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Chapter 2

Weed Management: A Basic Component of Modern Crop Production

Ricardo Labrada

INTRODUCTION

Increased world population will demand more food production, which can be achieved only by increasing crop yields. There are few possibilities to incorporate new areas into crop production. As an example of the problem in the case of cereals, Pinstrup-Andersen (2001) stated that demand for cereals to feed livestock will increase considerably in coming decades, especially in developing countries, in response to the high demand for livestock products. Between 1993 and 2020, it is estimated that developing countries' demand for cereals for animal feed will double, while demand for cereals for food for direct human consumption will increase by 47 percent. These expected increases in cereal demand will be met primarily by productivity increases. Because most of the growth in cereal areas will be concentrated in the relatively low-productivity cereals of sub-Saharan Africa, increases in cultivated area will contribute less than 20 percent of the increase in global cereal production in the period from 1993 to 2020.

From this estimate it is clear that increased crop yields can be achieved only by a sustainable approach, i.e., more production with rational use of available resources, which also implies responsible use of land and water and enhanced food diversity. Efforts are needed to reduce crop losses due to pests through the use of resistant crop varieties, pesticides, and better cultural practices; herein integrated pest management (IPM) is expected to have a major role in reducing losses caused by pests, without harmful side effects (Pinstrup-Andersen and Cohen, 1998).

In this context, weeds are considered an important biotic constraint to food production (Parker and Fryer, 1975; Akobundu, 1987). In developed

This chapter does not reflect fully the FAO's (Food and Agriculture Organization of the United Nations) views on this matter.

economies the importance of weed control is evident due to the fact that present herbicide use exceeds the amount of insecticides and fungicides used. In several developing countries, weed management is not yet a priority due to the high incidence of insects and pathogens, which normally cause more spectacular losses within a few days, and lack of understanding of problems caused persistently by weeds.

This chapter explores the importance of weed management and how crop production can be improved with the introduction and use of technologies for better weed control.

INTEGRATED PEST MANAGEMENT

Since the mid-1960s, integrated pest management has been promoted by the FAO worldwide as a preferred strategy for pest control. IPM means the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agroecosystems and encourages natural pest control mechanisms (FAO, 2003).

There is general agreement that IPM must be science based and economically viable for farmers. Prevention is an important requirement as well as pest control during the crop cycle. The preventive approach requires regular evaluation of pest density and risk of entry of new pests into the crop. Common control strategies follow:

- *Cultural methods,* which include crop rotation, resistant cultivars, use of cover crops, intercropping, mechanical control, and efficient water management and fertilizer application
- *Biological control,* either the classic method of introducing new exotic organisms evaluated prior to their introduction or the augmentative method through rearing and release of existing beneficial natural enemies
- *Chemical control,* or the rational and judicious use of pesticides
- *Other methods,* including the use of soil solarization and other physical methods, which remain under investigation

The IPM approach has had a major impact on insect and mite control with some other positive results in disease control, but with little effect on weeds. The reasons for this lack of success with weeds are as follows:

1. Little understanding of the problems caused by weeds exists, particularly in developing countries.
2. Few or no ecological weed elements are included in IPM programs.
3. There is a pronounced tendency in industrial countries to use herbicides as the sole control option on large crop areas or to rely on hand weeding in poor or subsistence sites.

Devising integrated weed management (IWM) strategies that address a diversity of weed species with a diversity of life history traits is a difficult task (Mortensen, Bastiaans, and Sattin, 2000). In the context of IPM, particular importance must be given to the improvement of weed management, which is a minor component of the majority of available programs on IPM. Auld (1994) classifies the impact of weeds on any agricultural system as follows:

1. Reduced agricultural output (quantity and/or quality)
2. The costs involved in a given level of control of weeds within the existing farming system
3. A change in the farming system to a new system (e.g., new crop) brought about mainly because of particular weeds
4. External costs caused by weeds spreading across farm boundaries

While most other pests are under control in various crops, weeds continue to be a limiting factor to crop yields. Weeds directly affect crop growth and development by competing effectively for light, nutrients, and water; by releasing substances from their roots and leaves that are toxic to various crop plants; and by serving as hosts of many pest organisms that pose serious risks to crop production. Weeds also seriously affect inland water bodies and related activities (irrigation, navigation, fisheries, and the energy potential of hydroelectric stations).

Weeds cause important social problems as well. Small-scale farmers in developing countries spend more than 40 percent of their labor time on weeding, which is primarily the labor of women and children in the farmer's family. Children involved in this task often cannot attend school regularly (Labrada and Parker, 1994).

COMPONENTS OF INTEGRATED WEED MANAGEMENT

The inclusion of a weed component in IPM curricula requires the study of various elements of weed ecology and biology and interference with crops to actually achieve long-term weed control effects. Sustainable weed management should foresee the control of weeds during the so-called periods of weed competition but should also guarantee the reduction of viable weed seed bank in the soil.

Basic components of knowledge for sound weed management include

1. regular monitoring of weed infestation, which may include the detection of herbicide-resistant weeds in areas regularly treated with herbicides;
2. biology and ecology of the prevalent weed species;
3. identification of critical periods of competition and periods of massive weed rain seed; and
4. technically effective, economically viable, and environmentally safe control methods.

Monitoring of Weed Infestation

A fundamental basis for sound weed management is to know the species present and their level of infestation. The composition of weed communities varies greatly and is closely linked to cropping history. Regular evaluation of weed infestation in agricultural fields is advisable, particularly in areas currently treated with herbicides. In these surveys weed identification plays an important role. It is essential to be able to identify perennial or parasitic weeds, which will not respond to the standard traditional weeding practices, while more precise determination (even of annual weed species) can be vital for the optimum selection of any control method, including herbicides. Obviously, agricultural extension workers and other agents working in the field should conduct weed surveys using less tedious methods and based on visual assessment to enable them to evaluate large crop areas.

In this context, it is no less important to know about the weed seed bank as a primary source of weeds in cultivated soils. Because the persistence of most weed species is contingent upon the presence of a buried seed bank, knowledge of seed bank size and the flux of seeds within it, in relation to land cultivation practices, is essential (Forcella and Burnside, 1993). If the seed bank is identified well in advance, it is possible to predict weed infestation at least in the medium term. However, existing methods to estimate weed seed bank have always been based on large numbers of samples (e.g., soil cores) and counting visually seeds of weed species, which is a tedious and slow process. However, a strong correlation has been found between seedlings emerged in the greenhouse and seeds extracted in the laboratory for the most abundant weed species (Forcella, 1998; Rahman, James, and Grbavac, 2001).

Forcella (1993) indicated that the "seedling emergence" method of seed bank analysis avoids the problems of seed-soil separation and seed identification inherent in the "seed extraction" method. In this method, multiple soil cores from a field may be aggregated, thoroughly mixed, spread as a 2 to 5 cm deep layer of soil onto a single tray, and stored in conditions that promote germination. Emerged seedlings are counted by species after two or three weeks. After counting seedlings, soil in the trays is dried, thoroughly remixed, and the cycle repeated. For weeds of arable soils, two or three cycles are often sufficient to estimate seed banks. The seedling emergence method makes the collection of seed bank data less time-consuming and cheaper to carry out.

Another method for predicting weed "pressure" was proposed by Gordon Harvey (1993). Harvey considered the best predictor of future weed problems to be a knowledge of previous weed problems. By keeping long-term records of weed problems in replicated untreated check areas within each field, growers should be able to not only anticipate the severity of weed infestations, but also recognize early changes in species composition of weed populations. He finally proposed monitoring weed infestation by making weed pressure (WP) ratings. WP is defined as the visual estimate of the percentage with which weeds contribute to the total volume of both crop and weeds in a plot.

Other Elements of Weed Ecobiology

Weed management means control of weed population and, to this end it is important to estimate some elements of population equilibriums and life-stages for regulating population size. Understanding the ecobiological behavior of weeds is a prerequisite for developing guidelines for environmentally sound weed control (Zimdahl, 1995).

Mortimer (1998) suggests that ecological studies of weeds and weed management may be conducted with a diversity of objectives in mind, for example,

1. autoecological comparison of weed species;
2. measuring the impact of new technologies on the dynamics (change in abundance) of "hard-to-kill" species; and
3. quantifying weed community structure and analyzing its causes.

In practical terms, it is necessary to have information on the behavior of prevailing weeds. Data are needed on germination of diaspores, phases when the plant starts fruit setting (and/or emissions of new vegetative organs in the case of perennial species), factors affecting its growth and development, and production of reproductive organs. In conclusion a picture of the cycle (see Figures 2.1 and 2.2) should be completed to the further extent possible.

Weed germination patterns generally result in cohorts of seedlings emerging over an extended period of time and are heavily influenced by weather conditions, soil type, and cropping system (Vleeshouwers, 1997). Here it is important to know the number and periods of weed flushes. In hot climatic countries, several weed flushes may occur during the crop cycle, and knowledge of this is essential when designing better control measures to prevent weed seed bank buildup.

Critical Periods of Interference

Weeds interfere severely with the growth and development of crops. Interference comprises *competition* with crops for light, nutrients, and water, and *allelopathy,* which refers to the adverse effect of substances produced by one plant on the growth and development of other plant(s). When referring to interference some authors simply use the term *competition.*

For understanding competition, it is common to study the so-called critical period of weed competition, which has been defined as the period during which weeds must be controlled to prevent yield losses (Sattin, Berti, and Zanin, 1998). Knowledge of critical periods of weed competition may help to determine when to implement control measures in order to minimize yield losses for many crops (Zimdahl, 2004).

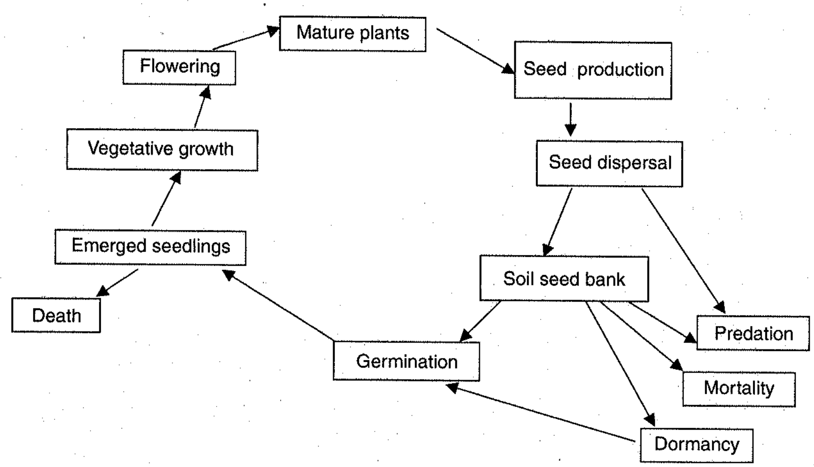

FIGURE 2.1. Cycle of an annual weed.

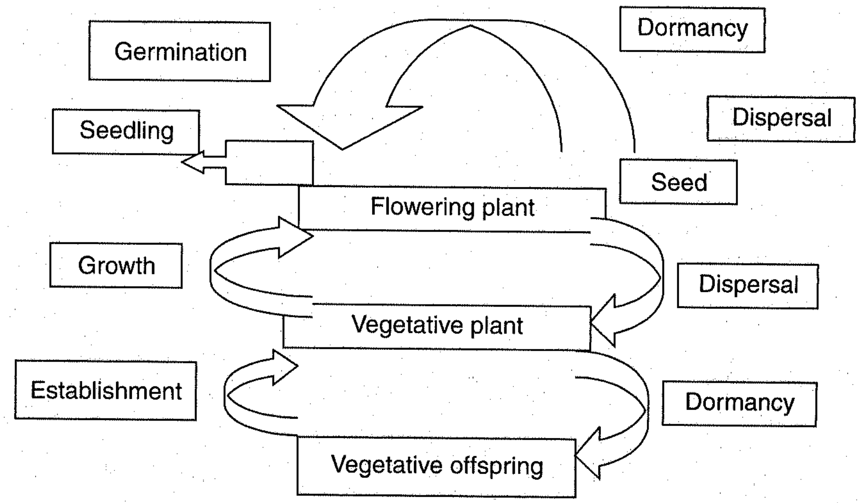

FIGURE 2.2. Cycle of a perennial weed.

Pitelli and Durigan (1984) proposed a classification of periods of competition for practical purposes. These are as follows:

1. *Period for preventing interference* starts from crop emergence or sowing when the crop should be kept weed free. This period is also known as the "weed-free period" (see Figure 2.3).
2. *Period of pre-interference* is the period starting from crop emergence or sowing, when the crop is able to tolerate the presence of some weeds without its productivity being affected.
3. *Initial period of interference* refers to the period when competition becomes important and starts affecting crop productivity.
4. *Critical period for preventing competition* is the period when the presence of weeds is critical, i.e., the maximum period of admissible weed presence.

Knowledge of the "critical periods" would enable farmers to make the most efficient use of limited labor resources. The critical periods vary with the relative competitiveness of the crop and the weed infestation: the lower the crop competitiveness (and/or the higher the weed flora competitiveness), the longer the period the crop must be kept weed free to prevent significant yield losses (Sattin, Berti, and Zanin, 1998).

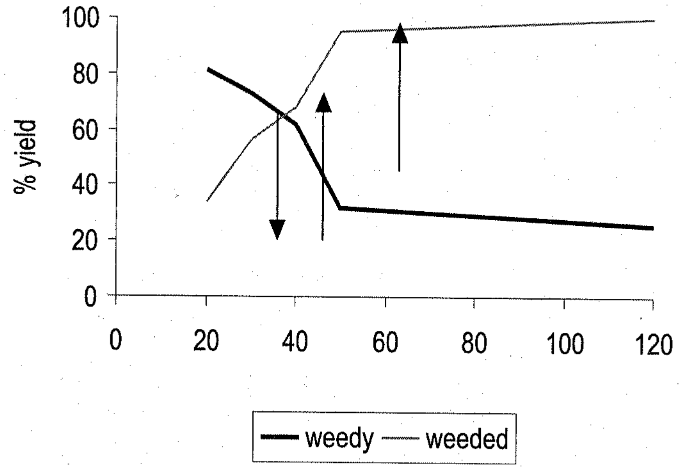

FIGURE 2.3. Critical period of weed competition. Ascending and descending arrows show the critical period of weed competition. The far-right ascending arrow shows the weed-free period, which indicates that there is no further need to weed during the remaining cycle to obtain high crop yields.

Studies have already been conducted on determining weed-free and critical periods of weed competition, but these data, although useful, do not provide advice regarding intervention on weed flushes thriving after the critical periods. It may be that combining knowledge of these periods and weed flushes in a particular site may give a more complete idea of what has to be done to control weeds during the crop cycle in order to prevent weed seed bank buildup in the soil.

CONTROL STRATEGIES

With the advent of herbicides many people thought that the problem of weeding was solved. At that time, the main aim was to identify a selective herbicide that would minimize hand weeding or mechanical cultivation. As a pregraduate student, the author was given to understand that with the use of herbicides, crop rotation would become unnecessary. Experience has demonstrated that these ideas were completely erroneous. Chemical control has been useful and helpful to increase crop yields, but other problems have arisen.

The main weed control strategies that farmers can successfully implement are as follows:

1. Land preparation or tillage systems (minimum till, zero till, and conventional tillage)
2. Cultural: Crop rotation, use of competitive and/or allelopathic cultivars, living or dead cover crops, water management, fertilizer application, mulching, and intercropping
3. Physical: Interrow cultivation and hand weeding
4. Biological control by releasing insects or other animals using beneficial pathogens
5. Chemical control through the use of herbicides
6. Other control methods, e.g., soil solarization

It should be remembered that weed management comprises various operations before and during the crop cycle to reduce weed infestation. From tillage through to harvest, weed control is of major concern to farmers.

Crop Rotation

The key to a successful cropping system is good crop rotation, which helps reduce pest problems. Several weeds can adapt to a specific crop. Rotation with morphologically different crops and with different growing requirements may help to break the cycle of adapted weeds. A good example is when upland crops are rotated with irrigated rice and vice versa. Unfortunately, this is not always possible because either several crops cannot grow in any type of soil or a market for the crop in rotation does not exist and, subsequently, it becomes unprofitable. In fact, monocropping is unsustainable for crop production because of heavy dependence upon agrochemicals, including herbicides.

Cropping sequence has an enormous influence on variations of weed populations as a direct result of implementing various weed management practices associated with crops involved in rotation. The use of densely seeded and competitive plants as preceding crops, such as cereals and legumes, significantly reduces weed density from one season to another. An interesting study has been conducted in Canada by Doucet and colleagues (1999) on the dynamics of standing weed vegetation in *Zea mays* L. (maize), *Glycine max* [L.] Merr. (soybeans), and *Triticum aestivum* L. (wheat). From these studies, maize was shown to be poor preceding crop with respect to weeds, while wheat in the crop rotation reduced weed density. The authors applied an integrated approach, and concluded that the best control was achieved when crop rotation was combined with herbicide use.

In Romania, Petcu and Ionita (1998) examined the effect of some cropping systems on weeds. The systems were wheat monocropping, a two-year wheat-maize rotation, and rotations of wheat-maize-peas or wheat-sugar beet-maize-sunflowers. After 25 years, the authors established that weed infestation decreased within all cropping systems, and it was much lower in the rotations compared when with wheat monocropping.

Tillage Systems

Tillage systems are essential for land preparation, and weed infestation may dictate the type of tillage to be used. Tillage based on plowing and harrowing during land preparation has always been a conventional method of weed control and is still widely used for growing roots, tubers, and vegetables. Minimum- or zero-tillage practices are becoming more widespread in the production of direct-seeded grains. These tillage systems leave the residues and stubble from preceding crop covering the soil, which reduces weed infestation to some extent. However, it is clear that with the switch from conventional tillage to other less disturbing soil methods, weed population changes may take place. For example, a survey conducted in Manitoba (Canada) (Kelner, 1997), in areas with conventional and zero tillage, showed that high densities of perennial weeds, including quackgrass [*Agropyron repens* (L.) Beauv.] and some annual weeds such as *Avena* spp. and volunteer canola, prevail under zero tillage. However, other annual weeds, such as *Setaria* spp., volunteer barley, wild mustard, redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.) and Kochia [*Kochia scoparia* (L.) Schrad.] had lower densities under zero-tillage crop production. When perennial weeds start prevailing consistently in zero-tillage areas, plowing becomes necessary in order to drag the rhizomes of these weeds to the soil surface to desiccate under the influence of the sun and wind.

Tillage systems alone may reduce the stand of certain species. In conservation agriculture, zero till may succeed in reducing weed infestation in general if combined properly with other control measures, e.g., crop rotation, use of cover crops, increased crop seed densities, and rational use of herbicides.

Competitive and/or Allelopathic Crops

One way to combat weeds is by encouraging the competitive nature of crops at an early stage of growth. Therefore, those plant varieties that are able to compete with weeds and to suppress them are preferable in the con-

text of integrated weed management. Science has demonstrated that plant competitiveness does not necessarily mean tall and robust cultivars. Some studies have been carried out on the competitive ability of rice cultivars with weeds jungle rice [*Echinochola colona* (L.) Link.], late water grass [*E. phyllopogon* (Stapf.) Staph. ex Koss.], early water grass [*E. oryzoides* (Ard.) Fritsch], palisade signal grass [*Brachiaria brizantha* (C. Hoschst ex. A. Rich Stapf], or *Brachiaria decumbens* Stapf. (Fischer and Gibson, 2001), which showed that it is possible to have modern high-yielding, semidwarf cultivars able to compete with weeds efficiently. Competitive rice cultivars, such as semidwarf cv. M-202 effectively suppressed the infestation of *Echinochloa oryzoides* and *E. phyllopogon* emerging 20 days after the crop in California and may help reduce herbicide dependency and decrease selective pressure for resistance (Gibson et al., 2001).

The other area of interest is allelopathic crop varieties. Plants in general are able to produce and exude substances suppressing the growth of other plants in their vicinity. Selection for crop cultivars with allelopathic potential is undergoing research in various crops, with promising results. To date, progress has been made in understanding the genetics of crop allelopathic activity, and successful genetic manipulation of this trait has also been demonstrated (Wu et al., 1999).

Several crop cultivars may exhibit a high level of allelopathic effect over certain weed species. For example, results have shown that there is a wide variation in allelopathy among rice cultivars, some of which are able to suppress both monocot and dicot weed species (Olofsdotter, 2001). Similar results have been obtained in South Korea (Lin, Kim, and Shin, 2000; Chung, Ahn, and Yun, 2001), which represents a potential for improved weed management in the near future. Similar research is being conduced in wheat. Some cultivars such as 'Bezostaya-1', 'Naveed', and 'Niknejad' expressed positive allelopathy against wild oat [*Avena sterilis* ssp. *ludoviciana* (Durieu) Nyman] (Rizvi et al., 2000). Such research has shown that an increase in the wheat sowing density improved the allelopathic inhibition of the weed without any problem of autotoxicity. According to Wu and colleagues (1999), both wheat residue allelopathy and wheat seedling allelopathy can be exploited for managing weeds, including resistant biotypes. Wheat varieties differ in allelopathic potential against weeds, indicating that selection of allelopathic varieties might be a useful strategy in integrated weed management. Several categories of allelochemicals for wheat allelopathy have been identified, namely phenolic acids, hydroxamic acids, and short-chain fatty acids.

Mulch and Cover Crops

Mulches are excellent for weed management. They normally exclude light and serve as a physical barrier against emergence; they also affect soil temperature and moisture. Nonliving mulches can be divided into either *natural materials,* such as plant leaves, stalks, straw, compost, and dry soil, or *synthetic materials,* such as plastic polyethylene, which are widely used in pineapple and strawberry production. Natural mulches add organic matter and nutrients to the soil with their decomposition, and are inexpensive provided that the materials do not have to be transported from distant areas. The major problem is that natural mulches require large quantities to be applied per unit area. It is important to check that these materials are weed seed-free. Experiments show that natural mulches may exert good control of annual weeds but not of perennial weeds.

Before discussing *cover crops,* it is important to clarify that these are crops grown to produce soil cover, regardless of whether they are later incorporated. *Green manures* are plants incorporated into the soil while in an early vegetative stage, or soon after flowering, in order to enrich the soil. The term *green manure* has sometimes been used loosely and may sometimes refer to plants or plant vegetation that may be applied as mulch to the soil.

A cover crop intercropped or interplanted with an annual or perennial crop is called *living mulch,* which is useful to suppress weed infestation and prevent soil erosion, enhance soil fertility, and improve water infiltration. Cover crops also exclude light with their shading, limiting weed emergence. Examples of cover crops in temperate climate countries are seeded hairy vetch, clover, and annual ryegrass. In Brazil, sorghum is planted between rows in citrus with good results. In Colombia, pinto peanut (*Arachis pintoi* Crap. & Greg.) has been identified as an effective cover crop for the control of weeds in grapes (Rojas and Porras, 1999). It was found that 100 percent weed control was reached 240 days after planting, which significantly reduced weed populations without affecting crop yield or quality.

Allelopathic Cover Crops

Allelopathic cover crops are one of the most promising applications for weed control. Fujii (2001) evaluated the allelopathic activity of 53 cover crop plant species, including 26 leguminous, 19 graminaceous, and 8 others. The author found that leguminous cover crops such as hairy vetch (*Vicia villosa* Roth) and velvetbean [*Mucuna pruriens* (L.) DC.] grass cover crops such as oat (*Avena sativa* L.) and rye (*Secale cereale* L.), and certain

cultivars of wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) were promising. Some of these results were later successfully validated in field experiments, where hairy vetch was found to be the most promising for weed control in abandoned fields. This was due to its ability to die off during the summer season and make thick strawlike mulch.

Cover crops fit well into many different cropping systems during the fallow or noncrop season. Interesting results have been obtained with the use of *Mucuna pruriens* in crop rotation in West Africa. Galiba and colleagues (1998) conducted a survey in farming areas of Benin, where 74 percent of the surveyed farmers were using *Mucuna* for at least three consecutive years, either in crop rotation or intercropped with maize. The farmers acknowledged the contribution of *Mucuna* to soil fertility and its ability to eradicate the stand of perennial weed cogon grass [*Imperata cylindrica* (L.) Beauv.]. The only problem was that farmers did not find any use for *Mucuna*. Because the products of the plant are not used, it is important to identify less persistent varieties of the plant. Carsky and Eteka (1999) are conducting a study to explore these opportunities.

It is obvious that legume cover crops reduce the need for the application of N fertilizers, but indirectly they may also reduce the incidence of some pests including weeds, with subsequent reduction of pesticide inputs. So promoting the use of cover crops is a contribution toward increased sustainability of crop production.

Interrow Cultivation or Weeding During the Crop Cycle

To control weeds by cultivation or manual weeding in the interrows is a traditional practice. These methods have to be used in organic agriculture in several crops to avoiding using herbicides. Organic farming using interrow cultivation to combat weeds in developed economies should carefully consider fuel expenditure and the number of mechanical interventions required. The idea of minimizing or eradicating herbicide applications should be welcome, provided the methods are not high energy and/or labor consuming.

Small-scale farmers in developing countries use hand labor for weed eradication. The problem here is to minimize the work required, which can easily take up to 40 percent of farmers' time. As Mortimer (1998) indicated, a desirable working maxim in developing integrated weed management must be to attempt to minimize the number of interventions per se and, where interventions are necessary, to minimize any negative environmental impacts. In some crop areas of poor small-scale farmers, where root parasitic weeds such as *Striga* and *Orobanche* spp. prevail, hand weeding before flowering of the parasites is advisable.

Biological Weed Control

Control through monophagous/oligophagous natural enemies is a highly sustainable way of managing troublesome weeds, and there are many good examples of effective biological control. One the most important achievements is the control of floating aquatic weeds using various specific insects. Many weeds have been introduced into various countries inadvertently, and the best way to control them is using the classic approach, i.e., introducing specialist natural enemies from the weed's area of origin. Table 2.1 gives some idea of agents that have proved effective in the control of specific weeds.

Biological control is highly specific, and it is impossible for one organism to be able to control several weeds without affecting the crop. However, some herbicide-resistant weeds or other highly invasive plants are extremely difficult to control using mechanical or chemical means. In such situations, the best method of control—if available—is to release biological

TABLE 2.1. List of organisms used effectively for biological control of some weeds.

Weed	Biological control agent
Eichhornia crassipes (Mart.) Solms. (Water hyacinth)	Weevils: *Neochetina eichhorniae, N. bruchi* Moth: *Sameodes albigutalis*
Hydrilla verticillata (Hydrilla)	Grass carp: *Ctenopharyngodon idella* Tuber weevil: *Bagous affinis* Leafmining fly: *Hydrellia pakistanae*
Pistia stratiotes L. (Water lettuce)	Weevil: *Neohydronomus affinis*
Salvinia molesta Mitchell (Water fern)	Weevil: *Cyrtobagous salviniae*
Alternanthera philoxeroides (Mart.) Griseb. (Alligator weed)	Flee beetle: *Agasicles hygrophila* Stem borer: *Vogtia malloi*
Parthenium hysterophorus L. (Ragweed parthenium)	Fungus: *Puccinia abrupta* var. *partheniicola*
Euphorbia esula L. (Leafy spurge)	Flea beetles: *Apthona* spp.
Chromolaena odorata (L.) King & Robins. (Siam weed)	Moth: *Pareuchaetes pseudoinsulata*
Lantana (*Lantana camara* L.)	Lacebug: *Teleonemia scrupulosa*
Cordia curassavica (Jacq.) Roem. & Schult. (Black sage)	Beetle: *Metrogaleruca obscura*
Orobanche spp. (Broomrape)	Stem feeding fly: *Phytomyza orobanchia*

control agents, which are able to spread to areas that cannot be reached, e.g., in large water bodies or forests.

Knowledge of the organism to be used is required as well as methods for rearing and release. It is also essential to know its host range in order to avoid undesirable effects on crops. *The Code of Conduct for the Import and Release of Exotic Biological Control Agents* (FAO, 1996), which is now under revision, gives good guidance on how to proceed in order to introduce new exotic organisms for biological control.

Chemical Weed Control

Herbicides were introduced into agricultural practice more than 50 years ago. At that time 2,4-D was the only chemical available and used solely for the control of annual weeds, mainly broadleaf weeds in cereals. By the mid-1950s selective herbicides started to be used in several crops and, 40 years after the advent of 2,4-D, the list of herbicides has increased (see Table 2.2). In several crops, mixtures of two or three herbicides have been used, giving better results than the application of a single herbicide. Chemical weed control has become cheaper over large areas of crops such as wheat, maize, sugar cane, direct-seeded rice, cotton, soybean, citrus, in vineyards, etc. The use of herbicides has also reduced losses caused by weeds. However, herbicides have been used and handled incorrectly on many occasions, particularly on small farms in developing countries. Accidents and problems affecting human health have often occurred, sometimes involving children; polluted water has been caused mainly by waste cans or herbicide containers; and some carryover effect in subsequent crops due to the high rates of herbicide used. This indicates the need for farmers to be educated in efficient and safe use and handling of herbicides.

The frequent evolution of herbicide resistance is no less serious, particularly with the repeated use of soil-acting herbicides and herbicide groups such as ALS and AACase inhibitors, which have a selection pressure higher than many other herbicide groups. At present there are 296 herbicide-resistant biotypes belonging to 178 crops. Of these 107 are dicots and 71 are monocots, which infest more than 270,000 fields (Heap, 2005).

The evolution of herbicide resistance shows that weed control cannot be solved by using herbicides alone. Herbicides rationally applied are effective tools combined with other control methods (crop rotation, tillage, cover crops, and others). Chemical control should be considered simply as one of a number of alternatives available.

With the repeated use of herbicide, weed monitoring becomes more important in order to detect the shift of weed populations and the development

TABLE 2.2. List of most important herbicide groups and their mode of action.

Herbicide group	Mode of action	Examples of herbicides
Iimidazolinones, sulfonylureas, triazolopyrmidines, pyrimidinylbenzoates, sulfonylaminocarbonyl-triazolinones	Inhibition of acetolactate synthase ALS (acetohydroxyacid synthase AHAS)	Chlorsulfuron, imazaquin, flumetsulam, bispyribac-Na flucarbazone-Na
Aryloxyphenoxy-propionates, cyclohexanediones	Inhibition of acetyl CoA carboxylase (ACCase)	Diclofop, fenoxaprop-ethyl, sethoxydim
S-triazines, trazinones, triazolinone ureas, uracils, amides	Inhibition of photosynthesis at photosystem II	Atrazine, diuron, amicarbazone, propanil, metribuzin, bromacil, desmedipham, pyrazon
Nitriles	Inhibition of photosynthesis at photosystem II	Bromoxynil, ioxynil
Bipyridiliums	Photosystem-I-electron diversion	Paraquat, diquat
Dinitroanilines	Microtubule assembly inhibition	Trifluralin, nitralin, dinitramine, pendimethalin
Mitosis inhibitors	Inhibition of mitosis/ microtubule polymerization inhibitor	Propham
Chloroacetamides, oxyacetamides, and acetamides	Inhibition of cell division (Inhibition of synthesis of very long chain fatty acids)	Butachlor, napropamide, mefenacet
Synthetic auxins	Synthetic auxins (action like indoleacetic acid)	2,4-D, MCPA, MCPB
Thiocarbamates	Inhibition of lipid synthesis—not ACCase inhibition	Triallate, EPTC, butylate
Triazoles	Bleaching: Inhibition of carotenoid biosynthesis (unknown target)	Amitrole
Pyridazinones, pyridinecarboxamides	Bleaching: Inhibition of carotenoid biosynthesis at the phytoene desaturase step (PDS)	Norflurazon, diflufenican
Glycines	Inhibition of EPSP synthase	Glyphosate, sulfosate
PPO inhibitors (diphenylethers, phenylpyrazoles, N-phenylphthalimides, oxadiazoles)	Inhibition of protoporphyrinogen oxidase (PPO)	Oxyfluorfen, fluazolate, oxadiazon
Carbamates	Inhibition of DHP (dihydropteroate) synthase	Asulam
Phosphinic acids	Inhibition of glutamine synthetase	Glufosinate-ammonium bialaphos

of herbicide-resistant weeds. To delay herbicide resistance, it is essential to provide information on the cropping system in place and the number of years and applications for the resistance to evolve. This information may help researchers, extension workers, and farmers to combat problems of resistance.

It is also advisable to avoid continued use of herbicides with the same mode of action unless this is used with other weed control practices and, in the case of probable metabolic resistance, with the use of herbicides that degrade by different metabolic means.

To devise effective herbicide resistance management strategies it is important to have a good understanding of the causes, nature, genetics, mechanisms, and solutions of herbicide-resistant weeds (Heap and LeBaron, 2001). Although this task is extremely difficult, every effort should be made to accomplish it.

Herbicide-Tolerant or Resistant Crops (HRCs)

The use of transgenic crops is a reality in several countries of the western hemisphere. Crops that are either tolerant to herbicides or resistant to insects are increasingly used in the United States (47.6 million ha), Argentina (16.2 million ha), and Canada (5.4 million ha) (James, 2004). Herbicide-resistant crops allow the application to the crops of a broad-spectrum herbicide, e.g., glyphosate or gluphosinate-ammonium, without affecting their growth once the weeds are emerged. Certainly the productivity of the process increases and zero or minimum tillage combined with direct-seeding of several grains becomes easy, with a resulting saving of energy and labor for weeding and prevention of soil erosion problems.

The use of HRCs offers better options for controlling problem weeds. For example, weeds that have become resistant to conventional herbicides can be controlled with the corresponding HRC herbicide. Thus HRCs may provide an additional tool in the management of herbicide-resistant weeds (Hurle, 1998). However, the recent commercialization of crop cultivars containing transgenes for herbicide resistance in North America, Europe, and other parts of the world offers a potential blessing to agriculture as well as posing a potential threat to the well-being of the agroecosystem (Rubin, 1998). There are several concerns about the consequences of development and deployment of transgenic herbicide resistance (HR), including the following:

- The potential transfer of genes from HRCs to wild relatives, thus creating "super" weeds

- The possibility of HRC volunteers becoming weeds in subsequent crops
- Increased selection pressure on weeds due to the repeated use of the herbicide associated to the HRC

The first problem necessitates avoidance of the repeated use of one herbicide mode of action, which may cause a switch in the weed flora toward less sensitive species. Therefore, alternative weed control strategies will have to be adopted to prevent (solve) problems. Farmers should be encouraged to rotate crops and herbicides. For the second problem, again, alternative weed control strategies are required to control HRC volunteers. In addition, certain conditions are necessary for the approval of any new HRC, such as the following:

1. Each country must have a regulatory authority to oversee the introduction of HRCs.
2. Approval should be based on crop, cultivar, HR transformant/gene, and herbicide.
3. The herbicide should already be approved by the pesticide registration scheme in the country concerned or approval should be sought simultaneously with the HR crop approval.

Another important aspect is monitoring the use of HRCs, which requires the following:

1. Postrelease monitoring to assess any significant changes in the weed flora as a result of the use of the HRCs (e.g., presence of surviving weeds and/or volunteers, and overall efficacy).
2. The relevant national agency or institution of the country concerned with the company seeking approval should agree on financial support to this work.
3. Users must keep good records of which HRCs have been used, where planted, and which herbicide has been used. Preferably, regulatory authorities or their local representatives should record this information.

Particular attention should be paid to the use of HRCs in centers of crop origin, where the hazards of gene transfer are higher. Special care should be taken to ensure that native germplasm is not jeopardized by the transfer of herbicide resistance genes.

In order to help national authorities, researchers, and other people involved with the use of HRCs, the FAO (2001) has recently published draft guidelines for risk assessment of the ecological hazards of the use of herbicide- and insect-resistant crops. These draft guidelines provide useful advice for identifying potential hazards of the use of these materials prior to their use in agricultural practice.

As rightly stated by Rubin (1998), too hasty adoption of HRCs may result in irreversible damage to the agroecosystem. It is essential to avoid such damage and to take the necessary precautions before introducing such crops.

Other Control Methods

One of the methods most successfully used during the past 15 years for weed control has been *soil solarization*. This is a safe and effective alternative to toxic, costly soil pesticides and the lengthy crop rotations now needed to control many damaging soil pests. Solarization provides good weed control in some situations, particularly commercial vegetable production, where effective herbicides are unavailable (Hagan and Gazaway, 2000). The method works similarly to a greenhouse. It consists of using a transparent polyethylene sheet (3 to 6 mm) to cover wet soil and trap sun radiation. Soil exposed for four to six weeks reaches the necessary temperature to kill several soilborne pests, including weed seeds. Many countries, particularly those with strong sun radiation (e.g., Mexico, the United States, Israel, Jordan, and others in the Mediterranean basin), use this method effectively to control soilborne pests and also to replace the use of the fumigant methyl bromide. Being nonchemical by definition, solarization has a definite advantage in the framework of nonchemical cropping systems, such as organic and biological farming, and offers potential as an alternative method to chemical soil fumigation. Solarization is compatible with integrated pest management and biological control systems (Grinstein, 1992).

Other control methods are under research, e.g., the use of hot water and hot foam for weed control in western Australia (Collins et al., 2002), band steaming for weed control in Denmark (Melander, Heisl, and Jorgensen, 2002), water-jet cutting for weed control in Sweden (Fogelberg and Blom, 2002), and others. These methods remain to be developed further and economic feasibility, particularly fuel consumption, has yet to be studied for application in developing countries.

Integrated Weed Management

From the various methods described, it is clear that weed management is an integral part of crop and farm systems. Many of the activities carried out by farmers involve weed control. In fact, substantial progress has been made on methods to improve weed management. Crop rotation, tillage, use of cover crops, and flooding (as in rice, mulches, and interrow cultivation) are largely based on the need to prevent weed interference and to avoid losses caused by competition. To regard weed management as a sole method of control is incorrect and will not reduce existing weed problems. Some of the methods listed previously are technically applicable anywhere, but the constraints under which each farmer works vary from one country to another or from one region to another. Farmers in the industrial economies have means that are not available in developing countries, particularly in small farming systems. In the same way that labor can be regarded as a production constraint, sufficient cash or capital may not be available to undertake all the activities that would be profitable if money could be readily borrowed at "market" interest rates (Auld, Menz, and Tisdell, 1987). Therefore, methods applicable in one area may not be applicable elsewhere because farmers may lack the necessary resources (labor and capital) to implement new methods.

However, due to the implications of weed interference in the whole agricultural process, improved crop production (i.e., higher yields and quality) will be attainable only when weed problems and related expenses are minimized. Therefore, methods bringing more productivity and reducing actual cost of weed control will be welcome. In the case of small-scale farming systems, the immediate objective should be to substantially reduce the time farmers and their families spend hand weeding. Accomplishing such an objective will have an enormous socioeconomic impact on the economies of small-scale farmers.

ECONOMIC AREAS AFFECTED BY WEEDS AND THEIR MANAGEMENT

It is worth highlighting briefly the different areas affected by weeds, the most important species in each case, and the causes of incidence. Some sources in the literature give more detailed information on each of the species mentioned, but here the intention is to present only an overview of the problems posed by these troublesome species, together with an explanation of the importance of accepting an integrated management approach for their control.

Weeds affect three major economic areas: agriculture and forestry, industrial and recreational sites, and inland water bodies. Since our work is mainly concerned with agricultural production, industrial and recreational areas are not included in this chapter.

Agricultural Areas

In agricultural areas it is necessary to differentiate between perennial and annual crops. Differentiation of geographic regions is convenient since climatic and soil conditions are important factors affecting the weed flora of any territory or country.

Grass Weeds

Several difficult-to-control grass weeds cause important crop losses worldwide, among them the perennial *Imperata cylindrica,* which is largely found in plantations and fallow areas of Asia and Africa. The weed should be combated with the integration of various methods, including the use of cover crops during fallow periods and the use of broad-spectrum herbicides, particularly to control the cover crop during the process of land preparation for a subsequent crop.

The incidence of johnsongrass [*Sorghum halepense* (L.) Pers.] is no less important in the western hemisphere. This weed is found in annual and perennial crops; its control is difficult due to its extraordinary reproductive capacity, and it is necessary to use systemic herbicides (e.g., glyphosate and asulam) to avoid regrowth and/or the emission of new rhizomes. In heavily infested areas, land preparation by dragging the rhizomes to the soil surface to desiccate is the recommended control method.

The annual grass itchgrass [*Rottboellia cochinchinensis* (Lour.) Clayton] has also been introduced into the western hemisphere; it causes important losses in several annual crops, such as maize, beans, cotton, as well as perennial sugar cane. Its control requires the implementation of cultural methods (including crop rotation) plus chemical control to minimize infestation. Several chlorotriazinic herbicides selectively used in maize and sorghum have not proved effective for its control.

In cereals, *Avena* spp. cause serious problems in North Africa, the Middle East, and Asia. Crop rotation of cereals with other crops, as well as selective chemical control, is required. As with the case of *R. cochinchinensis,* the use of clean seeds is an important preventive control measure.

Broadleaf Weeds

Major problems are those of introduced invasive weeds such as parthenium (*Parthenium hysterophorus* L.) in some parts of Africa, Asia, and Australia. The weed not only affects crop growth but also causes severe skin allergy problems to farmers touching the weed when hand weeding. In highly infested areas, development and implementation of biological control seem to be the best option. In Australia, the weed is largely controlled by the use of biological control agents.

Introduced slamweed [*Chromolaena odorata* (L.) King & Robins] in Africa and Asia, as well as *Prosopis* spp. in Africa and the Middle East, are serious weed problems which are discussed next.

Parasitic Weeds

There are three important complexes of parasitic plants:

1. *Striga* spp., well distributed and causing severe crop losses in Africa south of the Sahara;
2. *Orobanche* spp. in North Africa and the Middle East, with a similar negative effect in legumes, vegetables, sunflower, and tobacco; and
3. *Cuscuta* spp., which are found worldwide and affect a long list of crops.

The first two complexes are root parasitic, while *Cuscuta* spp. are aerial parasites. For the control of these species an integrated approach is required. The idea of combating these species by herbicide use alone is not practical. First, it is important to understand that monocropping is the main cause of the persistent incidence of these weeds, so implementation of crop rotation to substantially reduce the stand of root parasitic weeds should be understood as the key to their control. The use of clean crop seeds, organic manure, and N-fertilizers help to reduce infestation. In the case of *Striga,* intercropping the cereal with a leguminous crop may also reduce infestation. Herbicide use may be helpful if contact compounds are applied over the flowers of emerged parasites to avoid seed-setting of the plants, thus reducing weed seed bank build-up in soil as well. Obviously, the herbicide and its rate of application should be safe to the commercial crop, something that it is not always easy to achieve.

Water Bodies

At present, large dams, lakes, and rivers also become infested by some weeds. The most common species follow:

1. Floating: water hyacinth *(Eichhornia crassipes),* water fern *(Salvinia molesta),* and water lettuce *(Pistia stratiotes);*
2. *Rooting: Typha* spp; and
3. *Submerged: Hydrilla verticillata, Egeria* spp., Canadian waterweed (*Elodea canadensis* Mich.), and others.

Heavily infested water bodies pose a number of serious problems. The weeds limit navigation, reduce fishing, hinder irrigation network, create serious problems for good functioning of hydroelectric power stations, and serve as good habitats for the development of various vectors of human diseases.

The origin of the problem is normally the inappropriate introduction and dissemination of the plant species to the country. These plants always arrive without their natural enemies, so biotic factors able to regulate their reproduction are absent and areas quickly become infested. Another important factor is that these plants become more prolific in water bodies heavily polluted with organic substances. Therefore, a prerequisite for arresting the proliferation of aquatic weeds is to reduce the disposal of organic waste into the water.

Free Trade and Introduced Exotic Plants

As has made clear earlier, several weeds are alien plants in many countries and regions of the world, where they cause serious problems (see Table 2.3). Increased world trade, international travel, and world demographic growth have brought about serious problems of introduced plants, some of them being highly invasive. An active global market is one of the major causes of introduced weeds into new territories. In the United States, losses caused by introduced invasive weeds in the agricultural sector were estimated at US$15.2 billion in 1994 (Bridges, 1994, cited by Westbrooks, 1998).

Table 2.3 contains examples of weed species which have been introduced in various regions, e.g., the Compositae *Parthenium hysterophorus* has been introduced into India, some parts of east and southern Africa and Australia, and presumably in grains coming from the United States. In other cases, species have been introduced by error. Clear examples are *Chromo-*

TABLE 2.3. Examples of introduced weeds in various regions of the world.

Species	Area of introduction
Sorghum halepense	Western hemisphere
Rottboellia cochinchinensis	Western hemisphere
Cyperus rotundus	Western hemisphere, Africa
Mimosa pigra	Africa, Asia, and Oceania
Chromolaena odorata	Africa, Asia, and Oceania
Parthenium hysterophorus	Africa, Asia, and Oceania
Euphorbia esula	North America
Lantana camara	Africa, Asia, and Oceania
Eichhornia crassipes	Central America, Caribbean, Africa, Asia, and Oceania
Hydrilla verticillata	North America
Prosopis spp.	Middle East and Africa
Striga asiatica	North America
Orobanche ramosa	Pacific Coast of Mexico and Cuba

laena odorata (formerly *Eupatorium odoratum*), which was brought from the Caribbean and introduced as a cover crop in plantations of Africa and Asia. This later became an invasive weed that seriously affects crop production and plant biodiversity. Another example is the perennial grass *Sorghum halepense* from the Mediterranean area, introduced into North America as pasture, and at present causing problems in several crops as a highly competitive weed. More recently there is evidence that certain species of *Prosopis*, introduced into arid areas of Africa and the Middle East, are invading large fertile areas of countries in the region.

The invasiveness and economic damage of introduced weeds should be minimized. To this end, some activities are recommended to prevent and/or reduce their effect:

1. Risk assessment of possible adaptation of exotic plants known to be weeds in other countries
2. Provision of knowledge and tools to quarantine inspectors about exotic weed species, their potential for introduction, and methods for their detection

In each country, quarantine services should have a check list of hazardous plants in order to prevent their entry. The list should be prepared on the basis of weeds currently absent and those potentially able to establish themselves in the country. Quarantine inspectors should also have available methodologies for the detection of weed seeds in imported agricultural products. Prevention is an important activity in the context of integrated weed management to avoid future problems and losses caused by exotic plants.

SUGGESTIONS FOR IMPROVED WEED RESEARCH MANAGEMENT

From the present review, the importance of weed management to augment crop production and its quality is evident. Modern agriculture will increasingly depend on the methods used for weed control, and research should regularly provide information and validated weed control methods to achieve such improvement. In conclusion, it is worth emphasizing the studies and actions required to improve weed management. These recommendations are mainly directed to weed scientists in developing countries. The studies include the following:

1. Ecology and biology of prevailing weed species including weed seed bank, and the effect of biotic and abiotic factors on the growth and productivity of the species
2. Weed interference to determine critical periods of competition
3. Tillage systems and their short- and long-term effects on weed flora
4. Use of cover crops and mulches
5. Identification of competitive and/or allelopathic crops for providing more effective competition with weeds
6. Intercropping
7. Preventive methods of weed control, including regulatory measures and weed risk assessment
8. Biological control of prevailing weeds
9. Monitoring of herbicide resistance
10. Hazard assessment of ecological impact of the use of HRCs

No single control measure is perfect for all weed situations. Different actions are required for effective control. IWM is a rational combination of control methods that will reduce a particular weed infestation efficiently, with minimal adverse impacts to the environment.

IWM requires farmers to understand the ecobiology of the main weed species before selecting any control strategy. Knowledge of the life cycle of the species is essential for conducting control at the weeds' most vulnerable stages.

IWM should include practices that prevent the introduction and spread of weeds as well as others that make the crop competitive with weeds. Important preventive methods are the consistent reduction of weed seed bank in the soil and avoiding the invasion of a new weed from one farm or field to another. These measures will make long-term weed management less costly.

Other weed control strategies are available, some of them market-driven such as crop rotation, but governments and growers associations should help farmers to enable them to implement sound crop rotations.

The use of herbicides should be considered as another control method, which must be carefully applied to avoid problems to human health and of environmental contamination, especially in water bodies, and problems of herbicide-resistant weeds. By following the principles of IWM it is possible to reduce the use of herbicides.

For water weed control, it is clear that physical methods combined with biological control provide the best effect, but no less important is to prevent the disposal of organic wastes that serve as nutrients for weeds in water bodies.

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