Chapter 13
Strategies for Reduced Herbicide Use in Integrated Pest Management

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Contents

Abstract The persistence of weeds in crop production systems leads to significant yield reductions, diminishing profitability, and ultimately translating to higher consumer prices. Chemical weed control has proven to be an economical and cost-effective method to manage weeds in agricultural settings. While herbicides are considered to be valuable tools in pest management, they account for about two-thirds of the total pesticide use in the United States. As the number of hectares planted under row crops is on the rise, management of weeds, especially herbicide-resistant weed biotypes, in cropping systems is increasingly important. Current weed control programs employed in crop production maintain the fields mostly weed-free during

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D. Pimentel, R. Peshin (eds.), *Integrated Pest Management*,
DOI 10.1007/978-94-007-7796-5_13,

the growing season. Managing the flora of such vast expanses of land under high selection-pressure is somewhat unprecedented given the long history of agriculture, and is worthy of scientific inquiry. In response to health and environmental concerns, scientists are exploring new methods to apply herbicides that could reduce the amount of herbicides used. This chapter explores several strategies to reduce herbicide inputs in crop production systems. Strategies such as banding herbicides, precision application, cultural methods, and novel mechanical and biological methods are discussed.

Keywords Integrated weed management · Weed control · Sustainable agriculture · Reduced pesticide use · Non-chemical weed control · Herbicide mitigation · Floral biodiversity · Cultural weed control · Mechanical weed control · Biological weed control · Herbicide application timing · Herbicide banding

List of Abbreviations

USDA-ERS	United States Department of Agriculture-Economic Research Service
NASS	National Agricultural Statistics Service
GE-Crops	Genetically Engineered Crops
IPM	Integrated Pest Management
PRE	Pre-emergence (herbicide)
POST	Post-emergence (herbicide)
VRT	Variable Rate Technology

13.1 Introduction

Services provided by vascular plants to the ecosystems are affected by reductions in floral diversity (Chapin et al. 2000). This phenomenon is to be taken into consideration under the assumption that the dynamic nature of ecosystems, as an ideal environment for life to thrive on the planet, tends to remain somewhat static in the human mind. In this context, it could be recalled that biodiversity is a process that evolves continually i.e., the existing levels of biodiversity are simply a snapshot of continual change that occurs through time and space. Natural and manmade causes may bring about such changes (Thuiller 2007). The relative rate at which such changes have occurred may have varied historically. The question that behooves our attention, however, is whether such changes are occurring at an accelerated rate and how this rate of change could be mitigated. Assuming that the static nature of this dynamicity is the ultimate goal, certain well-characterized changes to human activities may be necessary. If so, a practical option is to identify practices that have the potential to cause significant impacts referenced above and delineate well characterized mitigation efforts. Such efforts may include changes in weed management practices in agricultural systems as we attempt to increase efficiency in producing food, fiber, and of late, energy. This chapter attempts to examine possibilities to reduce our overall dependence on herbicides for weed management and understand the benefits as a result of doing so.

13.2 Herbicides: A Valuable yet Controversial Tool in Modern Crop Production

As plants ‘growing out of place’ and competing with crops for resources, weeds are managed to maintain and enhance crop productivity. On the other hand, as ‘plants whose virtues are not well-understood’, weeds may provide indirect albeit important services to ecosystems. One of the primary goals of weed scientists is to contribute towards a safe, secure, and abundant supply of food to meet the growing human demands. Based on a global review on crop losses to agricultural pests, weeds are considered to cause the highest potential yield losses with moderate estimates of 34 % (Oerke 2006). Total crop-losses could occur in fields infested by weeds coupled with other forms of stress (Ross and Lembi 2008).

In some instances, certain adverse crop responses may be the result of an interaction of herbicides with plant physiology. Oka and Pimentel (1976) documented increased levels of European corn borer (*Ostrinia nubilalis*) and southern corn leaf blight (caused by *Cochliobolus heterostrophus*) in corn (*Zea mays*) treated with 2,4-D (2,4-dichlorophenoxyacetic acid). They attributed these differences to higher levels of proteins in corn treated with 2,4-D, compared to untreated corn. Altman and Campbell (1977) presented a review of herbicides that can interact with crop plants and noted that a few commonly used herbicides such as 2,4-D, mecoprop, metribuzin, simazine, and trifluralin may predispose plants to disease pathogens upon exposure. The herbicides affected physiological processes of the crop such as wax formation and growth regulation, and certain metabolic pathways.

Doubtlessly, herbicides are a boon for farmers not only to keep production costs down but also to accommodate other cultural practices such as conservation tillage, crop rotation, efficient harvest, and as an integrated approach to manage cover crops, insects, and diseases. Apart from weed management in food and fiber production, herbicides now play a dominant role in managing weeds in biofuel production, turf and ornamentals, vegetation management and restoration in non-crop areas, aquatic systems, and woodlots for management of invasive weeds. While modern herbicides may pose minimal risks to the environment and human health, their indirect impacts on floral biodiversity, carbon sequestration, habitat for other living organisms, soil and nutrient run-off from cultivated fields are worth closer examination. Several effective herbicides are losing efficacy due to buildup of resistant weed biotypes. Judicious use of herbicides will help maintain their continued availability as a valuable tool in food production.

13.3 Historical Perspective

Weed science is considered an old art, yet a young science (Timmons 1970). Details of primitive tools used to control weeds remain sketchy. Drawings from 6000 B.C. show a ‘Y’-shaped portion of a tree with a bronze tip similar to hoe or mattock but its use is unclear (Gittins 1959). In his classic book Horse Hoeing Husbandry, Jethro

Tull (1762) described the benefits of using a horse-drawn hoe to cultivate row-crops for weeds. More efficient mechanical tools were developed to control weeds during the 19th century and early 20th century.

Sodium chloride was perhaps he first chemical used to control weeds. Accounts of common salts used by Romans to kill bushes were mentioned in early recorded history (Ashton and Monaco 1991). In agriculture, chemicals were initially used to control plant diseases and insect pests prior to their use to control weeds (Anonymous 1958). Common salt was also documented to control orange hawkweed (*Hieracitum aurantiacium* L.) in 1896 (Jones and Orton 1896). Other chemicals such as copper sulfate, iron sulfate, and sulfuric acid were documented for their weed control attributes shortly thereafter (Bolley 1901; Anonymous 1907; Groh 1922). Apart from these compounds, various persistent chemicals such as arsenicals, chlorates and borates were used for weed control in the early 20th century (Wunderlich 1961; Ross and Lembi 2008).

The advent of modern weed control began with the discovery of 2,4-D in 1941 followed by the discovery of other compounds such as silvex, 2,4,5-T, amitrole, diuron and monuron in the 1950s. Several effective herbicides such as atrazine, ETPC, alachlor, trifluralin, and paraquat were subsequently developed and proved successful in controlling weeds in a broad range of crops. More than 75 herbicides were synthesized in the following two decades, a three-fold increase to the number of herbicides known till then (Timmons 1970). The area of land treated with herbicides in the United States also witnessed an exponential growth to 48.6 million hectares during this period. Glyphosate, introduced in early 1970s, was considered to be an 'ideal' herbicide resulting in its worldwide adoption in the subsequent decades. The 1980s also witnessed a reduction in soil erosion in the U.S. as a result of conservation tillage practices owing to herbicide use. This period also witnessed the introduction of several new classes of selective herbicides such as acetyl CoA carboxylase inhibitors, protoporphyrinogen inhibitors, diphenylethers and acetolactate synthase inhibitors. As the demand for food and fiber increased along with simultaneous advances in science and technology, chemical weed control became a mainstay to manage weeds in various crop production systems.

13.4 Herbicide Use Pattern in the United States

An examination of herbicide use patterns in the United States from 1980 to 2007 reveals that about 48 % of pesticide active ingredients used by agricultural producers were herbicides, which fluctuated (±4 %) but remained steady otherwise (USDA-ERS 2012). The total amount of herbicide used decreased by 12 % during this period from 504 to 442 million pounds. It should be noted however that drastic reductions were noted since the mid-1980s. This could be attributed to new classes of herbicides especially the sulfonyl ureas and the imidazolinones, effective at extremely low use rates.

Based on publicly available USDA data, Benbrook (2012), however, projected an increase of 527 million pounds of herbicide use in the U.S between 1996 and

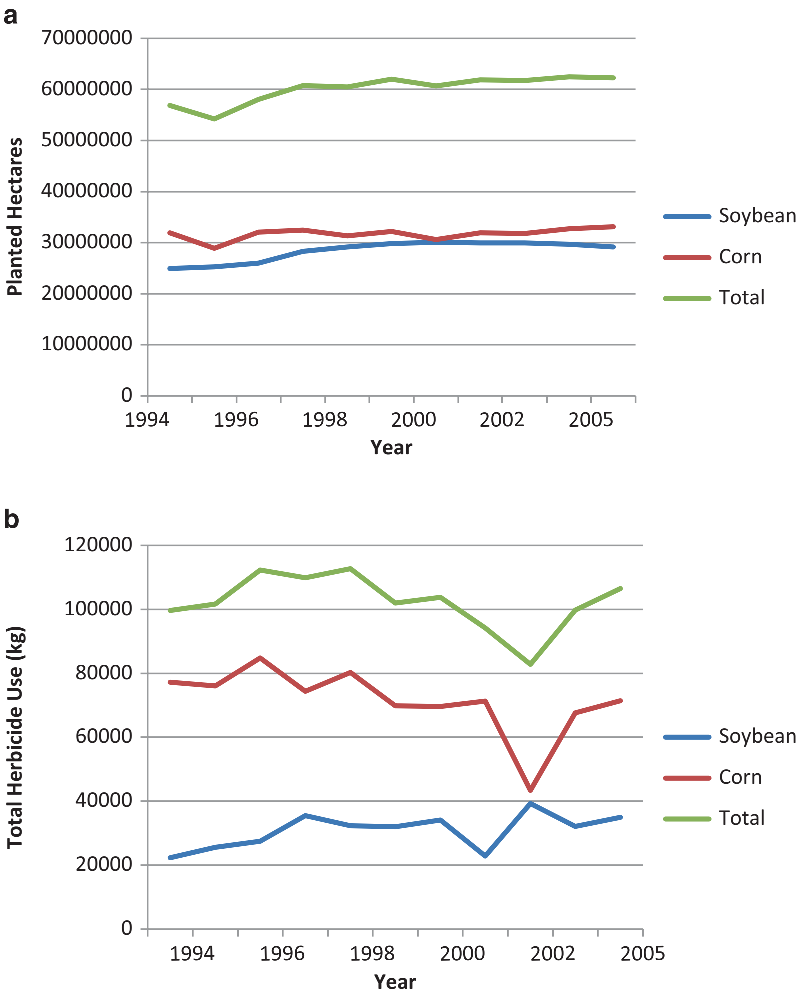

Fig. 13.1 **a**) Area planted to corn and soybean in the United States (*above*) **b**) compared to total herbicide use (*below*) prior to and after the introduction of genetically engineered crops

2011 as a result of weed management practices in herbicide-resistant crops. This was attributed primarily to the increased reliance on glyphosate in such crops. Benbrook also projected a two-fold rate of increase (2.7 % per year) in glyphosate use in soybeans resistant to glyphosate, per year from 2006 to 2011, compared to 1.3 % rate of increase in glyphosate use in conventional soybeans during the same period. The author also warned that such a trend could cause additional increases in herbicide use by approximately 50 % if herbicide resistant crops capable of tolerating growth-regulator herbicides are introduced into the market. In the United States, despite modest increases in area planted to corn and soybean, herbicide use in these crops began to rise since 2002 after a long-term decline (Fig. 13.1a, b).

Until the advent of glyphosate-tolerant soybean, less than 3 million kg of glyphosate was used in soybean production (Young 2006). By 2002, 30 million kg of glyphosate was used in soybean alone reducing the number of sites of action from seven to essentially one. The primary shift was from imidazolinone and dinitroanaline herbicides to glyphosate during this period. A similar trend was noted in cotton during the same period. Atrazine continued to dominate as the primary herbicide in corn as a cost-effective, broad-spectrum herbicide although glyphosate-resistant corn was introduced in 1998. However, by 2010, total glyphosate use exceeded that of atrazine by 2.9 million kg in corn (atrazine use in corn during 2010 was 23.3 million kg). Unlike soybean, at least three sites of action are still employed in corn production (USDA-NASS 2012). Due to increased adoption rates of glyphosate resistant crops and the availability of generic formulations of glyphosate in the market, the overall expenditure by U.S. agricultural producers of herbicides fell by 23 % between 2000 and 2007. Interestingly, Mortensen et al. (2012) pointed out that “agricultural weed management has become entrenched in a single tactic– herbicide resistant crops” as the ultimate result of such a trend.

13.5 Role of GE Crops in Weed Management

One of the most significant advances in agriculture towards the end of 20th century was the introduction of genetically engineered crops (GE crops). Genetically engineered crops have simplified weed management methods in most major field crops (Reddy and Koger 2006). Farmers in the United States have rapidly adopted GE crops that resist herbicides ever since their inception in the mid-1990s. The concomitant engagement of a narrow spectrum of herbicides in major crops resulted in an exponential increase in the use of otherwise benign pesticides such as glyphosate. The use of pesticides with benign attributes has increased to extremes that resulted in the engagement of a narrow spectrum of herbicides in major crops. A few applications of such herbicides can effectively control a broad spectrum of weeds causing no phytotoxic effect to the crop (Fig. 13.2). Farmers embraced this new tool not only based on simplicity but also based on cost-effectiveness.

Speculations were made by the scientific community about genetically engineered crops as a plausible tool in integrated pest management (IPM) and the resultant reduction in pesticide use. In the prevention, avoidance, monitoring, suppression (PAMS) strategy of IPM, use of GE crops was considered to fit under ‘avoidance’, where crops may be selected based on their genetic resistance to pests (North Central IPM Center 2010). Although such traits pertain more to insect pests and diseases, it may be applicable to weeds indirectly where GE crops that resist herbicides utilize such traits to attain selective weed control.

Today, GE crops capable of resisting glyphosate, glufosinate, bromoxynil, imidazolinone herbicides, and sethoxydim are used in major field crops such as corn, soybean, cotton and canola. Other crops such as alfalfa and sugarbeet have also been genetically engineered to resist glyphosate. However, biotypes of glyphosate-resistant weeds are reported to have increased exponentially since 2004 (Heap

Fig. 13.2 Progression of phytotoxicity symptoms in weeds following application of glyphosate (1.12 kg ai/ha) in alfalfa (*Medicago sativa*) genetically-modified to resist glyphosate

2012). Herbicide-resistant weed biotypes, especially those in row crops, continue to make headlines in weed management. Lately, biotypes of certain weeds—including Palmer amaranth (*Amaranthus palmeri*), water hemp (*Amaranthus rudis*), common and giant ragweed (*Ambrosia spp.*), horseweed/marestail (*Conyza candensis*), and johnsongrass (*Sorghum halepense*)—have been reported to be resistant to glyphosate in various parts of USA.

This technology continues to generate public interest as well as controversy. Scientific evidence to validate harmful health effects is yet to be documented (recently, a study demonstrated higher incidence of tumors in rats fed genetically engineered corn over a two year period, compared with those fed conventional corn during the same period, however, these findings have been refuted by the scientific community at the time of preparing this manuscript) (Séralini et al. 2012). Regardless, overdependence on this technology and related indirect effects on cropping systems and the ecosystem appear to be primary concerns among scientists. Conscientious use of this otherwise effective tool in the IPM toolbox will ensure its continued availability. Management practices to avoid the buildup of resistant biotypes of weeds will also ensure that such cost-effective herbicides remain available.

A minor problem encountered in row crops dedicated to the same crop or rotated to different crops capable of resisting the same herbicide is the periodic occurrence of volunteer plants from the previous crop interfering with the current crop. Management of such volunteers often requires broadcast application of otherwise unnecessary pre-emergence herbicides or spot treatment with limited options of post-emergence herbicides.

13.6 Public Perception

Herbicide use patterns and the buildup of herbicide-resistant weed biotypes since the advent of GE crops are alarming since the outcome has been contrary to expectations. Gasser and Fraley (1989), while explaining the benefits of genetic engineering tools to improve crops, had predicted that a shift in herbicide use towards more safe and environmentally benign chemicals, as opposed to an increase in overall use of herbicides, would be the driving force for the development of traits to resist herbicides. They also noted that the impact of GE crops would also be determined by factors including public perception. Goldburg (1992) recommended that public funds not be used to carry out research to develop herbicide-tolerant crops and that herbicide-tolerant crops should be regulated by governmental agencies especially if they pose a risk to human health and the environment. While there is a gap between “scientific truth” and “public perception”, it is critical to base important policy and regulatory decisions on sound knowledge. Generation of such information has not kept pace with technological advances over the past two decades. Long-term studies to determine various indirect effects of such innovative strategies will help us gain a better understanding. Until we have sufficient knowledge, such decisions may have to be made conservatively.

13.7 Biology of Weeds and Relative Susceptibilities

A sound understanding of the biology of weeds, their life-cycles, and their relative periods of susceptibility is essential to delineate effective control options and to optimize herbicide use. Weeds compete with crops during the crops’ active growth phase whether the crop is annual or perennial by nature. If the demand for resources coincides with the crops’ active growth phase, weed competition could significantly affect crop yields. Application timing of herbicide relative to the weed life-cycle/growth stage means applying the herbicide at the proper time of the year or crop stage is critical to maximize efficiency. A few common misapplications include applying pre-mergence herbicides after weed emergence without a post-emergence herbicide, applying systemic herbicides to actively growing annual weeds intensifying selection pressure or contact herbicides to manage perennial weeds, or systemic herbicides being applied during the time of the year when preferential flow of sugars is acropetal resulting in poor translocation to the below-ground vegetative parts. Herbicides are applied occasionally when the weeds have surpassed their competitive stage.

Substantial research has been carried out to optimize herbicide use. A summary of relevant literature related to herbicide application timings as they affect weed control is presented in Table 13.1. Certain general conclusions can be made based on these research findings. Annual weeds were most susceptible to herbicides earlier on during the growing season when weeds were young and actively growing. Systemic herbicides were usually effective to control perennial weeds as they become mature. The competitive phase often coincided with the maximum period of growth of crops in most instances. Control of weeds during this window was found to be most effective. In soybean, however, late season weed control was also considered to be important (Van Acker et al. 1993).

Table 13.1 Summary of relevant literature to reduce herbicide inputs by following proper application timings for effective weed control

Situation	Herbicide	Strategy	Reference
Grass and broadleaf control in *Zea mays*	Nicosulfuron + bromoxynil	Weed control optimal up to 15-cm weed height. Control and yield affected after 20-cm height	Carey and Kells 1995
Orobanche control in *Trifolium pratense*	Imazamox	Optimal small broomrape control attained when herbicide was applied at 1000 growing degree days (GDD)	Eizenberg et al. 2006
Giant foxtail control in glyphosate-tolerant *Zea mays*	Glyphosate; atrazine and acetochlor	Applying glyphosate after weed was > 15-cm affected yield; applying residual herbicides did not increase corn yield	Gower et al. 2002
Eclipta prostrata, Ipomoea lacunose control in *Arachis hypogaea*	2,4-DB, acifluorfen, bentazon, imazapic, and lactofen,	Early POST (5-cm tall eclipta, and 8-cm long morningglory) herbicide application provided optimal weed control and peanut yields	Grichar 1997
Control of *Amaranthus rudis* in *Glycine max*	Diphenylether herbicides	Application to 5-cm tall weed provided better control compared to that to 10-cm tall weed	Hager et al. 2003
Ligustrum sinense control in forests	Glyphosate and triclopyr	October application of glyphosate provided 100 % control, followed by April application (93 %). Summer applications of glyphosate and fall application timings of triclopyr provided lower control levels	Harrington and Miller 2005
Translocation of herbicides to *Agropyron repens*r hizomes	Glyphosate, sethoxydim, fluazifop, and haloxyfop	Translocation of systemic herbicides to rhizomes was similar during all growth stages	Harker and Dekker 1988
Xanthium strumarium-control in *Zea mays*	Mesotrione	Control highest when herbicide was applied to 3–8 cm tall weeds (3-lf stage of corn)	Johnson et al. 2002
Xanthium strumarium, Chenopodium album, Panicum dichotomiflorum, Setaria faberi, and *Abutillon theophrasti* control in *Zea mays*	Atrazine, metolachlor	Applications made closer to planting time improved weed control and corn yields compared to those made more than 15 d before planting.	Johnson et al. 1997
Microstegium vimineum control in forests	Fenoxaprop-P, imazapic, sethoxydim	Weed control was not affected by early-, mid-, or late-season herbicide application timings.	Judge et al. 2005
Weed control in IMI-tolerant *Oryza sativa*	Imazethapyr	Rice yields were higher from herbicide application timings (PRE and POST) up to 2- to 4-lf stage	Masson et al. 2001
Weed control in glyphosate-tolerant *Zea mays*	Glyphosate	V4 stage of corn considered ideal timing for glyphosate applied once for all weed densities	Myers et al. 2005

Table 13.1 (continued)

Situation	Herbicide	Strategy	Reference
Control of rhizome-Sorghum halepense	Nicosulfuron	Application to johnsongrass with > 5 leaves controlled the weed better than when applied to johnsongrass with < 5 leaves	Obrigawitch et al. 1990
Sorghum halepense and *Ipomoea lacunosa* control in *Glycine max*	Imazethapyr and Fluazifop	Both weeds better controlled by imazethapyr at 15-cm stage of johnsongrass. Fluazifop controlled johnsongrass up to 60-cm	Shaw et al. 1990
Control of the perennial weed *Brunnichia ovata*	Clopyralid, dicamba, glyphosate	Early October application timing found to provide highest weed control	Shaw and Mack 1991
Avena fatua control in spring *Hordeum vulgare*	Imazamethabenz	Barley yield was higher when herbicide was applied 1 wk after emergence compared to 2 and 3 wks	Stougaard et al. 1997
Control of annual grasses in *Zea mays*	Nicosulfuron	Application at 5–10 cm height of annual grasses provided similar or higher yields compared to application of PRE herbicides	Tapia et al. 1997
Killing *Vicia villosa* cover crop prior to planting no-till *Zea mays*	Burndown herbicides	Killing the cover crop before planting the crop optimized crop yield	Teasdale and Shirley 1998
Early POST vs. Late POST application of systemic non-selective herbicides in *Zea mays*	Glufosinate and glyphosate	Herbicide application 28 d after planting resulted in better weed control compared to that 35 d after planting.	Tharp and Kells 1999
Critical periods for weed control in *Glycine max*	Residual and POST herbicides	Weed control up to fourth node stage of soybean necessary to prevent yield loss; subsequent weed removal necessary from bloom to seed stage	Van Acker et al. 1993
Control of the perennial weeds—*Rubus* sp., *Lonicera japonica, Toxicodendron radicans,* and *Lespedeza cuneata*	Glyphosate	Optimal timings for control were: blackberry—mid-June to August; Japanese honeysuckle—August; poison-ivy—mid June to mid-August; sericea lespedeza—flowering time	Yonce and Skroch 1989

13.8 Spatial Dynamics and Weed Management

13.8.1 Plants Growing Out of Place

Weeds are typically considered as "plants growing out of place". This definition takes into consideration its role as a pest that interferes with human activities including agriculture. Conventionally, agricultural systems are intensively managed to maximize productivity of crops. In such systems the tolerance level of weeds is close to “zero” based on the above definition. Due to the high competitive and reproductive characteristics of weeds, farmers make all possible efforts to minimize their incidence and subsequent infestations in crop fields. In field crops, for instance, a mixture of three or four herbicides is typically applied to obtain a broad spectrum of weed control, and to manage the development of resistant weed biotypes (Hagood et al. 2010).

Radosevich (1987) examined the interactions between crops and weeds and determined factors such as plant density, species proportion, and spatial arrangement to play roles in competition. He noted that competition be considered based on plant proximity responses as determined by germination, growth, and reproductive characteristics of individual species rather than inherent differences in fitness. Soybean yield was affected by common cocklebur, Palmer amaranth growing only within 12.5 cm of the crop, and by tall morningglory growing within 25 cm of the crop (Monks and Oliver 1988). In their study, the proximity of johnsongrass and sicklepod did not affect soybean yield. Weed competition based on spatial arrangement of weeds with respect to crops have also been referred to as “area of influence” or “zone of exploitation” by researchers. These areas or zones may also be affected by weed canopy diameter (Wilkerson et al. 1989). Besides, tall-growing weeds such as common cocklebur (*Xantbium strumarium*), velvetleaf (*Abutilon theophrasti*), and jimsonweed (*Datura stramonium*) can successfully compete with shorter crops such as soybean for light with densities of 0.7 to 2.5 plants/m^2 causing yield reductions of 12 to 51 % (Stoller and Woolley 1985).

A broader understanding of competitive zones of weeds will be of immense value to delineate site-specific weed management programs. Currently, we have a general understanding of the competitive nature of common weeds based on their ability to reduce yields, produce seeds, allelopathic attributes, etc. (Ross and Lembi 2008). Additional information on areas of influence of specific weeds will also be useful for targeted application of herbicides based on their prevalence and crop row spacing. Crop row spacing also plays a critical role in the ability of weeds to compete. Based on a mathematical model, crop plants grown in a square lattice, when all other factors are kept constant, provided optimal weed suppression (Fischer and Miles 1973).

13.8.2 Plants with Unknown Virtues

A weed is also known to many as “a plant whose virtues have not yet been discovered” (Blatchley 1912); or “considering all weeds as bad is nonsensical” (Cocannouer 1950); or “weeds have always been condemned without a fair trial” (King 1951). The relationship between weeds and crops growing side by side, and their mutual roles in the overall fabric of the ecosystem is complex and not well understood. In agricultural systems, crops are plants selected for survival whereas weeds are their cousins displaced gradually in the process. The role of weeds in improving soil quality and fertility, managing populations of herbivorous arthropod pests and their natural enemies, as self-sowing cover crops, as agents of biological tillage, as having edible value, as having an indirect role in plant breeding etc., have been described by Jordan and Vatovec (2004). The value of weeds as medicinal plants is yet another promising discipline worthy of renewed interest and due consideration.

Effective weed control methods developed in the recent decades, capable of managing the flora of large expanses of land are somewhat unprecedented given the long history of crop production. Harlan (1965) explained that weeds have served as reservoirs of germplasm and have periodically "injected portions of it" into crops to favor variability, herterozygosity and heterosis. According to the author, a biological significance exists between cultivated plants and their wild biotypes (weeds) and concluded that cultivated plants would never have succeeded without genetic support of their companion weeds. The implications of such phenomena are especially intriguing in the current era of genetically engineered crops where such "injected portions" belong to distantly related species and the two have essentially no survival tactics in common. Under this context, efforts to fill such voids in the literature will compliment current and future efforts to raise crops sustainably.

13.9 Sustainable Weed Management

Given the challenges faced by modern agricultural systems with shrinking levels of labor or human capital as a primary input in production, maintaining sustainability while remaining profitable can be a challenging task. This may apply to all activities related to agricultural production including weed management. This phenomenon can be explained by the bimodal nature of farms in the United States (Duffy 2006). The number of small farms (sales < \$1,000/yr), increased by 37 % during 1997 to 2002, and the number of the large farms (sales > \$1 million/yr), increased by 8 %. The numbers in all other farm size categories decreased during this period. In 2002, the large farms represented 3 % of total US farms but accounted for 61 % of produce sales. In such a situation, technology plays a critical role to maximize productivity and the expectation to shift from chemical to non-chemical methods for pest management could be largely unrealistic. On the other hand, sustainable practices may be more readily adopted in smaller farms where more intensive pest management practices can be carried out.

Wyse (1994) pointed out that weeds are a major deterrent to the development of sustainable agriculture systems since they dictate several crop production practices. He urged weed scientists to become leaders of collaborative integrated approaches to manage weeds in agricultural systems. Several strategies may be considered to manage weeds sustainably in agriculture. Developing cover/smother crops to suppress weeds, crop varieties with enhanced interference potential, biological weed control, and use of technology are a few areas of focus that would benefit from research.

The use of cover crops to manage weeds in agricultural systems continues to grow. Teasdale (1996) emphasized the viability of such crops in sustainable systems because of contributions to soil fertility and improved crop performance. Apart from this, crop residues from annual cover crops provide early-season weed suppression. The author also indicated that cover crops may also serve as living mulches that are effective to control weeds but may require chemical management to reduce competition with the crop.

Temporal and spatial diversification by adopting practices such as crop rotation and intercropping are strategies worthy of consideration to manage weeds in sustainable systems (Liebman and Dyck 1993). In a long-term study that lasted eight years, weed biomasses were recorded in four different rotations, which included two or three crops followed by fallow compared to a single continuous crop of proso millet (Anderson 2006). At the end of the study the weed biomass was 85 % lower in the wheat-millet-fallow rotational sequence compared to continuous proso millet. Carruthers et al. (1998) determined weed control levels comparable to conventional methods by intercropping corn with legumes compared to a monocrop of corn alone.

In an extensive study carried out in the Canadian prairies which spanned 56-site years, fewer perennial and biennial weeds were associated with minimum and zero-tillage compared to conventional tillage (Blackshaw et al. 2006). Several summer annuals were also less common under conservation tillage compared to conventional tillage. Winter annuals which germinated in fall and summer annuals dispersed by wind were higher in conservation tillage compared to conventional tillage. Melander et al. (2005) described the use of thermal and various mechanical devices to manage weeds in row crops in a number of investigations. Improved devices such flamers, harrows, brushes, hoes, torsion weeders, and finger weeders as well as certain novel devices such as robots were also reviewed. The authors indicated that such implements may be effective as an integrated approach to manage weeds that may include other approaches at the cropping systems level.

Sustainable approaches may be more readily applicable in non-crop situations such as turfgrasses, where weeds are primarily of aesthetic concerns. In turfgrasses, providing good growth conditions for the turf can reduce the opportunities for weed infestation (Chandran 2006). A fully functional turf with few weeds can be maintained sustainably. Occasional use of herbicides may be necessary to bring down the weed population to manageable levels prior to initiating or continuing a sustainable weed management program. Maintaining a dense turf with a competitive ability to reduce the emergence and establishment of weeds is perhaps the best strategy to minimize weed infestation in lawns. A good understanding of factors such as soil pH, species and cultivar selection, proper turf establishment, cultural requirements, etc., is essential to manage weeds proactively in turfgrasses. A summary of research findings related to weed management strategies based on reduced use of herbicides in various crops is presented in Table. 13.2.

13.10 Advances in Biological Weed Control

Biological control of weeds, which involves the use of other living organisms, is best regarded as a technique to be used in conjunction with other efforts in integrated weed management systems (Zimdahl 1999). While certain risks such as inconsistent results, possible escape to become a pest as a result of mutations, slow weed control etc., this method is considered to be more sustainable with a high ratio of benefit: cost. This is especially true in the case of managing certain invasive weeds that are widespread and chemical control methods are not feasible. While insects and fungi are the more commonly used biological control agents, fish,

Table 13.2 Summary of relevant literature on reduced herbicide application rates for weed management

Situation	Herbicide	Strategy	Reference
Post-emergence control of *Xanthium strumarium* and *Setaria faberi*, in Glycine max	Acifluorfen, bentazon, chlorimuron, and sethoxydim	Two sequential applications of tank-mixtures at 0.25X labeled rates of first three herbicides applied with sethoxydim (0.5X rate) provided similar weed control and yield as full rate of herbicides applied once	Defelice et al. 1989
Post-emergence control of *Xanthium strumarium*, *Ambrosia trifida*, *Helianthus annus*, *Amaranthus hybridus*, and *Abutilon theophrasti* in Glycine max	Acifluorfen, bentazon, and chlorimuron	Application of herbicides at 0.5X rate at 2 wk after planting controlled weeds similar to that of standard rate at 4 wk after planting; in some cases 0.25X rate provided similar results	Devlin et al. 1991
Pre-emergence weed control in Zea mays	Atrazine	Banding herbicide along with mechanical weeding as effective as broadcast application; reduced herbicide by 73 % and quantified lower atrazine residues in soil	Heydel et al. 1999
Early season weed control in Glycine max	Acifluorfen, bentazon, chlorimuron, and imazaquin	Reduced rates of herbicides provided 90 % weed control when applied 6–12 d after weed emergence	King and Oliver 1992
Pre-emergence weed control in Zea mays	Atrazine and metolachlor	Herbicide use was reduced by 50 to 75 % with minimal loss of corn yield or weed control by integrating mechanical control and banded application of herbicides	Mudler and Doll 1993
Broadleaf weed control in Glycine max	Bentazon, chlorimuron, imazaquin, imazethapyr	Single and sequential application of herbicides at reduced rates did not affect yield compared to full rates	Steckel et al. 1990

aquatic mammals, and vertebrates have also been effectively used to control weeds. The United States, Australia, South Africa, Canada, and New Zealand use biological agents to control weeds the most in natural ecosystems (McFadyen 1998). An updated list of invasive weeds in North America and potential biological control agents is provided in Table 13.3.

13.11 Technology in Weed Management

Herbicide application technology has improved considerably in recent years. Variable-rate technology (VRT) although used widely for fertilizer applications, has not yet been adopted widely for herbicide application. Variability in weed spectrum,

Table 13.3 Recently reported biological control agents with potential to control certain invasive weeds in North America

Weed/s	Potential biological control agent	Reference
Lythrum salicaria (purple loosestrife)	*Galerucella calmariensis* and *G. pusilla*	Blossey et al. 2001
Cirsium arvense (Canada thistle)	*Ceutorhynchus litura*	Collier et al. 2007
Persicaria perfoliata (mile-a-minute)	*Rhinoncomimus latipes*	Colpetzer et al. 2004
Tamarix spp. (salt cedar)	*Diorhabda elongata* Brulle *deserticola* Chen	DeLoach et al. 2003
Ailanthus altissima (tree-of-heaven)	*Eucryptorrhynchus brandti*	Ding et al. 2006
Microstegium vimineum (Japanese stiltgrass)	*Bipolaris* sp.	Kleczewski and Flory 2010
Melaleuca quinquenervia (melaleuca)	*Puccinia psidii*	Rayachhetry et al. 2001
Fallopia japonica (Japanese knotweed)	*Aphalara itadori* Shinji	Shaw et al. 2009
Phragmites australis (common reed)	*Rhizedra lutosa, Phragmataecia castaneae,* *Chilo phragmitella, Schoenobius gigantella.* *Archanara, Arenostola* and *Platycephala planifrons*	Tewksbury et al. 2002
Fallopia japonica (Japanese knotweed)	*Gallerucida bifasciata*	Wang et al. 2008

seed bank, age, and spatial distribution of emerged weeds in the field are some of the barriers to be overcome for this otherwise promising technology. In a field study to test the effectiveness of VRT in soybeans involving three herbicides rates (100, 67 and 33 % use rates), the medium rate provided weed control similar to that of the full rate (Thorp and Tian 2004) while the 33 % rate failed to provide acceptable levels of weed control. To overcome the difficulty associated with weed distribution differences, Dammer and Wartenberg (2007) designed a sprayer capable of applying variable rates of herbicides by detecting weeds using a sensor. In 13 field trails carried out in cereals and peas an average of 25 % herbicide reduction was achieved without causing any crop yield reduction.

Slaughter et al. (2008) reviewed the status of using autonomous robots to control weeds and concluded that detection and identification of weeds under a wide range of conditions was the greatest challenge in agricultural situations. However, the authors indicated that there is potential for adopting this technology in the field. The authors presented concept diagrams of futuristic robots fitted with multiple cameras on mobile robotic arms to allow multiple views of each plant. Devices with onboard electronics and herbicide reservoirs would be used to discriminate weeds from crops and to manage them. Similar devices are being field-tested and developed for crop-thinning and mechanical weed control by Blue River Technology, California, USA (Fig. 13.3a). It is envisioned that autonomous robots capable of performing such tasks will play a significant role in weed management in the future (Fig. 13.3b).

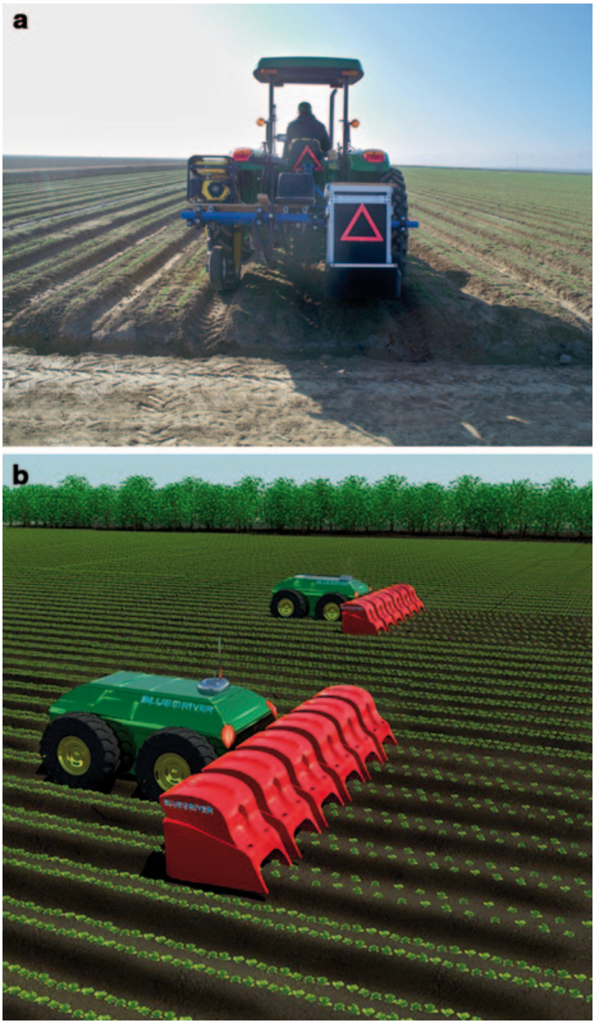

Fig. 13.3 **a** Field-testing of a prototype equipment developed by Blue River Technology, CA, USA, capable of mechanically thinning crops or rouging weeds (*top*); **b** a futuristic vision of autonomous robots performing such tasks (*bottom*). *Photo credit: J. Heraud*

13.12 Herbicide Use Reduction in Agronomic Crops

Among various crops in the United States, agronomic crops have historically ranked first in total amount of active herbicide ingredients used. Roughly 75 % of total herbicide use in the U.S. was in corn and soybean in 1990 (Zoschke 1994). This trend continues today for the relative amounts of herbicide use in agronomic crops compared to other crops such as horticultural crops, turf and ornamentals, aquatic and other non-crop areas. Significant reductions in herbicide use could be accomplished by identifying areas within agronomic crops where herbicide use reductions could be implemented. The strategy discussed below may have significant implications in reducing overall herbicide use.

13.12.1 Banded Herbicide Application—Herbicide Use Reduction in Corn.

In the United States, about 37 million hectares (92 million acres) were dedicated to corn production in 2011, generating revenue of $2,052/ha ($831/acre) (USDA-NASS 2011). About 98 % of US corn acreage in 2011 received herbicide application. The herbicide atrazine was applied to 61 % of the hectares, averaging 1.15 kg atrazine per hectare (1.03 lb/A). While the ecological attributes of atrazine are under public scrutiny (Hayes et al. 2002), this herbicide is a cost-effective weed management tool for corn producers (Williams et al. 2010). Measures to mitigate its use while optimizing its effectiveness may ensure the continued availability of this broad-spectrum pre-emergence herbicide.

Corn is most vulnerable to weed competition during the 3- to 14-leaf stage (Hall et al. 1992), which typically coincides with the first six weeks of crop growth or until canopy closure. Corn grown for grain, silage, or ethanol may be able to tolerate different levels of weed competition. Current weed control programs in corn typically provide close to 100 % weed control. The conventional weed management practice in corn is the application of a mixture of pre-emergence herbicides, which typically includes atrazine, along with a non-selective post-emergence herbicide, as a broadcast treatment. This practice keeps vast expanses of land under corn hectarage, more or less as a monoculture. Reduced biodiversity, reduced soil cover, habitat loss, decline of beneficial insects, increased nutrient and pesticide runoff, and reduced carbon sequestration are few of the drawbacks associated with this practice. Providing limited space for weeds to co-exist with the crop without affecting crop yields may also reduce selection pressure and the resultant development of herbicide-resistant weed biotypes.

Buildup of the weed seed bank and resultant yield losses due to weed competition are presumed risks that deter growers from adopting this practice. Burnside et al. (1986; p. 248) questioned “As farmers reduce the weed seed bank in soils, can they reduce their weed control expenditures without adversely affecting crop yields?” and indicated that “These and other questions will occupy considerable time of weed scientists in the future”. In their 6-yr long experiment, it was determined that viable weed seed levels in the soil declined 95 % during a 5-yr period during which weed seed production was eliminated by providing total weed control. However, the weed seed buildup recovered to > 90 % level when weeds were left unmanaged during the 6th year, at two out of five locations. In the remaining three locations, the weed seed buildup during the 6th year in untreated plots was similar to that in treated plots. They also determined that corn-yields were unchanged during the 6th year with minimum weed management.

Literature on the effect of banding herbicides on corn yield is limited and is restricted to older classes of herbicides. Uremis et al. (2004) determined that banding was as effective as broadcast application. In their study, different bandwidths gave similar levels of weed control and corn yield, and noted that banding decreased herbicide use by up to 78 %. In a Missouri study, Donald et al. (2004) determined that banding herbicides reduced application rates by 53 % when averaged over three years and that significant yield reductions were not seen compared to broadcast application of the same herbicides. Hansen et al. (2000) compared broadcast and banded application of a tank-mixture of PRE herbicides in tilled corn. They noted reduced levels of nutrient runoff as a result of ground cover provided by weeds in banded treatments compared to that from broadcast applications. No yield differences were recorded between broadcast and banded application of herbicides in this study also. In a study to compare atrazine leaching following broadcast or banded applications in corn, Heydel et al. (1999) quantified reduced levels of atrazine residues in the soil associated with banded applications without affecting corn yields.

Field experiments were conducted by the author at three locations in West Virginia to compare banded and broadcast applications of pre-emergence herbicides on corn yield and weed biodiversity levels, from 2009 to 2011. The objective of this research was to determine the effect of banding newer classes of pre-emergence herbicide mixtures containing atrazine on corn yield compared to conventional broadcast application of the same at grower level locations to simulate field conditions. The floral biodiversity at one location was also monitored. Corn rows, planted 75 cm apart, were treated with a pre-emergence mixture of atrazine, metolachlor, and mesotrione at 1.702, 1.702, and 0.220 kg ai/ha applied either broadcast or in bands of width 38 cm over 10- to 20-cm tall corn. Corn yield was estimated after determining its moisture content. All data were subjected to analysis of variance (ANOVA) and means were separated using LSD ($P=0.05$). Floral biodiversity levels were calculated using Shannon's Index.

Banded application resulted in 50% reduction of atrazine, metolachlor, and mesotrione, respectively, on a per-hectare basis, compared to broadcast application (Table 13.4). Yield data indicated no significant differences between plots that received banded and broadcast treatments (Table 13.5). Excellent (>95%) weed control was observed within band- or broadcast-treated areas until canopy closure. When the yield data from the four studies were combined, statistical differences could not be determined (Fig. 13.4a, b). Shannon's Index for Biodiversity analysis generated H values >1.5 which were considered to be biologically-diverse (Chandran et al. 2011). Banded application allowed for natural populations of weeds to establish between corn-rows. Broadcast application of herbicides kept the entire cornfields relatively weed-free.

A field-day was organized in 2010 to discuss this practice with growers (WVU Press Release 2010). One of the concerns expressed by growers was the buildup of the weed seed bank if weeds were left uncontrolled in banded fields. The growers requested data from long-term (5-yr) studies under different weed population levels and weather conditions to gain confidence. Future research to determine which years to warrant broadcast or banded application based on weed seed bank analysis will also be considered useful. Harvest weed seed control (HWSC) systems being developed in Australia, where machinery capable of harvesting and destroying weed seeds at the time of grain harvest, holds promise for the widespread implementation of herbicide banding in the future (Walsh et al. 2013).

Our results imply that it may be economically feasible to band-apply herbicides in cornfields that are relatively weed-free as a result of employing good weed control programs over several years. This is because the low weed seed bank may cause

Table 13.4 Use pattern of broadcast and banded applications of herbicides in corn at grower locations

Application [cm (inch)]	Spray Fluid L/ha (gal/acre)	Atrazine	Metolachlor	Mesotrione
		[kg/ha (lb/A)]		
Banded-38 (15.0)	56.77 (15)	0.85 (0.65)	0.85 (0.65)	0.11 (0.04)
Broadcast -76 (30)	113.55 (30)	1.702 (1.3)	1.702 (1.3)	0.22 (0.163)
Control	0	0	0	0

Table 13.5 Corn yield comparisons between banded and broadcast treatments at grower locations in Charles Town (Location 1), Moorefield (Location 2), and Point Pleasant, (Location 3), West Virginia

	Corn Yield				
	Year 2010	Year 2011			
Herbicide application[a]	Location 1	Location 1	Location 2	Location 3	Average
	kg/ha (*bushels/A*)				
Broadcast	6552 (*104*)	6048 (*96*)	10080 (*160*)	7623 (*121*)	7560 (*120*)
Banded	6363 (*101*)	5040 (*80*)	9576 (*152*)	6867 (*109*)	6993 (*111*)
Control	5103 (*81*)	630 (*10*)	5418 (*86*)	6363 (*101*)	4410 (*70*)
LSD ($P=0.05$)	1260 (*20*)	1008 (*16*)	7245 (*115*)	3213 (*51*)	2079 (*33*)

[a] A mixture of atrazine, glyphosate, metolachlor, and mesotrione was applied at 1.702, 1.702, and 0.220 kg ai/ha; banded treatments received half this quantity per hectare.

minimal weed pressure in such fields. However, if the weed seed bank is high, broadcast application may be necessary. In such instances, carrying out a bioassay by collecting representative soil samples from the field and recording viable seeds by transferring them to a greenhouse and testing for germination would be an appropriate decision making tool (Brainard and Bellinder 2004). Simpler methods such as scouting the fields for weeds during the growing season may also help make decisions for the following year. Perhaps, banded applications can be carried out periodically, based on weed pressure, or herbicides such as atrazine that carry higher risks may be applied separately in bands using modified spray equipment with separate tanks for broadcast and band applications. The implication of this strategy to reduce the buildup of herbicide-resistant weed biotypes by reducing selection pressure is worthy of further investigation. If deemed to be an effective strategy, it could be adopted as a practice to manage herbicide resistance for newer classes of herbicides and in regions where resistant populations are not present currently.

13.12.2 Horticultural Crops

As discussed earlier, the resurgence of small farms producing high-value horticultural crops provides opportunities for non-chemical weed control methods to be carried out. Ashworth and Harrison (1983) evaluated a variety of organic and synthetic mulch

Fig. 13.4 **a** Application of preemergence herbicides in bands over corn-rows reduced herbicide use by 50% while maintaining a biologically-diverse cornfield (*top*) without affecting yield, **b** compared to conventional broadcast application resulting in a weed-free cornfield (*bottom*)

treatments used around vegetable crops and woody ornamental species. They found that organic mulches required application to a depth of at least 5 cm and that the most effective weed control was provided by black polyethylene because it remained intact throughout the summer. Similarly, field-grown tomatoes grown under black polyethylene had significantly higher total yield than those tomatoes without the mulch (Abdul-Baki et al. 1992). Additionally, the use of black polyethylene mulch greatly increased fresh and dry weight yields of basil (*Ocimum basilicum*) and rosemary (*Rosmarinus officinalis*) (Ricotta and Masiunas 1991; Davis 1994). Straw mulch at 16 tons per hectare has the capacity to reduce weed biomass by 30 to 83% and increase the yield of pointed gourd compared to unmulched plots (Ghorai and Bera 1998).

Field experiments conducted by the author in West Virginia evaluated hand cultivation, plastic mulch, and straw mulch for weed control, growth attributes, and yield of sweet pepper (*Capsicum annum*) in 2000–2001. In 2000, under rain-fed conditions, plastic mulch resulted in maximum pepper yield with increases of ~150% compared to 20 cm straw mulch and 50% compared to hand cultivation (Table 13.6). In this study root dry weights correlated positively to pepper yields.

The use of composted poultry litter as a mulch in orchard systems was documented not only to reduce weed competition in apples but was also determined to

Table 13.6 Yield, shoot and root weights of rain-fed sweet pepper (*Capsicum annum L.*var. "Ace") as affected by physical weed control methods (2000)

Treatment	Pepper yield kg/plot	Pepper number (per plot)	Shoot dry wt. (g/plot)	Root length cm	Root dry wt g/plant
Hand Cultivation	14.68	321	714	11.3	3.25
Plastic Mulch	23.47	655	1161	17.5	3.17
Straw Mulch (5 cm)	5.02	173	296	11.5	1.66
Straw Mulch (10 cm)	3.47	152	246	9.5	1.38
Straw Mulch (20 cm)	9.41	285	554	13.0	2.74
Control	1.21	21	62	7.2	1.65
L.S.D (P=0.05)	3.83	104	156	1.5	1.32

be beneficial in an orchard ecosystem to manage tree fruit diseases and insect pests (Brown and Tworkoski 2006). Tworkoski and Glenn (2012) determined from a 4-yr study that certain cool-season grasses grown in tree-rows successfully deterred weed competition without affecting apple and peach yield. The authors concluded that growing an annually-mowed grass in tree rows may be a viable option to reduce herbicide use in orchards but fruit size may be reduced.

13.12.3 Engagement of Industry—A Potential Opportunity

Undoubtedly, the chemical industry plays a major role in crop protection (Gasser and Fraley 1989). If it were not for useful chemistries and other technology developed by the researchers in the industry, the supply of food and fiber would not have been able to keep up with the demands of a growing world population. These are valuable services seldom appreciated by an average individual. To maintain the ability of industry to remain innovative and service-oriented, profitability in the marketplace is critical. Conventionally, such profits are generated through sales of pesticides, hybrid seeds, and similar products of value to their clientele. It may be worthwhile for the industry to consider marketing other services to foster sustainable agriculture.

Mechanisms to engage the industry in sustainable agriculture may be fruitful in the long-term. It may require a process of "thinking outside the box" to generate and implement viable ideas. Including an 'IPM', 'Eco-friendly', or 'Green' facility under the infrastructural umbrella may be worthy of consideration by major chemical companies. Such facilities may provide a diverse array of services such as consultancy to help growers implement proven sustainable practices, insurance to minimize any associated risks, mass production of biological pesticides and other bio-control agents, development of novel application technologies, scouting and monitoring, development and marketing of cultural tactics to manage resistant biotypes of weeds, etc. Such products may counteract any losses in revenue as a result of reduced pesticide sales.

In the United States, several incentives are available to growers to conserve resources in agricultural settings. The industry could facilitate the adoption of such practices and be compensated by growers for the services provided. If such services are included under the same umbrella of larger corporates, operational costs could be reduced as activities of different entities are coordinated in a concerted manner. Moreover, such a system would dramatically improve the public perception and credibility of the industry among stakeholders and help build positive relationships with environmental groups towards a productive rapport.

13.13 Conclusion

Weed management will continue to play an important role to ensure the supply of conventional food and fiber to meet the demands of a growing global population in years to come. Currently we are at the crossroads of cutting-edge technology and growing concerns related to implications of the same on sustainability. At this juncture, it is important to realize that this phenomenon is the inevitable cost of fewer hands feeding more mouths worldwide. Based on the growth pattern of most economies, humans shift from a farm-based livelihood to one that is based on services. Production agriculture continues to remain the burden of a shrinking fraction of the human population. Therefore producers have limited choices but to depend on cost-effective technologies to remain viable. Unless corrections are in place such trends are bound to continue.

Conscientious efforts favoring locally-grown produce to those shipped from elsewhere are gaining popularity in urban communities. Weed management in small farms could be more sustainable compared to that in industrialized agriculture. Some of the strategies discussed in this chapter may be more readily applicable to small scale production. Currently most of the research related to weed management at universities in the United States is geared towards large-scale production agriculture. The current structure of most universities which foster a climate of revenue generation to remain competitive also tends to encourage such tendencies.

Agriculture has never been in balance with Mother Nature. Ever since man raised crops to feed and clothe himself, disturbances to the ecosystem have occurred progressively. Such imbalances may be correlated to changes in human population, economic growth, and land use patterns. While the demand for organic food has increased recently, the average consumer may not be able to afford them. If current trends in economic disparities of society continue to grow, industrialized agriculture may emerge as the only solution to feed the masses while foods posing fewer risks to human health and produced in an eco-friendly manner may become the convenient choice for others.

Acknowledgments The author wishes to thank Robert Clemmer, Carl Coburn, Wayne Currey, Daniel Foglesong, Michael Harman, Samuel Harper, Irvin King, Harold Kiger, Fred Roe, Kimberly Salinas, Rodney Wallbrown, Dave Workman, and Craig Yohn, for their assistance in conducting field experiments. Funding from the National Institute of Food and Agriculture is also acknowledged.

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