applied uniformly across the field even though all know the weeds are not uniformly distributed. As a result, yield loss from weed-crop competition may be overestimated by models and may lead to choosing the wrong management technique (Wiles et al. 1992).

The most common approach to quantify field weed populations for decision-aid models has been the use of weed density per unit ground area or weed density per unit length of row (Wilkerson et al. 2002). Garrett (1995) advocated sampling strips of defined length along a crop row as opposed to quadrats of defined size randomly placed in a field. Strip sampling, Garrett proposed, should more accurately identify different sizes of weed clusters. The report of Wilkerson et al. (2002) on methods used to describe multispecies interference is summarized below. Keisling et al. (1984) calculated yield loss by subtracting the percent loss caused by the most competitive weed and repeating the procedure for other weeds. Coble (1986) defined a crop- and weed-specific competitive index that ranked competitiveness from 0 to 10. Total competition (the total competitive load—TCL) was determined by multiplying the density of each species by its competitive index and using that to calculate percent yield loss. As reported by Wilkerson et al. (2002), this approach was used early and is still used in decision-aid models—HERB (Wilkerson et al. 1991; Coble and Mortensen 1992), NebHERB (Mortensen et al. 1993), GWM (Wiles et al. 1996), HADSSJ (Sturgill et al. 2001), WeedSOFTJ (Krishnan et al. 2001; Mortensen et al. 1999)—and for management of wild oats in irrigated barley (Dunan et al. 1994).

The ALMANAC model (Debaeke et al. 1997) was judged capable of distinguishing between environmental conditions that encourage large yield losses and those that allow corn to out-compete velvetleaf (McDonald and Riha 1999a, b).

PALWEED:WHEAT II (Kwon et al. 1998) is a bioeconomic decision-aid model used to determine profit maximizing postemergence herbicides for winter wheat in Washington. It consistently recommends rates of selected postemergence herbicides that comply with agronomic and economic theory about what ought to be done. The model uses exponential functions as opposed to linear ones, separate indices for broadleaved and annual grass weeds, and, consistent with most models, a hyperbolic function to relate weed density to yield. The model also considers the influence of crop rotation.

Others have used similar methods to account for competitive differences between weeds. Black and Dyson (1993) ranked competitiveness of annual weeds on a scale from 0 to 1 and calculated weed units that are functionally similar to the TCL. they found an approximately linear relationship between weed density after spraying and grain yield. Berti and Zanin (1994) predicted yield loss from the density equivalent for each species, which is the density of a reference species that would cause the same yield loss caused by the observed weed at its density. Aarts and Visser (1985) assigned standard weed units based on the maximum number of plants m^{-2} that could be tolerated. Standard weed units of the species were summed and control was justified if the sum was greater than "total tolerable standard weed units."

Decision-aid models, while not perfect, can aid weed management by predicting loss due to weed interference, determining if control (usually with a herbicide) will be cost effective, comparing control options, and aiding the selection of herbicides (Wilkerson et al. 2002). They are important concepts and may become important weed management tools (Oliver 1988). If decision-aid models were used, they could reduce application of prophylactic herbicides and thereby reduce environmental pollution and possible crop injury (Wilkerson et al. 2002). A major problem with decision-aid models, which is fully recognized by the developers, is that they oversimplify the complex weed-crop environment and therefore do not and perhaps never will be able to reflect reality. But they steadily come closer.

Spatial Distribution

An important aspect of the model's simplicity is the failure to consider the fact that weeds are aggregated in fields: they exist in patches (Cardina et al. 1997; Wiles et al. 1992). Consequently, predicting yield loss from an average density over a field underestimates competition between weeds and overestimates crop yield loss (Auld and Tisdell 1988). Auld and Tisdell (1988) modeled the general case of the effect of spatial distribution of weeds on competition with crops and concluded that field studies to establish the magnitude of the effect were required. To date, there is little information available on the effects of weed spatial distribution, the pattern of distribution, or field location on weed population dynamics (Cardina et al. 1997). It is commonly assumed, for control purposes, that weeds are uniformly distributed in a field but it is almost never correct. Weed distribution is neither regular nor uniform and mean density is rarely useful to estimate yield loss or describe a field's population (Cardina et al. 1997). Wiles et al. (1992) reported that while yield loss was more accurately estimated if the effects of variable spatial distribution were included in a decision-aid model, the quality of the decision making was not improved by the addition.

Models have been developed to predict the effect of both weed density and spatial distribution on crop yield loss. These all describe greater yield loss when weeds are aggregated. One approach is to replace the mean population density estimate with mean crowding, an index that represents the spatial distribution of a weed population as a function of the mean and variance of weed counts in quadrats throughout a field (Hughes 1989). In addition to overestimation of yield loss at higher density, overestimation increases with the variance of weed counts modeled. Based on the model, Hughes (1989) concluded that it was important to characterize the effect of spatial distribution of weeds on competition with a crop when establishing economic thresholds for patchy weeds.

A second model captures the effect of weed spatial distribution on competitiveness with parameters of frequency distribution of weed counts taken at locations throughout a field (Brain and Cousens 1990). This model compares crop yield loss based on a random distribution of weeds in a field to crop loss for a population described with a negative binomial distribution. The frequency distribution of weed counts for an aggregated weed population in a field is frequently described well with a negative binomial distribution. Most counts are zero and there are a few high counts. Based on simulation experiments for poverty brome in wheat, they concluded that the overestimation may be large for high weed density, but the error would be minimal for practical control decisions that are made at much lower densities.

Thornton et al. (1990) modeled the effect of the spatial distribution of weeds on crop yield loss with spatial distribution described by two attributes: the area of weed patches within a field and the variation within weed patches. Adding variation of weed density within a patch increased the overestimation of yield loss. However, results of computer simulations showed that for aggregated populations, variation of density within patches had little effect on the economic threshold compared to the effect of spatial distribution (that is, the area of the field in patches).

Sampling techniques that account for spatial distribution will increase sampling efficiency and reliability. Research to develop such techniques is important and will provide some understanding of why spatial distribution changes with time (Cardina et al. 1997). Spatial distribution of weeds in a field also will have a major effect on determination of the economic threshold (Thornton et al. 1990). Using aerial surveillance to estimate the extent of weed patches has been attempted (Thornton et al. 1990), but cost is limiting and further work is needed to perfect and test this technique to assess spatial distribution.

The Effect of Variability on Decisions

Realistically, modeling the effect of the spatial distribution of weeds on crop yield may do little for practical decision making. As the models indicate, the effect may be small or possibly insignificant at low density. Further, it may not be possible to describe spatial distribution accurately enough to improve yield loss estimates. Spatial distribution of weeds is highly variable between fields and over years, and the number of sample locations needed to describe the variation may be very large and acquiring the data may be too expensive (Cardina et al. 1997).

Wilkerson et al. (2002) note that the number of respondents to their survey about use of decision-aid models, who thought the models required too much information from users and that discouraged use was about equal to those with the opposite view. If models are kept simple and user friendly, they may be used for simple decisions. The models may also be regarded as too complex. If they become more complex and presumably more accurate or more able to predict accurately, they will become less user friendly, they will require more hard work to collect the required information, and the essential model validation will be more expensive and difficult. The fact that most of these models were developed after 1990, attests to how new decision-aid modeling is. The apparent fact that, as mentioned above, the models are not widely used is largely due to their perceived unreliability and their failure to yield a better decision than can be made without the trouble of acquiring the data models require.

As noted previously, there are many examples of model variability. Lindquist et al. (1999) found year and site variability in economic thresholds and that single, simple regional yield loss equations were probably not (yet?) feasible (Lindquist et al. 1996). Jasieniuk et al. (1999) agreed with Lindquist et al. (1996) because variation in parameter estimates indicated that management recommendations could not be based on a single yield loss function with the same parameters for all sites and years. Murphy et al. (2002) said a single, fixed equation should not be expected to be adequate without incorporation of seasonal effects. The challenge is to develop an effective and practical method to incorporate seasonal (environmental) effect in empirical yield loss equations. Morin et al. (1993) found a large variation in regression curves between years and a large variation in predicted values of corn's yield loss. They suggest their work confirms the inaccuracy of an empirical predictive model using weed density and biomass.

Moffitt (2001) suggested using a range of density for estimating parameters. It is common that parameters of the hyperbola have unusual sensitivity or are difficult to estimate. Moffitt's work shows that a wide range of weed densities that include "both small and large values is the critical element in econometric analysis." A wide range of densities is needed but they do not have to be varied systematically. Moffitt notes the conclusion stands in sharp contrast to Cousens's (1985a) conclusion. That debate is to be resolved.

THRESHOLDS

Everyone seems to be in favor of decisions made on the basis of knowledge of thresholds. It is not equally clear that all who use the term are using the same definition. Cousens (1987), a frequent and correct critic of weed science research methods and statistical analysis, reminded weed scientists that "fallacious statistics" have been used too often in the calculation of competition thresholds and that the statistical threshold (as it has been used in weed science) is irrelevant and totally lacking in practical value. Using examples from the weed science literature, Cousens (1987) showed that the economic thresholds that have been published often vary with herbicide cost, herbicide efficacy in a given season, and the price of the crop. Certainly not all, but many, of the economic threshold values that are available have not been determined with the help of economists. They have been determined by simple cost calculations made by weed scientists (biologists/agronomists). This does not mean that they are absolutely wrong, but it does mean that they are not precise and therefore may not be reliable.

It is reasonable to assume that weed scientists would be reluctant to accept weed management or herbicide recommendations made by economists. Weed scientists should be as serious about the accuracy and reliability of threshold calculations as they have been about management recommendations, and seek the active participation of trained economists (Cousens 1987). Thresholds will never rise to perfection because of the strong element of subjectivity (what does the grower want to achieve—perhaps a clean field is the highest value), which cannot be eliminated and must be recognized.

Cousens et al. (1985) also counseled weed scientists to be precise in use of terminology. The basic concept is that somehow action (weed management) will be related to need, in the development of a threshold for action. That threshold can be based on competition (biology) or cost (economics). Both are reasonable but they may not give the same answer to the question Cousens et al. (1985) asked, "To spray or not to spray." It is the grower's question, If I do X will X be profitable? Should the weeds be controlled and, if they are, will the cost of control exceed the gain? Models purport to help answer the question. In fact, Moffitt (2001) suggests it is likely that the biologists' and economists' needs for research information for model development can be met with common experimental designs, the results of which are analyzed with the rectangular hyperbola.

Cousens et al. (1985) correctly criticize my proposal (Zimdahl 1980) that a competition threshold based on the assumption of a sigmodial relationship between crop yield and weed density was adequate. After plotting data from many competition experiments, it is clear that the relationship is not sigmoidal but hyperbolic and, thus, there is no competition threshold. A weed in a field will affect the crop yield in that field, even if the effect cannot be measured on a field scale. Therefore, the only valid threshold in the view of Cousens et al. (1985) is an economic one. Population dynamic studies can be used to develop long-term economic optimum thresholds. The need remains to predict next year's problem based on this year's weed population and to handle subjective views of weed management and unpredictable environmental effects.

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 (see 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 [Oliver and Buchanan (1986) reviewed research methods for determining economic thresholds]. 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, see 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 a herbicide. Some models also incorporate mechanical and cultural methods (Wilkerson et al. 2002).

Attempts to determine the economic threshold have been most common. VanDevender et al. (1997) used a nonlinear, empirical model, which is a unique three-dimensional adaptation of the Richards equation to predict rice yield as a function of weed density. They proposed that to gain an economic assessment of any weed management strategy, one must have a quantitative estimate of the yield effect of a given weed management strategy.

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 percent. But even when only 4 to 5 velvetleaf m^{-2} competed with corn, velvetleaf still produced eight thousand to ten thousand seeds m^{-2}. Zanin and Sattin (1988) questioned the value of a threshold density for weed management when one must consider velvetleaf's ecological characteristic that permits 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 the ability of large 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 percent.

Roberts and Hayes (1989) proposed a decision criteria model for johnsongrass control in soybeans, based on actual data, which describes 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 combination 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 soybeans. 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 percent 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 1999a), 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 two of every ten years (McDonald and Riha 1999a). Therefore, economic thresholds based solely on the level of weed infestation (the weed density) are inherently flawed (McDonald and Riha 1999a). McDonald and Riha (1999a) 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, but simultaneously realistic, view that widespread management of weeds with economic thresholds is an unrealistic goal until the stability (i.e., their 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 the 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 (1985a) model. The first involved the use of two linked hyperbolic equations derived from Cousens (1985a) hyperbolic model. The second modification was first proposed for aboveground biomass by Baeumer and deWit (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's (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, 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.

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 this review), 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 that a model requires 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 and had 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 the primary goal of agriculture, 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 effects of weeds in one crop in one year, which is what most economic thresholds and the associated models advocate. The goal, consistent with Norris's recommendation is to deplete the seedbank 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. A single-season economic threshold is almost surely not the best model or management strategy.

CONCLUSION

Simulation models have been used primarily to predict crop yield losses from weed competition. Weaver (1996) recommended the next step should be to link crop-weed simulation models with weed population dynamics models. She suggests that part of the reason for lack of integration is that more time has been spent developing models than in applying them. The purpose of linking would be to improve the ability to predict the effect of different weed management strategies over time. To accomplish this, Weaver (1996) recommended that modeling and experimentation "should proceed in parallel, preferably in interdisciplinary groups" that regularly interact to validate models and to test hypotheses. In addition, models should be written in easily accessible programming languages and be developed in full consideration of the role of environmental variation and the effects of weed morphological and physiological variation across geographic regions.

Wilkerson et al. (2002) conclude by advocating the use of an economic threshold that, in their view, will be facilitated by use of decision-aid models. They offer the strong argument that more than 50 years of application of herbicides to most cropped fields each year has not reduced weed populations much.

Herbicides are applied to the land that grows nearly 95 percent of the major U.S. crops (e.g., corn, soybeans, cotton) (Nat. Agric. Statistics 2001). Instances of herbicide resistance are increasing, so isn't it time to consider an approach other than broad-scale herbicide application, even if it is not profitable? I think most weed scientists think it is time. Wilkerson et al. (2002) think that "bioeconomic decision-aid models, combined with scouting, can provide valuable assistance, even to those who reject the economic threshold approach to weed management." Time will tell if they are correct.

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NOTE

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11

Conclusion: The Complexity of Competition

More than 650 publications are cited in this book. It is reasonable to conclude that they represent the majority of the work that has been published on weed-crop competition in the journals *Weed Research*, *Weed Science,* and *Weed Technology* since 1979. One also knows that it is not all that has been done, and there is the nagging suspicion that more should have been done to survey other journals and to analyze more thoroughly what is reported here. The subject has been covered thoroughly but, one wonders, has it been covered in sufficient depth?

The review leads to three major conclusions. The first is that there is no question that what I have called the central hypothesis of *Weed Science* has been affirmed: *Weeds compete with crops and reduce crop yield and quality*. The work that has been done affirms this for numerous weeds in all of the important crops that have been studied. Enough is known to cite specific weeds as more damaging in some crops than in others (e.g., sicklepod in soybeans, jointed goatgrass in western U.S wheat). The well-known role of environmental variation prevents sweeping generalizations of the precise quantitative effect of a weed or a weed complex across geographic regions or between years.

The great majority of the studies reviewed here demonstrates that studies of weed-crop competition can be used to predict yield losses from the presence of a weed or a complex of weeds in many different crops (Radosevich 1987). The studies also demonstrate that weed-crop competition is “a complex phenomenon” (Radosevich 1987) that is governed by biological, environmental, experimental, and human factors. The biological factors (see chapters 4, 5, and 6) are clear and include the crop, the specific weed or weeds, crop and weed density, crop and weed genotype, growth rate, relative time of emergence, and proximity of the weed(s) and crop plants. Environmental factors (see chapters 8 and 9) include water (as irrigation or rain), drought, fertility, light (shading), monoculture versus mixed cropping or polyculture, crop sequence or rotation, tillage or lack thereof, and soil type and its associated features (pH, tilth, water-holding capacity, etc.). Experimental factors (see chapter 10) include the experimental design used and the interpretation of results permitted by that design. Human factors are important but usually not obvious. They include such things as why one chooses to do a particular study. The reasons range from wanting to know what happens, farmer demand for solutions to particular problems, achieving future predictability, meeting the demand of whoever provided support funding, obtaining an explanation of why things happen, or, perhaps, some problem is just interesting and may or may not have any obvious practical application.

The second major conclusion is found in a common theme of the work reported here: *weed science will benefit from closer integration with plant ecology and a consequent greater emphasis on study and understanding of the coexistence of plants.* Such studies, it is suggested, will complement the past emphasis on what happens when plants compete. Enough is known about what happens, and many authors suggest that study and understanding of weed biology and ecology are obligatory if weed science is to develop truly integrated weed management strategies. The foundation represented by all that has been done on weed-crop competition is adequate, but continuation of such studies will not lead to robust systems able to deal with a diversity of weed species with a diversity of life histories in a field and across years and environments (Mortensen et al. 2000). These robust systems should include (Forcella 1987) determination of crop traits that confer competitive ability. These have not been well documented and doing so will require comparing isogenic lines of crop cultivars. For example, Forcella (1987) suggested determining the value of leaf area expansion (LAE) rate as a competitive trait and concluded that a high LAE rate conferred weed tolerance and competitive ability in one case. Others have also demonstrated the utility of leaf area (see chapter 11). Weed science needs better and standardized methods that go beyond observation of weed control success to experiments designed to test hypotheses about identifiable traits.

The abundant knowledge of what happens when weed X competes for Y time in crop Z when combined with the equally abundant knowledge of how to reduce the population density of weed X selectively in crop Z has revolutionized developed-country agriculture. However, there exist widespread mistrust of our capital-, chemical-, and energy-intensive system and repeated accusations that it is not sustainable. There is not sufficient space remaining here, and the purpose of this book is not to enter that debate, even though it is a debate that weed science must not ignore. It is common knowledge that weed problems have not diminished in recent years and may even have become worse because some of the easy weed problems have been solved. Herbicide resistance is an increasing problem, and there is increasing public concern about the chemicalization of agriculture. Whether the public's concern is appropriate and correct may not be as important as the undeniable fact that it exists and has not diminished in intensity in recent years.

Mortensen et al. (2000) provide several examples of research studies that illustrate how knowledge of weed ecology has been used to address and solve weed management problems. Their examples demonstrate that studies of weed ecology and biology are not just good basic science without practical application but rather the basis of future practical solutions to weed management problems. An approach to weed management that begins with understanding the nature of the weed and how it behaves is scientifically and ecologically wise. It is similar to the approach we all desire when we take a sick child to the physician. It is unsettling and wrong to be given a prescription for some mysterious medicine after a cursory examination and to be told, as we depart, that the medicine will relieve the symptoms but probably won't solve the problem. That is not good science and it is bad medical practice. But it is close to what weed science has been doing. Without understanding the problem (the weed), we have prescribed solutions that almost always relieved the symptoms but usually did not solve the underlying problem. The evidence presented in figure 1.1 shows that weed scientists are moving in the ecological direction and may be moving away from herbicides as the major weed management technique.

Barbieri and Kropff (2002) suggest that crop-weed competition studies are increasingly applied to scenarios in which biological and cultural weed control methods play a major role. This review neither denies nor offers vigorous confirmation of their observation. Barbieri and Kropff (2002) propose that "if this trend toward system-thinking is real, it should be seen as a positive achievement for weed scientists." It is positive because it will produce research results that give farmers and consumers what they really want from weed science research. It is apparent that Barbieri and Kropff (2002) think that what farmers and consumers really want is improved accuracy and precision of weed management recommendations and reduced chemical use, not just more information on what happens when weeds and crops compete. This is achievable, in their view, through integration of weed science with other disciplines (e.g., ecology and environmental science) and that integration, in Barbieri and Kropff's (2002) view, may be the beginning of the loss of identity of weed science as a stand-alone discipline. It is not an objective of this book to engage in the legitimate debate about whether weed science has ever achieved standing as a discipline. However, perhaps weed scientists ought to or will be compelled by the direction of their science to begin to consider their future carefully and the benefits and losses of the desirable integration proposed by Barbieri and Kropff (2002). They suggest weed science is moving "from prediction of the time of weed emergence to quantification of the process, taking" special account of weather variability. Such information will be particularly useful for refining and development of modeling—the third major conclusion of this work.

Modeling has become an important aspect of modern weed management systems and it is likely to become more important to future weed management systems. Modeling depends on basic weed biology and weed ecology studies. Studies of population dynamics, density-dependent mortality, and complete life history studies that go beyond the accurate but too simple annual, biennial, and perennial classification. Studies that define competitive ability and how it may balance with yield potential will be part of complete weed management programs that take advantage of competitive crop genotypes. Jordan (1989) advocated use of multivariate analysis of weed populations to predict evolutionary responses of the population to various control techniques. Threshold weed management methods depend on knowledge of weed population dynamics, and economic optimum thresholds are dependent on population dynamic models (Jordan 1992).

A further example of the kind of study weed science needs is the work on community assembly by Booth and Swanton (2002), mentioned in chapter 3**.** Community assembly, a rare term in weed science, is a branch of ecology that examines how a community is assembled over time and what paths the members and the community follow over time. The paths are determined by biotic and nonbiotic factors or filters, each of which acts at multiple scales. Booth and Swanton (2002) present the basic ecological theory of community assembly and propose ways in which it can be applied to weed science research to predict how crop-weed communities change in response to what they call "imposed filters" such as tillage and crop rotation. Their work, if followed, may lead weed science toward fundamental theories of competition and away from continued emphasis on what happens. They acknowledge that a community assembly approach is the opposite of the current approach to weed management, which is "to look at weeds as a series of individual problems and to study the biology of each species in an attempt to identify weak links in their life cycle." Management techniques are then developed to address the identified weak links at specific sites under specific conditions. Booth and Swanton (2002) recognize the utility of the approach but caution that it does little "to broaden understanding of why weeds occur where they do or how they interact in communities." The present approach leads to solution of the weed problem addressed and creation of a new weed problem that the solution did not or could not address. The present methods lead to the kind of solution criticized by Berry (1981) as one that leads to a "ramifying series of new problems." Berry (1981) advocated, as Booth and Swanton (2002) do, solutions that cause a ramifying series of solutions. Understanding how communities are assembled and function should lead to a series of solutions.

If weed management is to progress away from what the Dutch Ministry of Agriculture policy toward the use of herbicides calls (Mortensen et al. 2000) a "Yes, provided that" to a "No, unless" attitude, those who formulate weed management plans will have to examine their attitudes and values and spend a lot of time with farmers to understand where, how, and by whom the weed management system will be used. As noted above, weed management systems will have to be developed in full knowledge of what farmers and consumers really want (Barbieri and Kropff 2002): improved accuracy and precision of weed management recommendations, not just more information on what happens when weeds and crops compete. To do this, basic ecological theory will have to become more commonplace in weed science, and ecological principles will have to be incorporated in weed management systems. Weed control in the world's crops will remain important, but it will progress from the control of weed X in crop Z to weed management based on ecological theory and biological knowledge that will be used in the context of how communities are assembled and how the species in them coexist.

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Appendix

Table A.1. Common and Scientific Names of Crops

Common name	Scientific name and authority
Alfalfa	*Medicago sativa* L.
Apple	*Malus domestica* L.
Barley	*Hordeum vulgare* L.
Bean	*Phaseolus vulgaris* L
Bean, broad	*Vicia faba* L.
Bean, green, red, snap, white	*Phaseolus vulgaris* L
Bean, lima	*Phaseolus lunatus* L.
Beet, red	*Beta vulgaris* L.
Birdsfoot trefoil	*Lotus corniculatus* L.
Broccoli	*Brassica oleraceae* Italica group
Cabbage	*Brassica oleracea* L.
Canola	*Brassica napus* L
Carrot	*Daucus carota* L.
Cassava, manioc, yucca	*Manihot esculenta* Crantz
Celery	*Apium graveolens* L.
Chickpea	*Cicer arietinum* L.
Cinquefoil, bush	*Potentilla fruticosa* L.
Clover	*Trifolium* spp.
Clover, crimson	*Trifolium incarnatum* L.
Clover, subterranean	*Trifolium subterraneum* L.
Clover, white	*Trifolium repens* L.
Corn = maize	*Zea mays* L
Corn, sweet	*Zea mays* L.
Cotton	*Gossypium hirsutum* L.
Cowpea	*Vigna unguiculata* (L.) Walp.
Crownvetch	*Coronilla varia* L.
Cucumber	*Cucumis sativus* L.
Dogwood, redosier	*Cornus* x *baileyi*
Flatpea	*Lathrus sylvestris* L.
Flax = linseed	*Linum usitatissimum* L.
Garlic	*Allium sativum* L.
Hemp	*Cannabis sativa* L.
Kentucky bluegrass	*Poa pratensis* L.

Common name	Scientific name and authority
Leek	*Allium ampeloprasum* L.
Lentil	*Lens culinaris* L.
Lettuce	*Lactuca sativa* L.
Lobolly pine	*Pinus taeda* L.
Meadow foxtail	*Alopecurus pratensis* L.
Melon, egusi	*Citrullus lanatus* L.
Mung bean	*Phaseolus radiata* (L.) Wilczek var. *radiata*
Oat	*Avena sativa* L.
Okra	*Abelmoshu esculentus* (L.) Moench
Onion	*Allium cepa* L.
Orchard grass	*Dactylis glomerata* L
Pea	*Pisum sativum* L.
Peanut	*Arachis hypogaea* L.
Pepper	*Capsicum annuum* L.
Pigeon pea	*Cajanus cajan* (L.) Huth
Ponderosa pine	*Pinus ponderosa* L.
Potato, sweet	*Ipomoea batatas* (L.) Lam.
Potato, white	*Solanum tuberosum* L.
Poverty brome	*Bromus sterilis* L.
Rapeseed	*Brassica napus* L.
Rice	*Oryza sativa* L.
Rice, wild	*Zizania palustris* L. = *Zizania aquatica* L.
Rye	*Secale cereale* L.
Ryegrass, Italian	*Lolium multiflorum* L.
Ryegrass, perennial	*Lolium perenne* L.
Safflower	*Carthamus tinctorius* L.
Setaria, nandi	*Setaria anceps* Stapf. cv. Nandi
Sorghum	*Sorghum bicolor* (L.) Moench
Soybean	*Glycine max* (L.) Merr.
Sugarbeet	*Beta vulgaris* (L.) Schrad.
Sugarcane	*Saccharum officinarum* L.
Sunflower	*Helianthus annuus* L.
Timothy	*Phleum pratense* L
Tobacco	*Nicotiana tabacum* L.
Tomato	*Lycopersicon esculentum* L.
Triticale	*X Triticosecale*
Unknown	*Macroptilium atropurpureum* (DC.) Urb. cv. Siratro
Vetch, hairy	*Vicia hirsuta* (L.) S.F. Gray
Wheat	*Triticum aestivum* L.
Willow	*Salix* spp.
Yam, Asiatic	*Discorea esculentum* L.
Yam, White	*Discorea rotunda Poir*

Table A.2. Common and Scientific Names of Weeds Listed by Common Name

Common name	Scientific name and authority
Amaranth, Palmer	*Amaranthus palmeri* S. Wats.
Amaranth, Powell	*Amaranthus powellii* S. Wats.
Amaranth, spiny	*Amaranthus spinosus* L.
Amaranth, spleen	*Amaranthus dubius* Mart. Ex. Thell.
Apple-of-Peru	*Nicandra physaloides* (L.) Gaertn.
Azolla = pinnate mosquitofern	*Azolla pinnata* R. Brown
Barnyardgrass	*Echinochloa crus-galli* (L.) Beauv.
Bearded sprangletop	*Leptochloa fascicularis* (Lam.) Gray
Bearmat	*Chamaebatia foliolosa* Benth.
Bermudagrass	*Cynodon dactylon* L.
Blackgrass	*Alopecurus myosuroides* Huds.
Bladder campion	*Silene vulgaris* (Moench) Garcke
Bluegrass, annual	*Poa annua* L.
Bluegrass, roughstalk	*Poa trivialis* L.
Bristly starbur	*Acanthospermum hispidum* DC.
Broadleaf dock	*Rumex obtusifolius* L.
Broadleaf signalgrass	*Brachiaria platyphylla* (Griseb.) Nash
Broomrape, branched	*Orobanche ramosa* L.
Broomrape, crenate	*Orobanche crenata* Forsk.
Broomrape, nodding	*Orobanche cernua* Loeffl.
Buckwheat, tartary	*Fagopyrum tataricum* (L.) J. Gaertn.
Buckwheat, wild	*Polygonum convolvulus* L.
Burcucumber	*Sicyos angulatus* L.
Canada thistle	*Cirsium arvense* (L.) Scop.
Canarygrass, hood	*Phalaris paradoxa* L.
Canarygrass, littleseed	*Phalaris minor* Retz.
Catchweed bedstraw	*Galium aparine* L.
Catclaw mimosa = giant sensitive plant	*Mimosa pigra* L.
Cheat	*Bromus secalinus* L.
Chickweed, common	*Stellaria media* (L.) Vill.
Cocklebur, common	*Xanthium strumarium* L. = *X. pensylvanicum*
Coffee senna	*Cassia occidentalis* L.
Corn, volunteer	*Zea mays* L.
Corn caraway	*Ridolfia segetum* (L.) Moris = *Carum ridolfia* Benth. & Hook.
Corn cockle	*Agrostemma githago* L.
Corn poppy	*Papaver rhoeas* L.
Corn spurry	*Spergula arvensis* L.
Cow cockle	*Vaccaria pyrimidata* Medicus = *Vaccaria hispanica* (Mill.) Rausch.
Cutleaf groundcherry	*Physalis angulata* L. var. *angulata*
Dandelion	*Taraxacum officinale* Weber in Wiggers
Deadnettle	*Lamium* spp.
Devil's-claw = unicorn plant	*Proboscidea louisianica* (Mill.) Thellung
Dodder, lespedeza	*Cuscuta pentagona* Engelm.
Downy brome	*Bromus tectorum* L.

Common name	Scientific name and authority
Ducksalad	*Heteranthera limosa* (Sw.) Willd.
Eclipta	*Eclipta prostrata* L.
Fall panicum	*Panicum dichotomiflorum* Michx.
Fescue, chewings	*Festuca rubra* L.
Fescue, meadow	*Festuca pratensis* Huds. = *F. elatior* sensu Hitchc.
Fescue, red	*Festuca rubra* L.
Field bindweed	*Convolvulus arvensis* L.
Field pennycress	*Thlaspi arvense* L.
Field violet	*Viola arvensis* Murr.
Fierce thornapple	*Datura ferox* L.
Flixweed	*Descurainia sophia* (L.) Webb. ex Prantl
Florida beggarweed	*Desmodium tortuosum* (Sw.) DC.
Florida pusley	*Richardia scabra* L.
Foxtail, giant	*Setaria faberi* Herrm.
Foxtail, giant green	*Setaria viridis* (L.) var. *major* (Gaudin) Pospichel
Foxtail, green	*Setaria viridis* (L.) Beauv.
Foxtail, robust	*Setaria viridis* (L.) Beauv. var. *robusta-alba* Schrieber or *Setaria viridis* (L.) Beauv. var. *robusta-purpurea* Schreiber
Foxtail, yellow	*Setaria pumila* (Poir.) Roem & Schult
Goosegrass	*Eleusine indica* (L.) Gaertn.
Gorse	*Ulex europaeus* L.
Great brome = Ripgut brome	*Bromus diandrus* Roth.
Greater ammi	*Ammi majus* L.
Groundsel, common	*Senecio vulgaris* L.
Halberdleaf orach	*Atriplex patula* var. *hastata* (L.) Gray
Hardinggrass	*Phalaris aquatica* L.
Hemp = Marijuana	*Cannabis sativa* L.
Hemp dogbane	*Apocynum cannabinum* L.
Hemp sesbania	*Sesbania exaltata* (Raf.) Rydb. ex A.W.Hill
Hogpotato	*Hoffmanseggia glauca* (Ortega) Eifert
Horsenettle	*Solanum carolinense* L.
Horse purslane	*Trianthema portulacastrum* L.
Itchgrass	*Rottboellia cochinchinensis* (Lour.) W. Clayton
Japanese millet	*Echinochloa crus-galli* var. *frumentaceae*
Jerusalem artichoke	*Helianthus tuberosus* L.
Jimsonweed	*Datura stramonium* L.
Johnsongrass	*Sorghum halepense* L.
Jointed goatgrass	*Aegilops cylindrica* Host
Junglerice	*Echinochloa colona* (L.) Link
Kochia	*Kochia scoparia* (L.) Schrad
Korean lespedeza	*Lespedeza stipulacea* L.
Kyllinga, green	*Kyllinga brevifolia* Rottb.
Kyllinga, white	*Kyllinga nemoralis* (J. R. Foster & G. Foster) Dandy ex Hutchinson & Dalziel
Ladysthumb	*Polygonum persicaria* L.
Lambsquarters, common	*Chenopodium album* L.
Lanceleaf sage	*Salvia reflexa* Hornem.
Large crabgrass	*Digitaria sanguinalis* (L.) Scop.

(*continues*)

Table A.2. Continued

Common name	Scientific name and authority
Lateflowering goosefoot	*Chenpodium stricta* Roth. var. *glaucophyllum* (Aellen) H.A.Wahl.
London rocket	*Sisymbrium irio* L.
Mayweed chamomile	*Anthemis cotula* L.
Medusahead	*Taeniatherum caput-medusae* (L.) Nevski = *T. asperum* (Sim.) Nevski
Milkweed, common	*Asclepias syriaca* L.
Morningglory, entireleaf	*Ipomoea hederacea* (L.) Jacq. var. *integriscula*
Morningglory, ivyleaf	*Ipomoea hederacea* (L.) Jacq.
Morningglory, pitted	*Ipomoea lacunosa* L.
Morningglory, tall	*Ipomoea purpurea* (L.) Roth
Mustards	*Brassica* spp.
Mustard, ball	*Neslia paniculata* (L.) Desv.
Mustard, dog	*Erucastrum gallicum* (Willd.) O. E. Schulz
Mustard, white	*Brassica hirta* Moench = *Sinapis alba* L.
Mustard, wild	*Brassica kaber* (DC.) L. C. Wheeler = *Sinapis arvensis* L.
Nettle, burning	*Urtica urens* L.
Nightshade, black	*Solanum nigrum* L.
Nightshade, eastern black	*Solanum ptycanthum* Dun.
Nightshade, hairy	*Solanum sarrachoides* Sendtner
Nightshade, silverleaf	*Solanum elaeagnifolium* Cav.
Noogoora bur	*Xanthium occidentale* Bertol.
Northern jointvetch	*Aeschynomene virginica* (L.) B.S.P.
Nutsedge, purple	*Cyperus rotundus* L.
Nutsedge, yellow	*Cyperus esculentus* L.
Orchardgrass	*Dactylis glomerata* L.
Pale smartweed	*Polygonum lapathifolium* L.
Pennsylvania smartweed	*Polygonum pensylvanicum* L.
Perennial sowthistle	*Sonchus arvensis* L.
Pigweed, redroot	*Amaranthus retroflexus* L.
Pigweed, smooth	*Amaranthus hybridus* L.
Pigweed, tumble	*Amaranthus albus* L.
Pigweeds	*Amaranthus* spp.
Poorjoe	*Diodia teres* Walt.
Poverty brome	*Bromus sterilis* L.
Prickly sida	*Sida spinosa* L.
Quackgrass	*Elytrigia repens* (L.) Nevski = *Elymus repens* (L.) Gould = *Agropyron repens* L.
Ragweed, common	*Ambrosia artemisiifolia* L.
Ragweed, giant	*Ambrosia trifida* L.
Rape	*Brassica napus* L.
Redstem	*Ammannia auriculata* Willd.
Redstem filaree	*Erodium cicutarium* (L.) L=Her. ex. Ait.
Redtop	*Agrostis gigantea* Roth
Rice, red	*Oryza sativa* L.
Roundleaf mudplantain	*Heteranthera reniformis* R. & P.
Russian knapweed	*Acroptilon repens* (L.) DC.
Russian thistle	*Salsola iberica* Sennen & Pau

Common name	Scientific name and authority
Rye	*Secale cereale* L.
Ryegrass, Italian	*Lolium multiflorum* Lam.
Ryegrass, perennial	*Lolium perenne* L.
Ryegrass, rigid	*Lolium rigidum* Gaudin
Sandbur, longspine	*Cenchrus longispinus* (Hack.) Fern.
Sandbur, southern	*Cenchrus echinatus* L.
Scentless chamomile	*Matricaria perforata* Merat
Shattercane	*Sorghum bicolor* (L.) Moench
Shepherd's-purse	*Capsella bursa-pastoris* (L.) Medic.
Sicklepod	*Cassia obtusifolia* L.
Silky bentgrass	*Apera spica-venti* (L.) Beauv.
Smallflower galinsoga	*Galinsoga parviflora* Cav.
Smallflower umbrella sedge	*Cyperus difformis* L.
Speedwell	*Veronica* spp.
Speedwell, ivyleaf	*Veronica hederifolia* L.
Speedwell, Persian	*Veronica persica* Poir.
Spreading dayflower	*Commelina diffusa* Burm. f.
Spreading orach	*Atriplex patula* L.
Spurred anoda	*Anoda cristata* (L.) Schlecht.
Squirreltail	*Elymus elymoides* (Rafin.) Swezey
Sterile oat	*Avena sterilis* L.
Sunflower, common	*Helianthus annuus* L.
Tall waterhemp	*Acnida altissima* Moq. ex Standl. = *Amaranthus tuberculatus* (Moq.) J.D.Sauer
Texas panicum	*Panicum texanum* Buckl.
Timothy	*Phleum pratense* L.
Torpedograss	*Panicum repens* L.
Tropical kudzu	*Pueraria phaseoloides* (Roxb.) Benth.
Tropic croton	*Croton glandulosus* var. *septentrionalis* Muell.-Arg.
Unknown	*Crotalaria goreensis* Guill. & Perr.
Velvetleaf	*Abutilon theophrasti* Medicus
Velvetgrass, common = Yorkshire fog	*Holcus lanatus* L.
Velvetgrass, German	*Holcus mollis* L.
Venice mallow	*Hibiscus trionum* L.
Watergrass, late	*Echinochloa phyllopogon* (Stapf) Koss.
Water plantain, common	*Alisma* plantago-aquatica L. = *Alisma* triviale Pursh
Wild oat	*Avena fatua* L.
Wild poinsettia	*Euphorbia heterophylla* L.
Wild-proso millet	*Panicum miliaceum* L.
Wild radish	*Raphanus raphanistrum* L.
Winter wild oat	*Avena ludoviciana* Durieu
Woolly cupgrass	*Erichloa villosa* (Thunb.) Kunth
Yarrow	Achillea millefolium L.

Table A.3. Scientific and Common Names of Weeds, Listed by Scientific Name

Scientific name	Common name
Abutilon theophrasti Medicus	Velvetleaf
Acanthospermum hispidum DC.	Bristly starbur
Achillea millefolium L.	Yarrow
Acnida altissima Moq. ex Standl. = *Amaranthus tuberculatus* (Moq.) J.D.Sauer	Tall waterhemp
Acroptilon repens (L.) DC.	Russian knapweed
Aegilops cylindrica Host	Jointed goatgrass
Aeschynomene virginica (L.) B.S.P.	Northern jointvetch
Agrostemma githago L.	Corn cockle
Agrostis gigantea Roth	Redtop
Alisma plantago-aquatica L. = *Alisma* triviale Pursh	Common water plantain
Alopecurus myosuroides Huds.	Blackgrass
Amaranthus albus L.	Tumble pigweed
Amaranthus dubius Mart. Ex. Thell.	Spleen amaranth
Amaranthus hybridus L.	Smooth pigweed
Amaranthus palmeri S. Wats.	Palmer amaranth
Amaranthus powellii S. Wats.	Powell amaranth
Amaranthus retroflexus L.	Redroot pigweed
Amaranthus spinosus L.	Spiny amaranth
Amaranthus spp.	Pigweeds
Ambrosia artemisiifolia L.	Common ragweed
Ambrosia trifida L.	Giant ragweed
Ammannia auriculata Willd.	Redstem
Ammi majus L.	Greater ammi
Anoda cristata (L.) Schlecht.	Spurred anoda
Anthemis cotula L.	Mayweed chamomile
Apera spica-venti (L.) Beauv.	Silky bentgrass
Apocynum cannabinum L.	Hemp dogbane
Asclepias syriaca L.	Common milkweed
Atriplex patula L.	Spreading orach
Atriplex patula var. *hastata* (L.) Gray	Halberdleaf orach
Avena fatua L.	Wild oat
Avena ludoviciana Durieu	Winter wild oat
Avena sterilis L.	Sterile oat
Azolla pinnata R. Brown	Azolla = pinnate mosquitofern
Brachiaria platyphylla (Griseb.)Nash	Broadleaf signalgrass
Brassica hirta Moench = *Sinapis alba* L.	White mustard
Brassica kaber DC.) L.C.Wheeler = *Sinapis arvensis* L.	Wild mustard
Brassica napus L.	Rape
Brassica spp.	Mustards
Bromus diandrus Roth.	Great brome = ripgut brome
Bromus secalinus L.	Cheat
Bromus sterilis L.	Poverty brome
Bromus tectorum L.	Downy brome
Cannabis sativa L.	Hemp = marijuana

Scientific name	Common name
Capsella bursa-pastoris (L.) Medic.	Shepherd's-purse
Cassia obtusifolia L.	Sicklepod
Cassia occidentalis L.	Coffee senna
Cenchrus echinatus L.	Southern sandbur
Cenchrus longispinus (Hack.) Fern.	Longspine sandbur
Chamaebatia foliolosa Benth.	Bearmat
Chenopodium album L.	Common lambsquarters
Chenopodium stricta Roth. var. *glaucophyllum* (Aellen) H.A.Wahl.	Lateflowering goosefoot
Cirsium arvense (L.) Scop.	Canada thistle
Commelina diffusa Burm. f.	Spreading dayflower
Convolvulus arvensis L.	Field bindweed
Crotalaria goreensis Guill. & Perr.	Unknown
Croton glandulosus var. *septentrionalis* Muell.-Arg.	Tropic croton
Cuscuta pentagona Engelm.	Lespedeza dodder
Cynodon dactylon L.	Bermudagrass
Cyperus difformis L.	Smallflower umbrella sedge
Cyperus esculentus L.	Yellow nutsedge
Cyperus rotundus L.	Purple nutsedge
Dactylis glomerata L.	Orchardgrass
Datura ferox L.	Fierce thornapple
Datura stramonium L.	Jimsonweed
Descurainia sophia (L.) Webb. ex Prantl	Flixweed
Desmodium tortuosum (Sw.) DC.	Florida beggarweed
Digitaria sanguinalis (L.) Scop.	Large crabgrass
Diodia teres Walt.	Poorjoe
Echinochloa colona (L.) Link	Junglerice
Echinochloa crus-galli (L.) Beauv.	Barnyardgrass
Echinochloa crus-galli var. *frumentaceae*	Japanese millet
Echinochloa phyllopogon (Stapf) Koss.	Late watergrass
Eclipta prostrata L.	Eclipta
Eleusine indica (L.) Gaertn.	Goosegrass
Elymus elymoides (Rafin.) Swezey *Elymus repens* (L.) Gould = *Agropyron repens* L.	Squirreltail
Elytrigia repens (L.) Nevski =	Quackgrass
Erichloa villosa (Thunb.) Kunth	Woolly cupgrass
Erodium cicutarium (L.) L=Her. ex. Ait.	Redstem filaree
Erucastrum gallicum (Willd.) O .E. Schulz	Dog mustard
Euphorbia heterophylla L.	Wild poinsettia
Fagopyrum tataricum (L.) J. Gaertn.	Tartary buckwheat
Festuca pratensis Huds. = *F. elatior* sensu Hitchc.	Meadow fescue
Festuca rubra L.	Chewings fescue
Festuca rubra L.	Red fescue
Galinsoga parviflora Cav.	Smallflower galinsoga
Galium aparine L.	Catchweed bedstraw
Helianthus annuus L.	Common sunflower
Helianthus tuberosus L.	Jerusalem artichoke

(*continues*)

Table A.3. Continued

Scientific name	Common name
Heteranthera limosa (Sw.) Willd.	Ducksalad
Heteranthera reniformis R. & P.	Roundleaf mudplantain
Hibiscus trionum L.	Venice mallow
Hoffmanseggia glauca (Ortega) Eifert	Hogpotato
Holcus lanatus L.	Common velvetgrass = Yorkshire fog
Holcus mollis L.	German velvetgrass
Ipomoea hederacea (L.) Jacq.	Ivyleaf morningglory
Ipomoea hederacea (L.) Jacq.var. *integriscula*	Entireleaf morningglory
Ipomoea lacunosa L.	Pitted morningglory
Ipomoea purpurea (L.) Roth	Tall morningglory
Kochia scoparia (L.) Schrad	Kochia
Kyllinga brevifolia Rottb.	Green kyllinga
Kyllinga nemoralis (J.R. Foster & G. Foster) Dandy ex Hutchinson & Dalziel	White kyllinga
Lamium spp.	Deadnettle
Leptochloa fascicularis (Lam.) Gray	Bearded sprangletop
Lespedeza stipulacea L.	Korean lespedeza
Lolium multiflorum Lam.	Italian ryegrass
Lolium perenne L.	Perennial ryegrass
Lolium rigidum Gaudin	Rigid ryegrass
Matricaria perforata Merat	Scentless chamomile
Mimosa pigra L.	Catclaw mimosa = Giant sensitive plant
Neslia paniculata (L.) Desv.	Ball mustard
Nicandra physaloides (L.) Gaertn.	Apple-of-Peru
Orobanche cernua Loeffl.	Nodding broomrape
Orobanche crenata Forsk.	Crenate broomrape
Orobanche ramosa L.	Branched broomrape
Oryza sativa L.	Red rice
Panicum dichotomiflorum Michx.	Fall panicum
Panicum miliaceum L.	Wild-proso millet
Panicum repens L.	Torpedograss
Panicum texanum Buckl.	Texas panicum
Papaver rhoeas L.	Corn poppy
Phalaris aquatica L.	Hardinggrass
Phalaris minor Retz.	Littleseed canarygrass
Phalaris paradoxa L.	Hood canarygrass
Phleum pratense L.	Timothy
Physalis angulata L. var. *angulata*	Cutleaf groundcherry
Poa annua L.	Annual bluegrass
Poa trivialis L.	Roughstalk bluegrass
Polygonum convolvulus L.	Wild buckwheat
Polygonum lapathifolium L.	Pale smartweed
Polygonum pensylvanicum L.	Pennsylvania smartweed
Polygonum persicaria L.	Ladysthumb
Proboscidea louisianica (Mill.) Thellung	Devil's-claw = unicornplant
Pueraria phaseoloides (Roxb.) Benth.	Tropical kudzu
Raphanus raphanistrum L.	Wild radish
Richardia scabra L.	Florida pusley

Scientific name	Common name
Ridolfia segetum (L.) Moris = *Carum ridolfia* Benth. & Hook.	Corn caraway
Rottboellia cochinchinensis (Lour.) W. Clayton	Itchgrass
Rumex obtusifolius L.	Broadleaf dock
Salsola iberica Sennen & Pau	Russian thistle
Salvia reflexa Hornem.	Lanceleaf sage
Secale cereale L.	Rye
Senecio vulgaris L.	Common groundsel
Sesbania exaltata (Raf.) Rydb. ex A.W. Hill	Hemp sesbania
Setaria faberi Herrm.	Giant foxtail
Setaria pumila (Poir.) Roem & Schult	Yellow foxtail
Setaria viridis (L.) Beauv.	Green foxtail
Setaria viridis (L.) var. *major* (Gaudin) Pospichel	Giant green foxtail
Setaria viridis (L.) Beauv. var. *robusta-alba* Schrieber *or Setaria viridis* (L.) Beauv. var. *robusta-purpurea* Schreiber	Robust foxtail
Sicyos angulatus L.	Burcucumber
Sida spinosa L.	Prickly sida
Silene vulgaris (Moench) Garcke	Bladder campion
Sisymbrium irio L.	London rocket
Solanum carolinense L.	Horsenettle
Solanum elaeagnifolium Cav.	Silverleaf nightshade
Solanum nigrum L.	Black nightshade
Solanum ptycanthum Dun.	Eastern black nightshade
Solanum sarrachoides Sendtner	Hairy nightshade
Sonchus arvensis L.	Perennial sowthistle
Sorghum bicolor (L.) Moench	Shattercane
Sorghum halepense L.	Johnsongrass
Spergula arvensis L.	Corn spurry
Stellaria media (L.) Vill.	Common chickweed
Taeniatherum caput-medusae (L.) Nevski = *T. asperum* (Sim.) Nevski	Medusahead
Taraxacum officinale Weber in Wiggers	Dandelion
Thlaspi arvense L.	Field pennycress
Trianthema portulacastrum L.	Horse purslane
Ulex europaeus L.	Gorse
Urtica urens L.	Burning nettle
Vaccaria pyrimidata Medicus = *Vaccaria hispanica* (Mill.) Rausch.	Cow cockle
Veronica hederifolia L.	Ivyleaf speedwell
Veronica persica Poir.	Persian speedwell
Veronica spp.	Speedwell
Viola arvensis Murr.	Field violet
Xanthium occidentale Bertol.	Noogoora bur
Xanthium strumarium L. = *X. pensylvanicum*	Common cocklebur
Zea mays L.	Volunteer corn

Table A.4. Conversions for Measurements

Abbreviation	Term abbreviated	To convert into	Multiply by
A	Acres	Hectares	0.4047
cm	Centimeter	Inch	0.3937
ft	Feet	Centimeters	30.4800
ft	Feet	Meters	0.3048
ha	Hectare	Acres	2.4710
in	Inch (inches)	Centimeter	2.5400
kg ha^{-1}	Kilograms per ha	Pounds per acre	0.8920
kPa	Kilopascals	Pounds square inch	0.1450
kPa	Kilopascals	Bars	100.0000
L ha^{-1}	Liters per hectare	Gallons per acre	0.1070
m	Meter	Yard	1.0940
m^{-2}	Square meter	Square yard	1.1960

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