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Weed management: a need for ecological approaches

Introduction

Agriculture is the process of managing plant communities to obtain useful materials from the small set of species we call crops. Weeds comprise the "other" set of plant species found in agroecosystems. Although they are not intentionally sown, weed species are well adapted to environments dominated by humans and have been associated with crop production since the origins of agriculture (Harlan, 1992, pp. 83–99).

The ecological role of weeds can be seen in very different ways, depending on one's perspective. Most commonly, weeds are perceived as unwanted intruders into agroecosystems that compete for limited resources, reduce crop yields, and force the use of large amounts of human labor and technology to prevent even greater crop losses. In developing countries, farmers may spend 25 to 120 days hand-weeding a hectare of cropland (Akobundu, 1991), yet still lose a quarter of the potential yield to weed competition (Parker & Fryer, 1975). In the USA, where farmers annually spend $6 billion on herbicides, tillage, and cultivation for weed control (Chandler, 1991), crop losses due to weed infestation currently exceed $4 billion per year (Bridges & Anderson, 1992).

At the other end of the spectrum, weeds can be viewed as valuable agroecosystem components that provide services complementing those obtained from crops. In India (Alstrom, 1990, pp. 25–9) and Mexico (Bye, 1981; Mapes, Basurto & Bye, 1997), farmers consume *Amaranthus*, *Brassica*, and *Chenopodium* species as nutritious foods before crop species are ready to harvest. In western Rajasthan, yields of sesame and pearl millet can be increased by allowing the crops to grow in association with the leguminous weed *Indigofera cordifolia* (Bhandari & Sen, 1979). Certain weeds may limit insect damage to crops by interfering with pest movement or by providing habitat for natural enemies of pests (Andow, 1988; Nentwig, Frank & Lethmayer, 1998). Weed species can reduce soil erosion (Weil, 1982), serve as important sources of fodder and medicine (Datta & Banerjee, 1979; Chacon & Gliessman, 1982), and provide habitat for game birds and other desirable wildlife species (Sotherton, Rands & Moreby, 1985; Sotherton, Boatman & Rands, 1989). These types of beneficial effects indicate that weeds are not just agricultural pests, but can also play beneficial roles in agroecosystems.

In this chapter, we outline the objectives of weed management systems and then discuss how weeds are managed conventionally. We follow with a discussion of why alternatives to conventional management strategies are needed. Finally, we suggest how a broad range of ecological processes and farming practices might be exploited to manage weeds more effectively, while better protecting human health and environmental quality, and potentially increasing farm profitability. In subsequent chapters, we will examine these ecological processes and farming practices in more detail.

Weed management objectives

From the standpoint of crop protection, weed management has three principal objectives:

(1) *Weed density should be reduced to tolerable levels.* Experimental studies with a range of species indicate that the relationship between crop yield loss and weed density can be described by a rectangular hyperbola (Cousens, 1985; Weaver, Smits & Tan, 1987; Norris, 1992; Blackshaw, 1993; Knezevic, Weise & Swanton, 1994; Chikoye, Weise & Swanton, 1995). The specific parameters of this relationship change with differences in weather and soil conditions, species combinations, and other factors (Mortensen & Coble, 1989; Bauer *et al.*, 1991; Lindquist *et al.*, 1996), but, in general, reductions in weed density reduce crop yield loss (Figure 1.1a). Although the relationship shown in Figure 1.1a might argue for total elimination of weeds from crops, eradication efforts may be excessively expensive, incur unacceptable environmental damage, and deprive farmers and others of the ecological services certain weeds provide. Thus, with the exceptions of particularly noxious or invasive species, weed management rather than eradication is desirable.

(2) *The amount of damage that a given density of weeds inflicts on an associated crop should be reduced* (Figure 1.1b). The negative effect of weeds on crops can be limited not only by reducing weed density, but also by minimizing the resource consumption, growth, and competitive ability of each surviving weed (Mortensen, Dieleman & Johnson, 1998). This can be accomplished

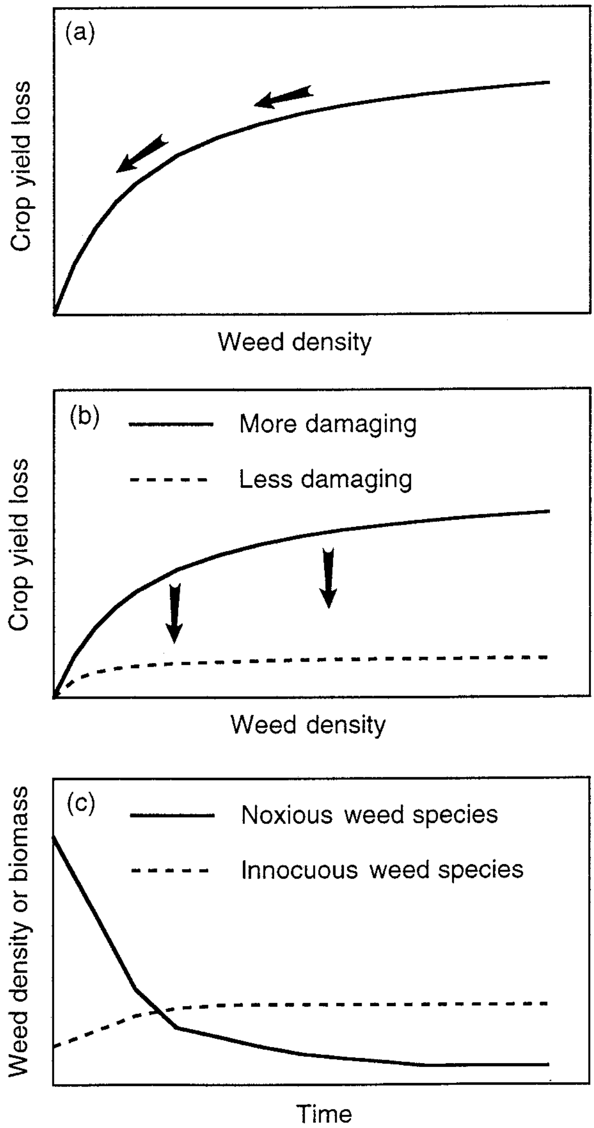

Figure 1.1 Three objectives of weed management: (a) reducing weed density to decrease crop yield loss; (b) reducing the amount of damage a given density of weeds inflicts on a crop; and (c) shifting the composition of weed communities from undesirable to desirable species.

by (i) delaying weed emergence relative to crop emergence (Cousens *et al.*, 1987; Blackshaw, 1993; Chikoye, Wiese & Swanton, 1995), (ii) increasing the proportion of available resources captured by crops (Berkowitz, 1988), and (iii) damaging, but not necessarily killing, weeds with chemical, mechanical, or biological agents (Kropff, Lotz & Weaver, 1993).

(3) *The composition of weed communities should be shifted toward less aggressive, easier-to-manage species.* Weed species differ in the amount of damage they inflict on crops and the degree of difficulty they impose on crop management and harvesting activities. Consequently, it is desirable to tip the balance of weed community composition from dominance by noxious species toward a preponderance of species that crops, livestock, and farmers can better tolerate (Figure 1.1c). This can be achieved by selectively and directly suppressing undesirable weed species while manipulating environmental conditions to prevent their re-establishment (Staver *et al*., 1995; Sheley, Svejcar & Maxwell, 1996). Selective vegetation management is particularly well suited to agroecosystems dominated by perennial plants, such as orchards, pastures, and rangelands.

Other, broader objectives are also important for weed management systems. Because farming is beset by uncertainties caused by variations in prices, weather, and pests, farmers seek weed management systems that predictably and consistently suppress weeds and reduce risks of crop yield loss. Convenience and profitability considerations lead farmers to seek weed management systems that use a desirable blend of labor, purchased inputs, and management skills. Farmers also seek weed management systems that fit well with other aspects of their farming system, such as crop sequence, tillage, and residue management practices. Over the long term, weed management systems are needed in which the number of effective management options holds steady or increases, rather than decreases. Finally, weed management systems need to protect environmental quality and human health.

What specific practices can be used to regulate weed density, limit the competitive impact of weeds, and manipulate weed community composition in ways that are compatible with broader, more systemic management objectives?

Weed density can be reduced by using tillage practices and crop residues to restrict the number of microsites at which weed seedling recruitment occurs (see Chapters 4, 5, and 7). Weed density can also be reduced by using tillage and cultivation tools (see Chapter 4), biological control agents (see Chapter 8), grazing livestock (see Chapter 9), and herbicides to kill or displace weed seeds, vegetative propagules, seedlings, and mature plants. Monitoring and decision-making are key components of managing weed density, and the development and implementation of procedures for doing so are discussed in Chapter 3.

Weed competitive ability can be reduced by killing early-emerging cohorts of weeds with herbicides or cultivation tools (see Chapter 4) and by choosing particular crop densities, spatial arrangements, and genotypes to enhance crop resource capture and competitive ability (see Chapter 6). Sequences and mixtures of different crops can also be used to preempt resources from weeds (see Chapter 7). Allelochemicals released from live crops and crop residues (see Chapters 5, 6, and 7), biological control agents (see Chapter 8), grazing livestock (see Chapter 9), and herbicides may be used to damage weeds and improve crop performance.

Desirable shifts in weed species composition can be promoted by tillage practices (see Chapter 4), grazing practices (see Chapter 9), and manipulations of soil conditions (see Chapter 5) and crop canopy characteristics (see Chapters 6 and 7). Selective herbicides can also be applied to alter weed species composition.

Currently, herbicides are the primary method for managing weeds in industrialized countries and are becoming more widely used in developing countries. Although we do not believe that they should be excluded from the weed management tool kit, we have given them relatively little attention in this book. There are four reasons for our orientation.

First, a large amount of information about herbicides and their effects on weeds and crops already exists, whereas much less information is available about other management tactics. We hope this book contributes to the closure of that information gap. Second, we believe that, over time, heavy reliance on herbicides reduces their efficacy by selecting for resistant or tolerant weed species and genotypes. To maintain the effectiveness of herbicides as weed management tools, weeds should be exposed to them as infrequently as possible. Third, we believe that certain herbicides can jeopardize environmental quality and human health. To minimize the potential for damage, effective weed management systems that are less reliant on herbicides are needed. Finally, herbicides constitute a rising proportion of crop value at a time when farmers are challenged by serious economic pressures. To promote farm profitability, there is an important need to develop effective weed management strategies that maximize opportunities for farmers to reduce input costs and increase the value of the crop and livestock products they sell.

We examine these points in more detail in the following sections.

Herbicide sales and use

Herbicides dominate the world market for pesticides and pervade the production of staple crops. Worldwide in 1997, $16.9 billion was spent for 1.0 billion kg of herbicide active ingredients, compared with $11.6 billion for 0.7 billion kg of insecticides and $6.0 billion for 0.2 billion kg of fungicides (Aspelin & Grube, 1999). Global herbicide sales are greatest for materials used for maize, soybean, wheat, and rice (Figure 1.2).

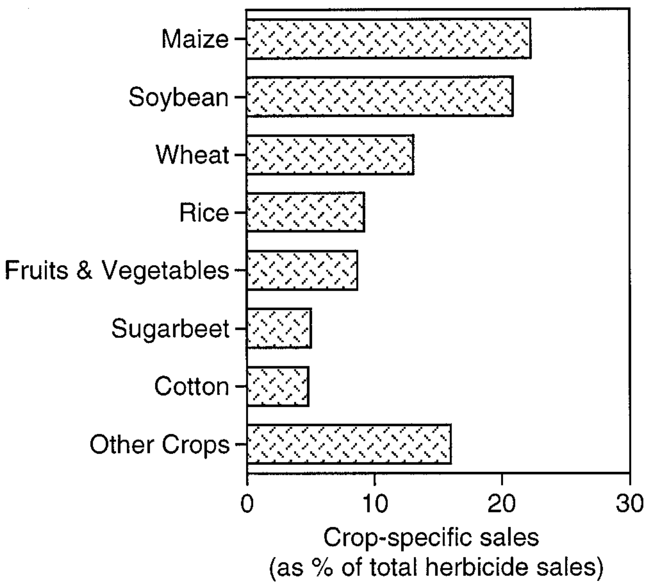

Figure 1.2 Global sales of herbicides in 1985 for the world's major crops. Data are expressed as percentages of total herbicide sales. (After Jutsum, 1988.)

In the USA, herbicide application to agricultural land has risen nearly fourfold since 1966 (National Research Council, 1989, p. 45), and now exceeds 200 million kg of active ingredients annually (Aspelin & Grube, 1999). Herbicides used for maize, soybean, wheat, cotton, and sorghum account for most pesticides applied to American cropland (Aspelin & Grube, 1999; United States Department of Agriculture, 1999*a*) (Table 1.1).

Herbicide use is also intensifying in many developing countries. In India, herbicide use increased more than 350% from 1971 to 1987, primarily for wheat and rice production (Alstrom, 1990, pp. 167–8). From 1987 to 1992, herbicide sales in South Asia and East Asia grew about 4% per year (Pingali & Gerpacio, 1997). By the early 1990s, herbicides were applied to half of the area planted with rice in the Philippines (Naylor, 1994) and more than 40% of the land planted with wheat in Punjab and Haranya, the two states that account for a third of India's total wheat production (Gianessi & Puffer, 1993). Sales and application of herbicides and other pesticides are also expanding in many regions of Latin America and certain areas of Africa (Repetto & Baliga, 1996, pp. 3–8).

Multiple factors promote the use of herbicides as primary tools for weed management. Herbicides can markedly reduce labor requirements for weed management in both mechanized (Gunsolus & Buhler, 1999) and nonmechanized (Posner & Crawford, 1991) farming systems. Consequently, herbicides

Table 1.1. *Estimated applications of pesticides[a] used in greatest quantities for crop production in the USA in 1987 and 1997*

Pesticide	Use	Active ingredients (millions of kg) Applied in 1987	Applied in 1997
Atrazine	herbicide	32–35	34–37
Metolachlor	herbicide	20–23	29–31
Metam sodium	fumigant (broad-spectrum biocide)	2–4	24–26
Methyl bromide	fumigant (broad-spectrum biocide)	no data	17–20
Glyphosate	herbicide	3–4	15–17
Dichloropropene	fumigant (broad-spectrum biocide)	14–16	15–17
Acetochlor	herbicide	0	14–16
2,4-D	herbicide	13–15	13–15
Pendimethalin	herbicide	5–6	11–13
Trifluralin	herbicide	11–14	10–11
Cyanazine	herbicide	10–11	8–10
Alachlor	herbicide	25–27	6–7
Copper hydroxide	fungicide	0.4–0.9	4–6
Chlorpyrifos	insecticide	3–4	4–6
Chlorothanil	fungicide	2–3	3–4
Dicamba	herbicide	2–3	3–5
Mancozeb	fungicide	2–3	3–5
EPTC	herbicide	8–10	3–5
Terbufos	insecticide	4–5	3–4
Dimethenamid	herbicide	no data	3–4
Bentazon	herbicide	3–4	3–4
Propanil	herbicide	3–5	3–4
Simazine	herbicide	1–2	2–3
MCPA	herbicide	2–3	2–3
Chloropicrin	fumigant (broad-spectrum biocide)	no data	2–3

Note:
[a] Excluded from this list are pesticidal uses of sulfur (22–34 million kg in 1997) and petroleum oils and distillates (30–34 million kg in 1997).
Source: Aspelin & Grube (1999).

are commonly used or becoming more widespread in regions where rising agricultural wages have reduced the cost-effectiveness of hand-weeding (Naylor, 1994; Pingali & Gerpacio, 1997) or mechanical cultivation (Miranowski & Carlson, 1993). Tractor-powered cultivation equipment greatly reduces manual labor requirements for weeding, but may be less consistently successful than herbicides in reducing weed density and protecting crop yield (Hartzler *et al.*, 1993). The cost-effectiveness and timeliness of cultivation can be particularly problematic on large farms with low crop diversity (Gunsolus & Buhler, 1999). Additionally, herbicide use is favored by the adoption of reduced and zero tillage practices (Johnson, 1994) and by the use of direct-seeding techniques in place of transplanting, as in the case of rice (Naylor, 1994).

Public and private institutions also play an important role in promoting herbicide use. In developing countries, herbicide use is encouraged by national and international organizations that provide technical advice and loans to farmers (Alstrom, 1990, p. 169; Pretty, 1995, pp. 26–57) and by government subsidies for herbicides and other pesticides, which lower their cost to farmers (Repetto, 1985). Throughout the world, advertising emphasizes chemical solutions to weed problems. Agrichemical companies spent an estimated $32 million for herbicide advertising in printed media in the USA in 1994 (Benbrook, 1996, p. 165), and herbicide advertisements on radio and television are also common.

A concentration of scientific research upon herbicides has strongly contributed to their importance as weed management tools in both industrialized and developing countries (Alstrom, 1990, pp. 162–5; Wyse, 1992). Abernathy & Bridges (1994) and Benbrook (1996, p. 163) surveyed weed science publications cited in *Weed Abstracts* and the *Agricola* database between 1970 and 1994 and reported that more than two-thirds of the articles focused on various aspects of herbicides and their application. Although some research focused on weed biology and ecology, only a small fraction of articles addressed components of alternative weed management strategies, such as tillage, cultivation, crop rotation, cover crops, mulches, and biological control.

Technical and social factors that favor the dominance of herbicides over other approaches for weed management are discussed in more detail in Chapter 11. Here we will review some of the unintended impacts of herbicide use that are leading a growing number of farmers, scientists, and policy makers to seek alternatives to heavy reliance on herbicide technology.

Unintended impacts of herbicide use

Herbicide resistance in weeds and herbicide product development

Reappraisal of herbicide technology has been driven, in part, by the detection of herbicide resistance in a growing number of weed species. Herbicide resistance is an evolved condition whereby exposure of a weed population to a herbicide leads to a predominance of genotypes that can survive and grow when treated with herbicide concentrations that are normally fatal in untreated populations. Before 1980, herbicide resistance was observed in only a few weed species and was generally limited to triazine compounds

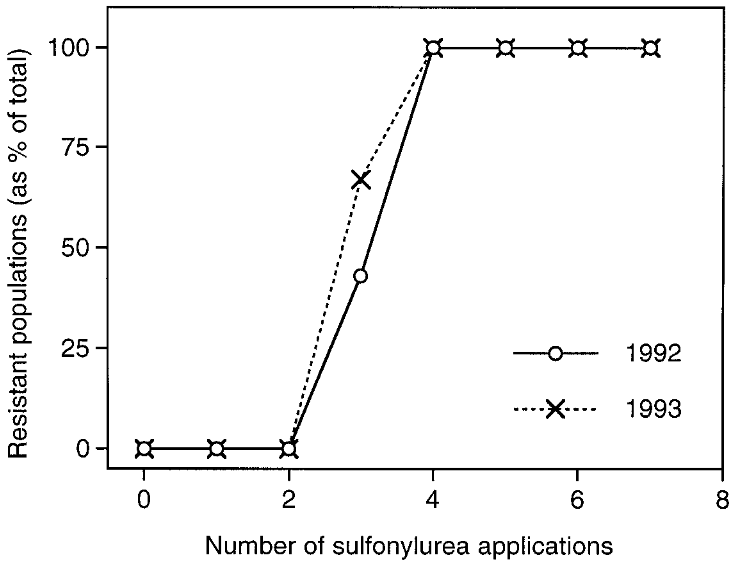

Figure 1.3 Relationship between the number of sulfonylurea herbicide applications made to individual fields and the percentage of *Lolium rigidum* populations with detectable resistance to sulfonylurea compounds. Plant collections were made in Western Australia in 1992 and 1993. (After Gill, 1995.)

(Warwick, 1991; Holt, 1992). Since that time, however, herbicide resistance has been reported for 145 weed species in 45 countries throughout the world (Heap, 1999). Herbicide resistance is appearing in additional weed species at a rate equal to that observed for insecticide and acaricide resistance in arthropod pests (Holt & LeBaron, 1990), and weed biotypes now exist with resistance to one or more herbicides in at least 16 different chemical classes, including the arsenical, aryloxyphenoxyproprionate, benzonitrile, bipyridilium, chloroacetamide, cyclohexanedione, dinitroaniline, dithiocarbamate, imidazolinone, phenoxy, substituted urea, sulfonylurea, triazine, and uracil compounds (Heap, 1999).

Under field conditions in which the same herbicide or chemical class of herbicides is applied repeatedly, herbicide resistance may evolve in four to five years (Holt, 1992). As shown in Figure 1.3, resistance to sulfonylurea herbicides was detected in all populations of the grass weed *Lolium rigidum* collected from Western Australia wheat fields that had been treated with those compounds only four times (Gill, 1995). Evolved resistance to glyphosate, which was thought unlikely to occur, was reported in 1998 for a *L. rigidum* population collected from an Australian orchard that had been treated with glyphosate two or three times a year for 15 years (Powles *et al.*, 1998).

Suggested strategies for preventing or delaying the evolution of herbicide resistance in weeds include using individual herbicides with different modes of action sequentially and using mixtures of herbicides with different modes of action concurrently (Gressel & Segel, 1990; Wrubel & Gressel, 1994). The underlying assumption in these strategies is that weeds are less likely to evolve resistance to several unrelated compounds than to a single compound.

The evolution of weed biotypes with resistance to multiple classes of herbicides is a real possibility, however. This phenomenon is common in insects (Georghiou, 1986) and has been observed in *Lolium rigidum* in Australia (Burnet *et al*., 1994; Gill, 1995) and *Alopecurus myosuroides* in the UK (Holt, 1992). Of particular interest is the ability of weeds to evolve resistance to distinct classes of herbicides as a consequence of exposure to, and selection by, chemically unrelated herbicides. Burnet *et al*. (1994) reported, for example, that a *L. rigidum* population in Victoria had become resistant to nine different chemical classes of herbicides after 21 years of exposure to five herbicides in only five classes. *Lolium rigidum* is a major cropland weed in southern Australia and, as a species, has demonstrated resistance to most of the major herbicide chemistries used there (Powles *et al*., 1997).

Increasing costs of research, development, and registration are reducing the rate at which new herbicides are introduced into the marketplace. The cost to a company of developing and registering a pesticide product increased from $1.2 million in 1956 to an estimated $70 million in 1991 (Holt & LeBaron, 1990; Leng, 1991). Concomitantly, the chances of a newly discovered chemical becoming a legally registered product have decreased greatly; Holt & LeBaron (1990) cited the odds as 1 in 1000 in 1956, compared with 1 in 18 000 in 1984. Increased costs of toxicological testing and legal work associated with the regulatory process are also leading many agrichemical firms to not seek reregistration for the use of herbicides in crops that occupy only small areas, e.g., vegetables and fruits (Anonymous, 1989).

Partly as a consequence of rising costs for discovering, developing, and registering new herbicides, agrichemical firms have merged with seed and biotechnology companies to produce new crop varieties with resistance to existing herbicides, especially glyphosate, glufosinate, bromoxynil, and sulfonylurea, cyclohexanedione, and imidazolinone compounds (Duke, 1999). Many of these varieties have been produced using recombinant DNA technologies. Worldwide in 1999, herbicide-resistant, transgenic varieties of soybean, maize, cotton, rapeseed, and other crops were planted on 28 million ha (Ferber, 1999). The broadscale deployment of these and other genetically engineered crops has been met with controversy in Europe, Japan, the USA, and elsewhere because of environmental and consumer concerns. Thus, the extent to which herbicide-resistant crops will be used in the future is uncertain.