Ecological Management of Agricultural Weeds

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MATT LIEBMAN

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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

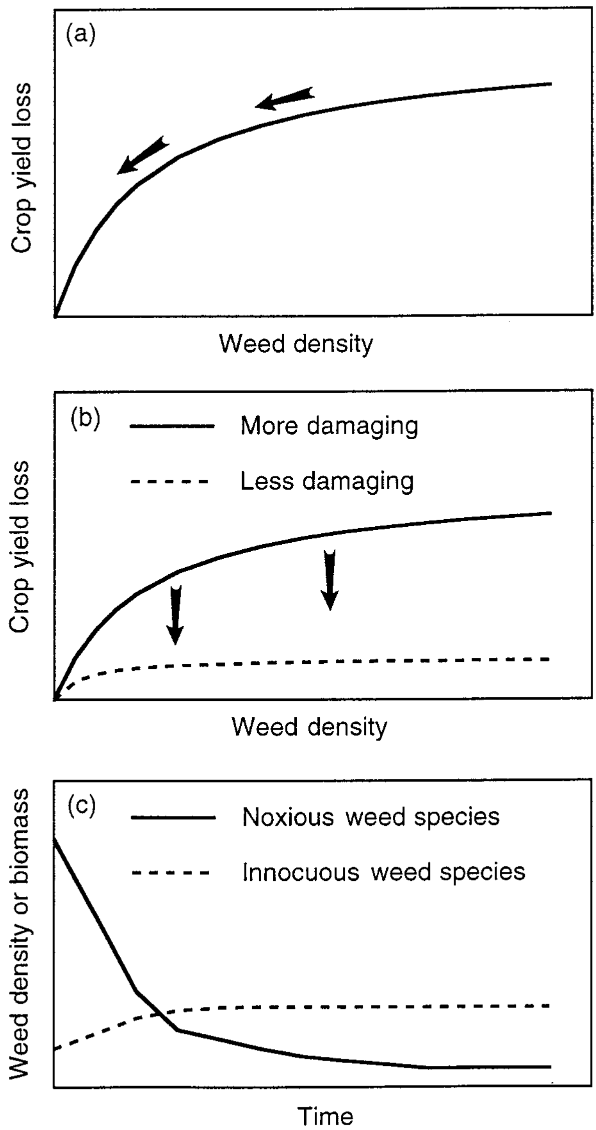

Figure 1.1 Three objectives of weed management: (a) reducing weed density to decrease crop yield loss; (b) reducing the amount of damage a given density of weeds inflicts on a crop; and (c) shifting the composition of weed communities from undesirable to desirable species.

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).

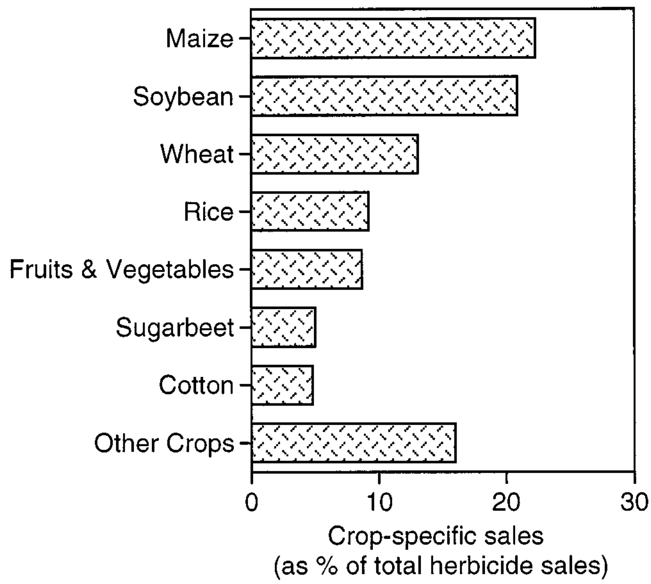

Figure 1.2 Global sales of herbicides in 1985 for the world's major crops. Data are expressed as percentages of total herbicide sales. (After Jutsum, 1988.)

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

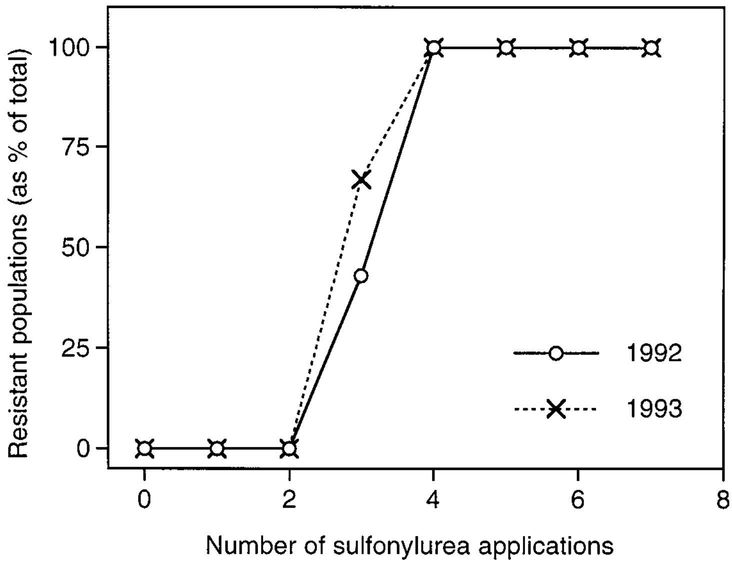

Figure 1.3 Relationship between the number of sulfonylurea herbicide applications made to individual fields and the percentage of *Lolium rigidum* populations with detectable resistance to sulfonylurea compounds. Plant collections were made in Western Australia in 1992 and 1993. (After Gill, 1995.)

(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 re-registration 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.

If herbicide-resistant crops are accepted and used widely in coming years, herbicide resistance in weeds will remain a concern, since herbicides used with these crops will exert the same types of selection pressures that they do in herbicide-tolerant, non-genetically engineered crops. Shifts in weed community composition toward species pre-adapted to tolerate herbicides applied to herbicide-resistant crops are also possible (Owen, 1997). In addition, transfer of herbicide resistance from crops to related weed species through pollen movement may create new herbicide-resistant weed populations (Snow & Morán-Palma, 1997; Seefeldt *et al.*, 1998), which would have to be controlled by different herbicides or other means.

The combination of herbicide resistance in an increasing number of weed species, slower introduction of new herbicides, and withdrawal of older herbicides means that farmers are likely to have fewer chemical control options within the next several decades. For this reason, alternative weed management strategies that make full use of nonchemical tactics need to be developed.

Herbicides and water quality

Since the 1980s there has been increasing recognition that herbicides, applied in the course of normal farming practices, have contaminated surface and ground water in many agricultural regions (Barbash *et al.*, 1999; Larson, Gilliom & Capel, 1999; United States Geological Survey, 1999). Among the herbicides detected most frequently in drinking-water sources, there are a number of compounds classified as probable (e.g., acetochlor), likely (e.g., alachlor), and possible (e.g., atrazine, cyanazine, metolachlor, and simazine) carcinogens (United States Environmental Protection Agency, 1999). Several herbicides contaminating drinking-water sources are also under scrutiny as possible disrupters of human immune, endocrine, and reproductive systems (see section "Acute and chronic effects of herbicides on human health" below). The effects of low-level exposure to herbicides are poorly understood, but there is considerable popular and regulatory concern over contamination of drinking-water sources.

Herbicide contamination of the Mississippi River drainage basin has been particularly well documented (United States Geological Survey, 1999). The 12 states that drain to the Mississippi River contain about 65% of the harvested cropland in the USA, and fields of maize, soybean, sorghum, rice, wheat, and cotton are dominant features of the region's landscape (United States Department of Agriculture, 1999*b*). The Mississippi River basin receives the majority of herbicides applied in the USA; during the late 1980s, more than 125 000 metric tons of herbicide active ingredients were applied annually to cropland in the watershed (Gianessi & Puffer, 1991; Goolsby, Battaglin & Thurman, 1993).

About 18 million people rely on the Mississippi River and its tributaries as their primary source of drinking water (Goolsby, Coupe & Markovchick, 1991). Public water systems serving that population are required to take at least four samples each year to measure concentrations of pollutants, including certain herbicides, for which the US Environmental Protection Agency (1996) has set legally enforceable safety standards called maximum contaminant levels. A public water system is out of compliance with the federal Safe Drinking Water Act of 1986 if the yearly average concentration of a pollutant exceeds its maximum contaminant level, or if a pollutant's concentration in any one quarterly sample is more than four times higher than its maximum contaminant level.

For several herbicides currently lacking legally enforceable standards, the US Environmental Protection Agency (1996) has specified health advisory levels, which are maximum chemical concentrations that may be consumed in drinking water over an average human lifetime with minimal risk that they will cause "adverse non-carcinogenic effects." Health advisory levels can eventually become enforceable standards. Both maximum contaminant and health advisory levels have been established only for individual compounds; standards have not been set for mixtures of herbicides and other chemicals, including metabolites of herbicides (Goolsby, Battaglin & Thurman, 1993).

After application to cropland in the midwestern USA, herbicides not degraded or bound to soil are detected in surface water in pulses corresponding to late spring and summer rainfall (Thurman *et al.*, 1991). In 1991, the US Geological Survey detected atrazine, which is widely used for weed control in maize and sorghum, in each of 146 water samples collected at eight locations throughout the Mississippi River basin (Goolsby, Coupe & Markovchick, 1991). More than 75% of the samples also contained other herbicides used in maize, soybean, and sorghum production: alachlor, metolachlor, cyanazine, and simazine. Between April and July 1991, atrazine concentrations exceeded the US Environmental Protection Agency's maximum contaminant level of 3 $\mu g\ L^{-1}$ for 6 to 9 weeks at sites in the Illinois, Mississippi, Missouri, Platte, and White Rivers (Figure 1.4). In those same rivers, cyanazine concentrations exceeded the US Environmental Protection Agency's health advisory level of 1 $\mu g\ L^{-1}$ for 7 to 14 weeks. Alachlor concentrations exceeded the agency's maximum contaminant level of 2 $\mu g\ L^{-1}$ for 1 to 3 weeks in the Illinois, Platte, and White Rivers.

In a review of data from 12 studies of herbicide concentrations in finished tap water and raw drinking-water sources (rivers and reservoirs) in the

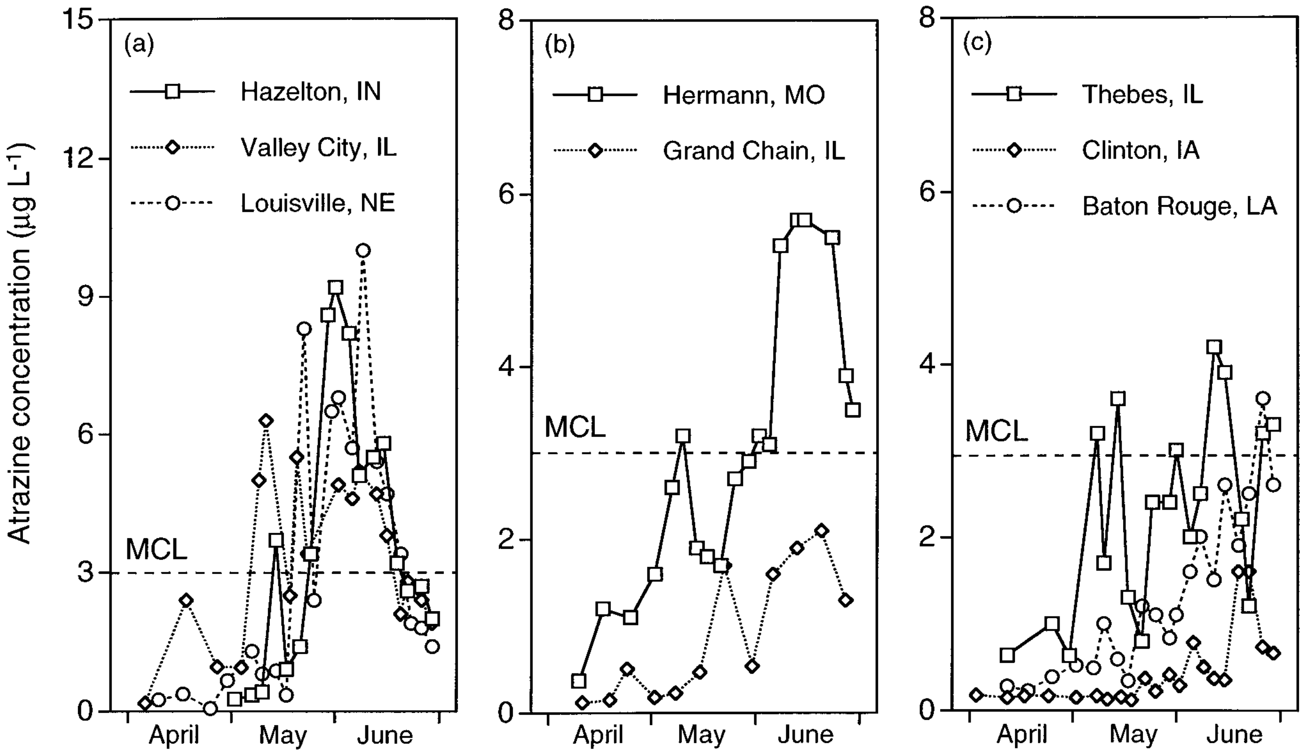

Figure 1.4 Atrazine concentrations during April through June 1991 in the White River at Hazelton, IN (a); the Illinois River at Valley City, IL (a); the Platte River at Louisville, NE (a); the Missouri River at Hermann, MO (b); the Ohio River at Grand Chain, IL (b); and the Mississippi River at Thebes, IL, Clinton, IA, and Baton Rouge, LA (c). The maximum contaminant level (MCL) set by the US Environmental Protection Agency for atrazine in drinking water is 3 $\mu g\ L^{-1}$. (After Goolsby, Coupe & Markovchick, 1991.)

American maize belt, Nelson & Jones (1994) noted that a substantial proportion of sampled locations had at least one measurement of atrazine, cyanazine, or alachlor that was more than four times higher than maximum contaminant or health advisory levels. Most community water systems in the Mississippi River drainage basin are not equipped with technology that can reduce herbicide concentrations to levels lower than government health standards (National Research Council, 1989, p. 101; Goolsby, Coupe & Markovchick, 1991; Nelson & Jones, 1994). Consequently, the American Water Works Association has expressed concern that costly additional treatment systems, such as granular activated charcoal, will have to be installed in many public water systems in the midwestern USA to address violations of the federal Safe Drinking Water Act (Nelson & Jones, 1994).

Because certain herbicides can be harmful to aquatic organisms, "aquatic life guidelines" have been set for several herbicides found in surface water. Canadian standards, which are also used as nonenforceable benchmarks in the USA, are 1 $\mu g\ L^{-1}$ for metribuzin, 2 $\mu g\ L^{-1}$ for atrazine and cyanazine, 8 $\mu g\ L^{-1}$ for metolachlor, and 10 $\mu g\ L^{-1}$ for simazine (Larson, Gilliom & Capel, 1999). It is clear from the data presented in Figure 1.4 that atrazine concentrations in American rivers can exceed the Canadian aquatic life standard. Aquatic life standards for other herbicides detected in rivers and streams are also often exceeded (Larson, Gilliom & Capel, 1999).

An additional concern is how herbicides affect coastal ecosystems. Goolsby, Battaglin & Thurman (1993) estimated that discharges of atrazine from the Mississippi River into the Gulf of Mexico from April through August were 296 000 kg in 1991, 160 000 kg in 1992, and 539 000 in 1993 (a flood year). The possible impacts of such discharges on aquatic organisms in the Gulf of Mexico and elsewhere are inadequately understood and require more research.

Herbicides and their degradation products are common contaminants of groundwater in many agricultural regions (Hallberg, 1989; Leistra & Boesten, 1989; National Research Council, 1989, pp. 107–9; United States Geological Survey, 1999). In the USA, groundwater is used for drinking water by nearly half of the total population and by more than 95% of the population in rural areas (National Research Council, 1989, p. 105). Herbicides that have been measured in wells of American agricultural areas at concentrations greater than maximum contaminant or health advisory levels include alachlor, atrazine, cyanazine, 2,4-D, DCPA, dicamba, dinoseb, metolachlor, metribuzin, and simazine (Hallberg, 1989). In a survey of private wells used for drinking water in Ohio, Indiana, Illinois, West Virginia, and Kentucky, Richards *et al.* (1996) detected chloroacetamide and triazine herbicides in 9.7% and 4.9% of the 12362 samples tested; maximum contaminant levels for alachlor and atrazine were exceeded in 1.1% and 0.1% of the samples, respectively. Two large-scale, multistate investigations of herbicides in American wells and springs detected at least one of seven targeted compounds in 35% to 40% of the sites sampled, although maximum contaminant or health advisory levels were exceeded at fewer than 0.1% of the sites (Barbash *et al.*, 1999).

Although concentrations of individual herbicides in American groundwater rarely exceed existing regulatory standards, important concerns remain concerning health risks. Detection of one herbicide in groundwater at an individual site is often accompanied by the detection of others (Barbash *et al.*, 1999), but little is known about the health-related impacts of exposure to multiple herbicides, or to herbicides in combination with nitrates, which are also common water contaminants. Breakdown products of herbicides are generally found in well water more frequently and at higher concentrations than the corresponding parent compounds (Kolpin, Thurman & Goolsby, 1996), but little is known about their possible effects on human health. Health-based standards for breakdown product concentrations in groundwater generally do not exist.

Herbicide drift

Herbicides can contaminate off-target sites by moving in air as well as in water. Generally, herbicide drift from tractor-mounted sprayers is about 5% to 10% of the material applied, with most off-site deposition occurring within 20 m of field edges (Freemark & Boutin, 1995). However, depending on meteorological conditions, application equipment, and physical characteristics of herbicide products, spray drift concentrations of 0.02% to 2% of application rates may occur at distances as great as 400 m from application sites (Fletcher *et al.*, 1996).

The implications of aerial movement of herbicides are especially problematic for highly phytotoxic chemicals, such as sulfonylurea and imidiazolinone compounds. Although these compounds may have low mammalian toxicity, their drift onto nontarget crops and wild land areas, even at low concentrations, may greatly alter plant performance, particularly reproduction. Fletcher *et al.* (1996) found that flower and seed production by rapeseed, soybean, sunflower, and *Polygonum persicaria* could be reduced by exposure to chlorsulfuron at rates from 0.1% to 0.8% of those recommended for field applications to cereal crops. For certain combinations of plant species, chlorsulfuron rates, and application times, reproductive damage occurred even when effects on vegetative growth were minimal. For example, chlorsulfuron treatment of rapeseed (at 9.2×10^{-5} kg a.i. ha^{-1}) and soybean (at 1.8×10^{-4} kg a.i. ha^{-1}) during anthesis reduced seed yield 92% and 99%, respectively, compared with untreated plants, whereas height was reduced only 12% and 8%. Similarly, treatment of cherry trees with low rates of chlorsulfuron reduced fruit yield but created little or no foliar damage (Fletcher, Pfleeger & Ratsch, 1993).

Other herbicides do not necessarily have such potent effects at low concentrations. Rapeseed and soybean were unaffected by applications of atrazine, glyphosate, and 2,4-D at rates and stages of plant development at which chlorsulfuron suppressed reproduction (Fletcher *et al.*, 1996). None the less, the experiments with chlorsulfuron indicate that low doses of certain compounds can profoundly affect plant reproduction, and the results emphasize the potential for serious off-target damage due to herbicide drift. Currently, data concerning the impacts of chlorsulfuron and other herbicides on nontarget plant reproduction are not required for product registration in the USA (Fletcher *et al.*, 1996).

Acute and chronic effects of herbicides on human health

Although much remains to be learned about the acute and chronic health impacts of herbicide use, public health reports and epidemiological studies indicate that certain herbicides can be responsible for direct, unintentional poisoning and may be associated with increased incidence of cancer and other disorders. Farmers, farm families, and agricultural workers are exposed to herbicides at higher concentrations than the general public and consequently may be subjected to greater health risks. Health issues relating to exposure to herbicides and other pesticides are particularly important in developing countries, where safe use is difficult because of unavailable or prohibitively expensive protective equipment, inadequate and poorly enforced safety standards, poor labeling, illiteracy, and insufficient knowledge of hazards by handlers and applicators (Pimentel *et al.*, 1992; Repetto & Baliga, 1996, pp. 9–16).

Acute symptoms of pesticide poisoning include headache, skin and eye irritation, fatigue, dizziness, nausea, cramping, fever, diarrhea, and difficulty in breathing (Stone *et al.*, 1988). Most incidents of pesticide poisoning go unreported (Jeyaratnum, 1990), but it is conservatively estimated that one million serious accidental pesticide poisonings occur throughout the world each year (World Health Organization, 1990, p. 86). Pesticide poisonings of farmers and agricultural workers occur in industrialized countries, such as the USA (Stone *et al.*, 1988), but are more frequent in developing countries (Repetto & Baliga, 1996, pp. 9–16).

Public health data from Costa Rica suggest that herbicides may contribute to a significant portion of acute pesticide poisonings in developing countries. Hilje *et al.* (1992, p. 79) reported that bipyridilium, chloroacetamide, dinitroaniline, phenoxy, picolinic acid, substituted urea, and triazine herbicides accounted for 19% of the 787 pesticide poisonings registered in 1984 by the Costa Rican National Poison Control Center. Similarly, Dinham (1993, p. 105) noted that various herbicides were responsible for 22% of the acute pesticide poisonings in the region of Limón, Costa Rica, in the first six months of 1990. Hilje *et al.* (1992, p. 79) stated that the actual number of pesticide poisonings in Costa Rica is higher than that reported to government agencies, but that available data accurately reflect the percentage of poisonings attributable to different types of pesticides.

Chronic health effects of chemical exposure can include cancer and disorders of the immune, endocrine, neurological, and reproductive systems. Unambiguous cause-and-effect relationships are often difficult to establish for these types of health problems because a long lag period typically exists between exposure to causative agents and presentation of clinical symptoms, and because exposure to other chemicals or behaviors such as smoking may be contributing factors. Epidemiological studies can be conducted, however, to determine patterns of risk associated with exposure to herbicides and other pesticides.

Thirty-nine herbicide active ingredients are classified by the US Environmental Protection Agency (1999) as probable, likely, or possible carcinogens, and a number of epidemiological studies have examined possible links between herbicides and cancer in human populations. Significant correlations between herbicide use and several types of cancer were noted by Stokes & Brace (1988) in a study of cancer deaths in 1497 nonmetropolitan counties in the USA. The percentage of land area treated with herbicides in each county was significantly correlated with the incidence of genital, lymphatic, hematopoietic, and digestive system cancers. Herbicide use had no relationship with urinary system cancers, however, and was negatively correlated with respiratory system cancers. On Saskatchewan farms of less than 400 ha, death of male farmers due to non-Hodgkin's lymphoma (NHL) rose significantly with increasing numbers of hectares sprayed with herbicides (Blair, 1990; Wigle *et al.*, 1990). No significant relationship was found on farms of more than 400 ha, where farmers may have been less likely to apply herbicides personally or may have used aircraft for applications.

Hoar *et al.* (1986) reported that the incidence of NHL among men in Kansas increased significantly with the number of days per year that they used herbicides; men who used herbicides more than 20 days per year had a six-fold higher chance of contracting NHL than did nonfarmers or farmers not using herbicides. Increased risk of NHL was specifically associated with use of phenoxy herbicides, especially 2,4-D, which is widely used in field crop production in Kansas. Exposure to phenoxy herbicides has been linked to increased risks of NHL, Hodgkin's lymphoma, and soft-tissue sarcoma in a number of other studies (Hardell & Sandstrom, 1979; Hardell *et al.*, 1981; Blair, 1990), although reviews of the subject have concluded that no consistent cause-and-effect pattern exists (Smith & Bates, 1989; Ibrahim *et al.*, 1991).

In addition to concerns about possible links to various cancers, concerns also exist about potential effects of herbicide exposure on other aspects of human health. Repetto & Baliga (1996, pp. 17–49) noted that three widely used herbicides – atrazine, 2,4-D, and paraquat – are immunotoxic to laboratory animals whose immune systems are similar to that of humans, and they suggested that exposure to these and other pesticides may increase human susceptibility to infectious diseases and certain types of cancer because of immune system suppression. They noted, however, that the epidemiological studies necessary to test that hypothesis have not been conducted. The herbicides alachlor, atrazine, 2,4-D, metribuzin, and trifluralin have been identified as potentially disruptive to the human endocrine system (Colborn, vom Saal & Soto, 1993), but how actual exposure through agricultural use affects endocrine function is unknown. Public health data from Minnesota suggest that exposure to 2,4-D and MCPA significantly increased the rate of birth defects in offspring of pesticide applicators and members of the general population in areas with high application rates (Garry *et al.*, 1996). However, exposure to 2,4-D and MCPA was confounded with exposure to a number of fungicides, making it impossible to draw firm conclusions about the reproductive system effects of specific compounds.

Because manipulative experiments with human subjects and possible toxins are unethical, uncertainty about the chronic health effects of herbicides will continue. How should this uncertainty be dealt with? Many proponents of herbicide use do not find available data sufficiently compelling to assume that herbicides pose important human health risks. Opponents believe there is adequate evidence that they do, particularly in developing countries. We suggest that it is prudent to err on the side of safety by minimizing herbicide exposure and toxicity. Greater safety could be obtained by producing and distributing superior application and protective equipment, and by developing new herbicides whose chemistries limit their persistence, mobility, and toxicity to nontarget organisms, including people. The development of effective nonchemical weed management strategies would address the problem at its source and is the focus of this book.

Weed management and farm profitability

An additional factor motivating the development of ecologically based weed management strategies is the need to increase farm profitability. In both industrialized and developing countries, the economic viability of many farmers has been challenged as input costs rise faster than the market values of the crops they produce. Weed management strategies that make better use of ecological processes may improve profitability by reducing production costs and helping farmers produce crops and livestock that are worth more in the marketplace.

The cost–price squeeze

The cost–price squeeze confronting farmers in the USA is exemplified by the maize–soybean cropping system used in much of Iowa, where a total of 9.3 million ha was planted with the two crops in 1998 (United States Department of Agriculture, 1999*c*). Average yields of maize and soybean in Iowa rose 28% and 24%, respectively, from 1972–80 to 1990–98 (Figure 1.5a). For those same periods, average non-land production costs in constant dollars fell 37% for maize and 31% for soybean (Figure 1.5b). Costs for maize and soybean herbicides, in constant dollars, decreased 9% and 13%, respectively.

Increases in yields and reductions in production costs would seem to bode well for profitability, but prices fell precipitously for both crops. Between 1972–80 and 1990–98, the average price of a metric ton of maize, in constant dollars, decreased 60%; soybean price dropped 62% (Figure 1.5c). Consequently, gross returns declined 47% for maize and 52% for soybean (Figure 1.5d). Returns over non-land costs also declined sharply. For maize, average returns in constant dollars dropped from $396 per hectare in 1972–80 to $153 per hectare in 1990–98, a 61% decline; for soybean, average returns dropped from $530 to $182 per hectare, a 66% decline (Figure 1.5e).

For many Iowa farmers, reductions in returns per unit of cropland have reinforced the importance of herbicides within the production process. Herbicides accounted for 7% of non-land production costs for maize in 1972–80, but 11% in 1990–98; for soybean, the proportion of non-land costs spent on herbicides rose from 12% to 15% (Figure 1.5f). As discussed in Chapter 11, these increases reflect, in part, the greater land area farmers must harvest to maintain farm-derived income, the shift toward hired applications of agricultural chemicals to cover more hectares, and the limited time available for weed management and other farming activities when farmers add nonfarm jobs to their existing responsibilities.

A cost–price squeeze also confronts farmers in developing countries. Beets

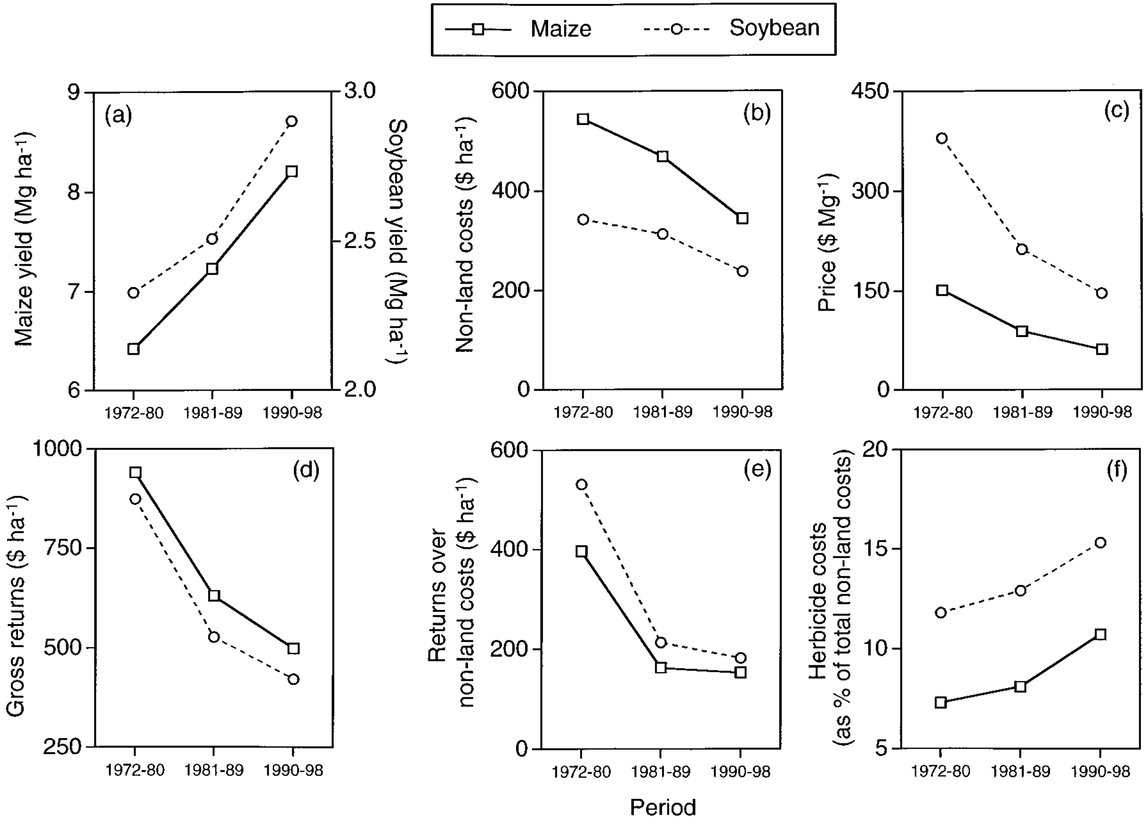

Figure 1.5 Economic characteristics of maize and soybean production in Iowa, 1972–98: (a) yields, (b) non-land production costs, (c) prices, (d) gross returns, (e) returns above non-land production costs, and (f) herbicide costs as percentages of total non-land production costs. Prices, costs, and returns have been adjusted for inflation using the Consumer Price Index of the US Bureau of Labor Statistics (base period: 1982–4). Production costs are for machinery, seeds, pesticides, fertilizers, and labor. Gross returns have been calculated as the product of state average yields (Mg ha^{-1}) and prices ($ Mg^{-1}). Sources: Duffy & Vontalge (1998 and previous years), and M. D. Duffy, Iowa State University, personal communication (2000).