Chapter 16
Challenges and Opportunities in Weed Management Under a Changing Agricultural Scenario

K. K. Barman, V. P. Singh, R. P. Dubey, P. K. Singh, Anil Dixit and A. R. Sharma

Introduction

The world's population is expected to reach 9 billion by 2050 [1]. Meeting the food requirements of this huge population will not be easy. The farmers around the world will have to produce higher yields, and simultaneously will have to give attention to a fragile environment and conserve the valuable resources of land and water. Further, population growth and economic development will result in more demand for meat and other animal products as well as fruits and vegetables [2]. Presently, about one-third of global cereal production is used as animal feed to obtain eggs, dairy products, and meat [3], and due to this increased demand for animal products, the world will face an increased pressure on cropland, fossil fuel energy, and water [4]. It is estimated that food production will need to increase by 50–100 % to support the growing and changing population [5].

Agriculture is characterized by unique combinations of soil, climate, topography, hydrology, and biological diversity, as well as a diversity of crops and production systems. A single farming system or approach will not be able to best feed the

A. R. Sharma (✉) · K. K. Barman · V. P. Singh · R. P. Dubey · P. K. Singh · A. Dixit
Directorate of Weed Science Research, Indian Council of Agricultural Research,
Jabalpur, Madhya Pradesh 482004, India
e-mail: sharma.ar@rediffmail.com

K. K. Barman
e-mail: barmankk@gmail.com

V. P. Singh
e-mail: vpsinghnrcws@gmail.com

R. P. Dubey
e-mail: dubeyrp@gmail.com

P. K. Singh
e-mail: drsinghpk@gmail.com

A. Dixit
e-mail: dranildixit@in.com

B. S. Chauhan, G. Mahajan (eds.), *Recent Advances in Weed Management,*
DOI 10.1007/978-1-4939-1019-9_16,

planet, while also protecting the environment, because of the enormous variation in agroecological circumstances across the planet as well as unpredictable weather and market conditions. A wide diversity of crops, livestock, and farming systems will help promote resilience, and will likely play a key role in future food and ecosystem security. Hence, like any other farming activities, weed management under diversified farming systems will require flexible, adaptive, and localized management systems that cannot be covered by one-size-fits-all policies. This chapter deals with the probable future agricultural scenario and consequent challenges in weed science research.

What do Weeds Cause?

Weeds have been known to humans since the very beginning of civilization. The term "weed" is used to describe a plant considered undesirable within a certain context, and usually applied to unwanted plants in human-controlled settings, viz. farm fields, gardens, lawns, and parks. The word weed does not carry any significance in relation to botanical classification, since a plant that is a weed in one context is not a weed in another context where it is wanted. For example, Bermuda grass (*Cyanodon dactylon*), unlike in crop fields, is not a weed in lawns where it is grown and nurtured. In an agricultural field, all other plants except those grown with an aim to harvest are termed as weeds. Thus, a weed may be defined as "any plant that is objectionable or interferes with the activities or welfare of man" [6]. Despite several modern weed control technologies developed with an aim to keep weeds under control, they are still a threat to agricultural productivity [7]. Weed management is more than control of existing weed problems and places greater emphasis on preventing weed reproduction, reducing weed emergence after crop planting, and minimizing weed competition with the crop [8, 9].

Weed science is an integrative, applied scientific discipline typical of most other pest management and production-oriented disciplines of modern agriculture [10]. It combines fundamental and applied sciences to study weeds, and focuses on mitigating the negative impacts of weeds in human-controlled settings, especially in agricultural production systems. Purdue University described weed science as "the study of vegetation management in agriculture, aquatics, horticulture, and right-of-way, essentially anywhere plants need to be managed. It involves the study of all the tools available for this purpose, such as cropping systems, herbicides, management techniques, and seed genetics. It is not just the controlling of plants, but the study of these plants. This includes plant ecology, physiology, and the genetics of plants species that have been identified to have impact on the economy and our ecology" [11]. Weed scientists focus their research on basic biological and ecological characteristics of weeds, and develop tools and tactics to reduce weeds and their effects in crops, rangelands, forest plantations, roadsides, and aquatic environments [12].

Weeds can effectively compete for nutrient, water, space, and light and thereby can irreversibly harm the desired plants in agricultural and horticultural farming systems. Besides that, weeds may directly or indirectly affect the management of all the terrestrial and aquatic resources and interfere with the values and activities of

Table 16.1 The negative impacts of weeds in managed ecosystems

Decrease in crop yield
Interference in harvesting operation
Increase in production cost of crops
Reduced quality of crop yield
Steal shelter and food from animals by invading the grazing areas
Inflict injury or death of animals
Act as a potential source of fire hazard in forests
Impart odors to milk and meat
Act as alternative hosts for insects and pathogens
Interfere in fisheries/aquaculture and navigation
Reduce the aesthetic and recreational value of water bodies, public parks, etc.
Interfere in irrigation water management by hindering free flow of water through canals
Cause health hazards like skin allergy, fever, asthma, nasal diseases, etc.
Restrict visibility of signs, intersections, and traffic signals along road and railways
Create hindrances in electricity installations and security operations

people belonging to various segments of society, viz. foresters, ranchers, etc. Some routinely encountered negative impacts of weeds in human-controlled settings and managed ecosystems are listed in Table 16.1.

The competitive ability of weeds is determined by several plant characteristics. One of the most common traits of a weed species is its tendency to be an annual or biennial, rather than a perennial; this allows the species a faster reproduction rate leading to a higher fecundity [13]. Another characteristic that determines the "weediness" of a species is the ability to colonize under high sunlight and low soil moisture conditions. Plants that have capabilities of dealing with herbivores as well as plants that have allelopathic traits tend to be better at outcompeting surrounding plant species. Some non-native species of plants are considered to be very weedy in nature, as they can grow faster and bigger, increase reproduction rates, and can have increased survival rates when outside of their native habitat. This may be due, in part, to the loss of environmental checks needed to keep these plants in balance within their natural habitat. Genetic makeup also determines the ability of a plant to become weedy in nature; however, a genetic pattern has yet to be described [14]. In India, out of the total 826 reported weed species, 80 species are considered as very serious and 198 as serious weeds.

History of Weed Science

Man has been plagued by unwanted plants among cultivated fields since the Biblical times. Importance of controlling weeds for better yield and use of tools for removing unwanted plants were depicted in ancient writings and archeological artifacts [10]. However, weed control received little attention or research efforts until the late 1800s and early 1900s, and for centuries, weed control has been accomplished as a by-product of seedbed preparation. Agricultural mechanization efforts largely ignored weed control implements until 1914 when the rodweeder was introduced primarily for weed control [15]. Even the modern hoe, which is synonymous with weed control, was specifically designed by Jethro Tull to break up the soil to make nutrients more readily available to the crop's roots [15]. Early methods of weed control include labor-intensive hand hoeing and hand pulling of weeds as well as cultural practices, such as crop rotation. Although *hoe-hands* are rare in developed countries, hand removal of weeds remains the dominant form of weed control in many undeveloped nations. Rotation practices were largely replaced by monoculture systems and chemical weed control by the 1940s [16]. However, in recent times, crop rotation has again become an integral part of weed management in organic farming as well as integrated weed management (IWM) practices in conventional farming systems.

Herbicidal action of some compounds for weed control was first highlighted in 1885 [17]. In fact the study of weeds as a science began with the introduction of phytotoxic chemicals for the control of weeds in the early 1900s [12]. The first chemical used to control weeds was inorganic copper salt, which was then followed by sulfuric acid. Thus, the history of weed science parallels the history of modern agriculture and is hardly 100 years old [10]. Planned weed-controlled opportunities, and thus the birth of weed science as a discipline, took place with the synthesis of 2,4-dichlorophenoxyacetic acid (2,4-D) in 1941 by Pokorny, followed by the discovery of its plant growth-regulating and herbicidal properties by Hammer and Tukey in 1944 [12]. This is the first account of a synthesized organic chemical used to control weeds [18]. Weed science received a major boost as a valid scientific discipline with the commercial acceptance of 2,4-D as an effective herbicide. Until this point, research was limited in funding as well as in interest by the scientific community; those who did dare tackle questions about weed control did so neither with the chance of recognition nor with insight from previous research. When 2,4-D appeared in the market, it offered users a cheaper option of weed control that could be applied at relatively low rates and in many agricultural settings [19]. The characteristics of 2,4-D offered hope that chemical weed control could revolutionize global food production, in turn, drawing a great deal of attention to weed control research. The success story of 2,4-D led to an explosion of synthesized herbicides during the 1940s and 1950s. By 1950, there were roughly 25 herbicides available for use [15]. By the 1960s, more than 120 effective herbicides were available for weed management, which were enough to ensure that chemical weed control was a viable replacement of labor-intensive mechanical weed removal. Thus, weed science was guaranteed a spot among respected subsets of agricultural sciences.

Introduction of glyphosate to the herbicide market in the year 1974, and subsequent development of glyphosate-resistant soybean and its commercialization in 1996, initiated a new era in modern weed science, similar to that of 2,4-D discovery [20]. This technology allowed the use of a non-selective herbicide within a row crop setting without injury to the resistant crop. This gave farmers the freedom of using a hassle-free means to control weeds in their fields as and when it was desired. Presently, attempts are being made to design an herbicide-resistant crop that contains resistance to multiple non-selective herbicides. If it becomes a reality, this feat would allow farmers greater flexibility in herbicide choice, reduce dependency on a single herbicide, and also reduce the apprehension with respect to probable evolution of glyphosate-resistant "super weed" species.

Modern Weed Management Strategies

Much advancement has been achieved in weed control since the beginning of modern weed science research. These achievements came through several complications and defeats; however, advancements have still been made and improved weed control methods have allowed farmers to witness dramatic increases in crop yield. In view of the continuous increase in world population and diminishing availability of agricultural land, it is imperative that the research in weed management progress further with the changing agricultural needs to guarantee adequate food for ourselves and posterity.

The main reason behind widespread adoption of herbicides in the industrially developed countries was socialistic, through a reduction in the need for labor and the concomitant release of people from farming [17]. Chemical weed control offered several benefits to farmers by reducing weeds, enabling early planting, reducing need for soil tillage, and providing economic advantages through reduced cost of production. However, it was not the only tool to manage weeds. The disadvantage associated with herbicide techniques is the development of herbicide resistance in weeds. The wheat growers in the Indian states of Punjab and Haryana suffered a lot during the late 1990s and early years of the last decade due to the development of isoproturon resistance in *Phalaris minor,* a major weed of this region. The problem persisted until alternative herbicides to control this weed became available in the market. The researchers developed and fine-tuned several other strategies to manage weeds to deal with various social, cultural, environmental, and economic issues. All those weed management strategies are typically grouped into five categories: preventive, cultural, mechanical (physical), biological, and chemical.

Preventive Strategies

Among all the weed control strategies, prevention is an important component, which needs greater attention. It comprises methods used for avoiding the introduction and spread of weeds, i.e., avoiding weed seed introduction into new areas including contaminated crop seeds; movement of seeds and plant parts, tillage, harvest, and processing equipment; livestock; manure and compost; irrigation and drainage water; and forage and food grains [21]. Prevention of weeds can be successful, depending upon the weed species, means of dissemination, and farm size [7]. Preventive weed management programs are successful when undertaken at a community level. Use of certified seeds by the farmers and enforcement of weed laws can make weed prevention programs successful.

Cultural Strategies

Cultural weed control comprises the principles of using plant competition or cropping practices to suppress weeds, through the use of either smother or competitive crops and crop rotation. Cultural methods may include crop sowing time and spatial arrangement, crop genotype, cover crops, intercropping, and crop fertilization.

Crop Sowing Time and Spatial Arrangement

Making modifications in crop sowing dates and sowing patterns can either reduce weed emergence or increase the competitive ability of the crop [22]. Increasing the seed rate may not only increase the competitive ability of a crop against weeds but also cause reduction in crop yield and quality of produce [23]. However, an optimum spacing may provide the benefit of both competitive ability of crop and better yield, showing the importance of closer spacing as a weed management strategy. A lower uptake of nutrients by weeds and higher weed control efficiency in closer spacing have also been reported [24].

Crop Genotype Choice

Crop genotypes may have higher or lower competitive ability against weeds. Genotypes having faster seedling emergence and quick canopy establishment [25] can reduce the need for direct weed control measures; however, the expression of competitive advantage of a genotype may vary depending upon the prevalent environmental conditions [26]. Some traits (for example, plant height) are known to provide competitive advantage against weeds [27]; however, they may not be exploited due to some other associated disadvantages (e.g., lodging). Allelopathy in some cultivars may be exploited as a part of cultural weed control [28].

Fertilization

Soil nutrition influences the crop-weed competition; hence, specific methods to use fertility management as part of IWM are needed. Management strategies that maximize nutrient uptake by crops may reduce the harmful effects of weeds to some extent and minimize nutrient availability to weeds [29]. Fertilizers applied in close proximity to the crop row can improve weed management as the probability of the crop to capture nutrients (especially nitrogen) increases [25]. Band placement of fertilizer lowered weed density, biomass, and N uptake and resulted in increased wheat yield [30]. Other methods to alter the relative nutrient availability to crops and weeds can also be manipulated by change in timing of fertilizer applications [31], altering nutrient sources [32], and by using materials, such as nitrification inhibitors [33].

Nutrient availability can also be altered by applying organic amendments, especially for nitrogen and phosphorous. Soil nutrient concentrations strongly influence the germination and early growth of many weed species [29, 34].

Crop Rotation

Crop rotation is considered as an important component of weed management. Growing similar crops in rotation over the years favors weed species that are similar to the crop. However, a diversified crop rotation disrupts the growing cycle of weeds and prevents selection of the flora toward increased abundance of problem species [35]. Environmental conditions specifically created by crop rotations affect weed survival, propagule production, and germination in the soil, and thereby subsequent weed population dynamics [36].

Intercropping

Intercropping compared to crop monocultures can influence the competitive suppression of weeds. Intercrops of differing growth forms, phenologies, and physiologies can create different patterns of resource availability, especially light, to weeds [37]. As resource availability influences weed occurrence the most [10, 38], increased resource utilization under intercropping can provide better opportunities for IWM. Intercrop sown in a row-by-row layout, besides increasing the ecological diversity in a field, decreases relative soil cover of weeds, and may result in increased total crop yield [39].

Cover Crops

Cover crops may be grown for weed control, thereby replacing an unmanageable weed population with a manageable cover crop [40]. There are at least two major types of cover crops that can be used for weed control [7]: Off-season cover crops may be taken to produce sufficient plant residue or allelochemicals to create an unfavorable environment for weed seed germination and establishment, while a smother crop displaces weeds from the harvested crop through resource competition. Basic understanding of the mechanisms by which cover crops change weed population dynamics is required for improving the effectiveness. The effect of cover crop on weeds depends upon cover crop species and composition of weed community [41]. It has been reported that small-seeded weed species are more sensitive to physical as well as to allelochemical effects of cover crops compared to large-seeded weed species [42].

Mechanical Strategies

Mechanical measures may include physical removal of growing weeds from the field by hand weeding, hoeing, mowing, burning, tilling, etc. Annual and biennial weeds and non-creeping perennials can be removed by pulling them out. This is best done when the soil is moist and before seed is produced. However, it may not be suitable for large acreages.

Mulching is done to exclude light from the top of the weeds until the reserve food supply in the roots is exhausted and the weeds wither away. Mulches may include crop straw, hay or manure, sawdust, and transparent or black plastic.

Soil solarization technique is employed to kill weed seeds through solar heating. To make the solarization effective, the soil surface must be evenly prepared and contain enough moisture to favor heat transfer throughout the profile to damage reproductive structure of weeds, resulting in reduced weed seed germination [43].

Soil tillage influences the weed flora through changes in seed distribution in the soil, effects on seed predators, and effects on weed control practices [44, 45]. It is important to change the tillage practices in component crops year after year so that weed density is reduced greatly [41]. For example, conventional tillage (CT)—zero tillage (ZT) rotation was found better than CT–CT or ZT–ZT rotation in terms of weed management in a rice–wheat system [46].

Chemical Strategies

Several factors that must be looked into, while formulating chemical options of weed control, are the effectiveness of the chemical methods, such as application methods, stage of application, and selection of suitable herbicides on the basis of the nature of weeds. Faulty herbicide application methods may cause injury to the crop. Environmental factors, herbicide residues in the farm produce, residual effects of persistent herbicide in soil, compatibility problems with other pesticides, and occupational hazard to the applicator should be studied in detail. Development of herbicide-resistant weeds in recent years and its possible consequences on weed management suggest that over-reliance on chemical methods alone may not be the best strategy.

Biological Strategies

Biological control may be defined as the actions of parasites, predators, and pathogens in maintaining another organism's density at a lower average than would occur in their absence [47, 48]. It uses natural agents such as insects, nematodes, pathogens, herbivorous fish, and even grazing animals for the control of weeds. The objective in biocontrol is to reduce a weed's density to non-economic levels, not its eradication. Biocontrol is mostly followed for non-cultivated lands with troublesome biennial or perennial weeds. It is usually not practiced in cultivated lands as the weed (food source) for the biotic agent is removed periodically. An exception is the discovery of a specific fungus that controls round-leaved mallow in wheat fields [49].

Integrated Weed Management

The goal of a weed management program should be to keep the competition offered by weeds under check and not the complete removal or eradication from the ecosystem. To achieve this, a comprehensive action plan utilizing preventive methods, scientific knowledge, management skills, monitoring procedures, and efficient use of control practices should be devised, making conditions unfavorable to the weeds and their survival [7].

A successful IWM program must include prevention of weeds from invading, knowing the identity and details of the weed species, mapping its distribution and damage, formulating control strategy based on knowledge of potential damage, cost of control method, and environmental impact of the weed, using a combination of control strategies to reduce the weed population to an acceptable level, and, finally, evaluating its effectiveness. In a study, for example, integrating cultural and mechanical weed management practices was superior to the use of individual practices because they additively control weeds in an organic cropping system [50].

Challenges to Weed Management

Human population is still increasing at a faster rate, necessitating increased production of food grains in successive years. The food consumption patterns are also likely to change drastically. Economic development of a society also increases its consumption of fruits and vegetables. Thus, the future demand for increased production of fruits, vegetables, oilseeds, and fodders will be much higher than that of cereals over their existing production level. So far, major emphasis has been placed on the development of weed management technologies for cereals. It is time for weed scientists to change their focus and place increased emphasis toward the development of improved weed management technologies for oilseeds, vegetables, fruits, and fodder crops.

Weed problems are dynamic in nature, and these are likely to be more serious in the coming years due to high-input agriculture, climate change, globalization, and a host of other factors. Future weed science is likely to encounter the following challenges:

Economic Thresholds and Weed Management

From an economical perspective, there is no reason to apply control measures unless the weed population inflicts crop damage greater than the cost of the control measure. The economic threshold is the weed density at which the cost of control equals the value of the crop that would be lost if weeds are not controlled. According to this principle, weeds are not to be controlled if their densities are below the economic threshold. But, in some instances, the decision to control a weed will have to be made even when the cost of control may be more than the immediate damage inflicted by the weed. However, the concept of economic thresholds does not take into account the future effect of weed seed production. No use of control measures at below economic threshold densities of velvetleaf lead to rapid increase in its soil seed bank and subsequent densities [51–53]. Further, the yield loss caused by a specific weed infestation may vary, depending upon the environment and crop production practices. The distribution of weeds within agricultural fields is generally not uniform; usually, they occur in patches having a high relative density surrounded by areas with low density [54]. Hence, predicting yield losses assuming a regular distribution of weeds is of little value and often results in an over-estimation of weed-related yield losses [55]. Developing a mathematical model, taking into account the irregular distribution of weeds in a field, for using the economic threshold concept in precision agriculture is an issue that requires attention.

Weed Dynamics in High-Input-Intensive Production Systems

The scope for increasing area under crops is limited, and therefore enhanced food production will necessarily have to come from vertical growth, i.e., by increasing productivity per unit area per unit time. This will require a more intensive cultivation of crops with high doses of fertilizers, irrigation, and other inputs. While these interventions will put a greater constraint on the available natural resources, the weed problems are likely to shift in unpredictable ways. It is evident that with the discontinuation of some of the traditional practices such as crop rotations, intercropping, mulching, organic manuring, etc., the soil health as well as weed scenario has undergone a sea change in many parts of the India. The ability of weed communities to shift in response to control practices suggests the need for more integrated and diverse approaches to weed management [56]. It is therefore expected that future weed problems due to adoption of modern cultivation systems will be far more complex and challenging.

Interactions of Weeds with Other Pests

The interaction of weeds with insects and diseases plays an important role in formulating integrated pest management (IPM) program. For example, weeds serve as alternative hosts for plant-parasitic nematodes, thereby reducing the success of certain nematode management strategies [57]. Herbicides used for weed control may exert an effect on plant diseases, as weeds may serve as alternate hosts to pathogenic fungi and nematodes in fields [58, 59] that damage crops. Further, herbicides may also alter the ability of crop plants toward their response to pathogens. For example, sub-lethal rates of acetolactate synthase

(ALS)-inhibiting herbicides, imazamox and propoxycarbazone-sodium, could alter severity of injury symptoms caused by *Rhizoctonia solani* in barley [60]. According to Norris and Kogan [61], there are three types of interaction mechanisms: (1) weeds act as a food source for insect-pests or predators; (2) weeds may alter habitat, which may thus increase or suppress insect infestations; and (3) changes in non-target pest populations owing to control strategies. Most major weeds and plant-parasitic nematodes are place-bound organisms and passively dispersed. Weed–nematode interactions in agricultural production systems may be more intricate and complex than the simple function of weeds as alternative hosts [62]. It is a challenge to identify effective, compatible IPM strategies that address weed and nematode management collectively.

Crop–Weed Interaction under Changing Climate

Climate change is expected to influence weed communities, and management approaches must be adapted to take this into account. Global climate change is likely to cause a widespread shift in patterns of photosynthetic limitation in higher plants [63]. In a recent review, Yamori et al. [64] found that the inherent ability for temperature acclimation of photosynthesis was different: (1) among C3, C4, and crassulacean acid metabolism (CAM) species and (2) among functional types within C3 plants. These authors have concluded that C3 plants generally had a greater ability for temperature acclimation of photosynthesis across a broad temperature range; CAM plants acclimated day and night photosynthetic process differentially to temperature, and C4 plants adapted to warm environments. Hence, the long-term threat of increasing temperature and CO_2 concentration on crop–weed interaction should be viewed seriously, since a majority of crops belong to C3, whereas large numbers of weeds belong to the C4 category. C4 plants will have an advantageous position over C3 plants (e.g., rice) under higher temperatures and limited water availability. On the contrary, elevated CO_2 levels will improve the competitiveness of C3 crops relative to C4 weeds. Increased atmospheric CO_2 levels may also improve tolerance of rice against parasitic weeds, while prevalence of parasitic species may be amplified by soil degradation and more frequent droughts or floods [65]. Climate change is expected to promote a proliferation of new weed species and cause shifts in the composition of weed flora, especially in the tropics and subtropics. As weeds are highly dynamic and adapt quickly to new conditions, the management solutions have to address an ever-changing scenario. Some reports are available on the individual effects of CO_2 and temperature on crop–weed interaction. However, the combined effect of these two factors is yet to be studied in depth. Therefore, it is essential to undertake basic and strategic research, including physiological, biochemical, and molecular aspects, to evolve weed management technologies in the context of climate change. There is a need to generate information with respect to herbicide bio-efficacy, herbicide resistance development, behavior of bio-agents, and herbicide persistence vis-à-vis climate change.

Weeds in Conservation Agriculture Systems

It is widely believed that adoption of modern agricultural practices, such as intensive tillage, clean cultivation, fixed crop rotations, and other faulty management practices, including imbalanced fertilizer application and indiscriminate use of irrigation water, has led to serious resource degradation problems. In view of these, conservation agriculture (CA) technologies involving minimum soil disturbance, permanent soil cover through crop residues or cover crops, and dynamic crop rotations are being advocated for achieving higher and sustainable productivity. Globally, the concepts and technologies for CA are being practiced in about 128 million ha area, with the major countries being the USA, Brazil, Argentina, Canada, and Australia [66]. The area is further expanding rapidly due to their potential benefits on crop productivity and farm profitability. Farmers have been benefited due to the adoption of this technology in many ways, viz.: (1) reduction in cost of production [67, 68]; (2) enhancement of soil quality, i.e., soil physical, chemical, and biological conditions [69, 70]; (3) enhancement in C sequestration and buildup in soil organic matter in the long-term [71], which is important for mitigation of climate change effects; (4) reduction in incidence of *P. minor,* a major weed in wheat [67]; (5) enhancement in water- and nutrient-use efficiency [71, 72]; (6) enhancement in production and productivity [73]; (7) advances in sowing date [67]; (8) greater environmental sustainability [74]; (9) no loss of nutrients and no environmental pollution as crop residues are not burnt [75]; (10) opportunities for crop diversification and intensification [76]; (11) enhanced resource-use efficiency through residue decomposition, soil structural improvement, increased recycling and availability of plant nutrients [69]; and (12) moderate soil temperature, reduced evaporation, and improved biological activity through residue mulch [70, 77].

Changes from conventional to conservation farming practices often lead to weed flora shift in the crop field, which in turn also dictate the requirement of a new weed management technology. As the density of certain annual and perennial weeds increases under CA, effective weed control techniques are required to manage weeds successfully. The development of post-emergence broad-spectrum herbicides immensely ushered the way of controlling weeds in CA-based systems. However, weeds are still a big constraint toward the adoption of CA, and there is a need for developing more effective and economic IWM practices in diversified cropping systems by including various approaches, viz. preventive measures, cultural practices, and herbicides. There is a need to carry out an analysis of factors affecting adoption and acceptance of no-tillage agriculture among farmers. A lack of information on the effects and interactions of minimal soil disturbance, permanent residue cover, planned crop rotations, and IWM, which are key CA components, can hinder CA adoption [78]. This is because these interactions can have positive and negative effects, depending on regional conditions. The positive impacts should be exploited through system research to enhance CA crop yields. Information has mostly been generated on the basis of research trials, and more on-farm-level research and development is needed. Farmers' involvement in participatory research and demonstration trials can accelerate adoption of CA, especially in the areas where CA is a new technology.

Management of Herbicide Resistance in Weeds

Herbicide resistance in weeds is a major limiting factor to food security in global agriculture. Herbicide-resistant biotypes emerged in many regions of the world as a consequence of the intensive use of herbicides. Isoproturon resistance in *P. minor* in some parts of India was a costly lesson learnt, as the weed devastated the wheat crop and threatened the sustainability of the rice–wheat system for nearly a decade until some new alternate herbicides were introduced. This kind of phenomenon may continue to be a problem in the foreseeable future as well. The adoption of zero tillage is expected to further increase the use of non-selective herbicides, viz. glyphosate, glufosinate, and paraquat as a pre-plant application. There are currently 400 unique cases (species × site of action) of herbicide-resistant weeds globally, with 217 species (129 dicots and 88 monocots) [79]. Weeds have evolved resistance to 21 of the 25 known herbicide sites of action and to 148 different herbicides. Herbicide-resistant weeds have been reported in 65 crops in 61 countries. Therefore, it is important to monitor the impact of the evolution of resistance against nonselective herbicides under zero-till conditions and develop management strategies. Instead of depending on one particular technique, weed management methods are to be rotated and suitably integrated. Formation of broad-based special resistance management groups, involving both herbicide industries and core scientists, to monitor the resistance development and solutions is becoming imperative.

Minimizing herbicide resistance represents a big challenge that will require great research efforts to develop alternative control strategies. As pointed out by Busi et al. [80], weed scientists, plant ecologists, and evolutionary biologists should join forces and work toward an improved and more integrated understanding of resistance across all scales to facilitate the design of innovative solutions to the global herbicide resistance challenge. These authors have also noted that future research should integrate questions about standing genetic variation versus *de novo* resistance mutations, fitness benefits, and costs under herbicide selection and links between metabolic resistance and general detoxification pathways involved in stress-response dynamics.

Herbicide-Tolerant Crops and Evolution of Super Weeds

There has been a boom in the adoption of genetically modified (GM) crops over the past 15 years as the total area covered with GM crops has increased from 1.7 m ha in 1996 to more than 175 m ha in 2013. However, concerns are being raised about the possible environmental impact of this technology. Yet, few studies have conducted a critical needs analysis to assess the potential of specific GM traits in light of issues, such as climate change, increased environmental legislation (e.g., EU Water Framework, Nitrates Directive, proposed reform to the Pesticide Directive and Common Agricultural Policy reform), mitigating biodiversity loss, and sustainable biofuel production [81].

The potential for weed resistance to specific herbicide is always a concern with herbicide programs. It is more of a concern when talking about herbicide-tolerant crops (HTCs), as weed management in these crops depends on a specific herbicide only. On the other, some HTCs are becoming volunteer weeds and causing segregation and introgression of herbicide-resistant traits in weed populations [82]. Beckie and Warwick [83] reported that oilseed rape transgenes can survive in the environment for several years even if all cultivars with the conferred trait are removed from the area. There are also other apprehensions about HTCs as follows:

- Increase in use of a specific herbicide that may promote the development of herbicide-resistant weeds because of over-reliance on a single herbicide or a group of closely-related herbicides. *Conyza canadensis* has been reported to develop resistance against glyphosate in zero-till roundup ready corn–soybean rotations in the USA [84].
- Adverse effect on the biodiversity of the farm
- Gene-drift from HTCs to similar species may confer the resistance to their wild relatives, which can become serious weed in the crop
- Possibility of the development of "super weeds" due to introduction of these crops

Therefore, the HTCs should not be considered as a stand-alone component of weed management. Further, adoption of HTC has risen dramatically since their commercial introduction, but there is still no evidence of associated production cost reductions or enhanced yields [85], but the anticipated concerns about their actual benefits and effects on the environment are yet to be fully addressed.

Growing Infestation of Parasitic Weeds

Parasitic plants are problems mostly in the Mediterranean and tropical agriculture in major crops. The most economically damaging parasitic weeds are members of the genera *Striga* (witchweeds), *Orobanche* (broomrapes), and *Cuscuta* (dodder). For example, serious infestations of *Orobanche* in many tomato, mustard, tobacco, and potato-growing areas of India are causing huge losses in productivity. The weed emerges from soil in the middle and later stages of growth, by which time, it has already caused enough damage to the host plant. Biology of these weeds is not well understood, and there is no simple solution for their management worldwide. In spite of several efforts, the major problems of parasitic weeds have not been reduced to any significant degree [86] and in the case of *Striga,* there may even continue to be some spread and intensification of the problems [87].

The main focus of research on parasitic weeds has been around agronomic practices and the use of herbicides, although success has been marginal. In addition, global environment change together with changing land-use patterns means that some geographical areas and farming systems that do not currently suffer from parasitic weeds could become affected within coming decades [88]. It is, therefore, necessary to develop management technologies for these weeds, which are spreading to newer areas and parasitizing many other host plants. Biocontrol approach is expected to make valuable contributions to manage parasitic weeds, especially *Striga*. Increasing soil fertility is perhaps the only way to manage *Striga* as of now [87].

Environmental Impact of Herbicides

Herbicides have the capacity to move in the environment away from the target area and to cause damage to non-target plants and animals. More than 95 % of herbicides reach a destination other than their target species, including non-target species, air, water, bottom sediments, and food [89]. Hence, it is a big challenge to use herbicides in the safest way for ensuring food and biological security.

The impact of herbicides on soil, however, differs depending upon the soil type, experimental conditions, herbicide in question and its dose, and the sensitivity of the non-target species or strains. No severe ill effect on soil flora, soil biochemical indices, and soil fauna has been observed so far at recommended doses of herbicides under field conditions [90], but the adverse effects of their overdose or long-term use cannot be discounted. Systematic research on long-term herbicide usage on soil health and water bodies is needed. Widespread and increasing use of herbicides is likely to cause greater concern about potential ecological effects. Hence, how herbicide use offsets the delicate ecological balance should also be an area of priority. To avoid the potential ill effects, strict registration and stringent regulatory mechanisms are to be developed.

Monitoring herbicide residues in the environment and food chain should continue to be an important activity as new chemicals are expected to be introduced into the market. Permanent herbicide trials have to be planned in major cropping systems under different agroecological regions, which would yield a wealth of information on the long-term implications of herbicide use, including effect on crop productivity, weed flora shifts, resistance of weeds, etc. In addition, degradation pathways and mitigation strategies of herbicide residue hazards need to be developed to lessen their effect on the environment.

Weeds in Organic Farming Systems

Growing concern for human health and sustainability of agricultural production are giving way to organic farming in some parts of the world. However, weed management is a major concern for organic farmers and is seen as a major obstacle for the conversion toward organic farming [91]. Effective weed management strategies are limited in organic cropping systems owing to the prohibition of herbicide use. Organically cultivated fields show higher levels of weed infestation compared to conventional agriculture [92], and it is a big challenge to make the non-chemical methods of weed control effective and economical. Mechanical approaches, generally used to manage weeds in this system, provide lower weed control efficiency than herbicides [93]. But at some instances, weed harrowing may provide yields similar to weed-free situations [94]. Soil solarization may be a useful tool in nurseries and in high-value crops under organic agriculture; it is not yet a practicable option for field crops due to high cost. Although *P. minor* was controlled in wheat to some extent by using ZT technology in the Indo-Gangetic Plains, such success has not been achieved in other crops and weed species. Plant allelochemical or essential oil-based organic herbicides are available commercially, but these are very expensive and are utilized mainly for spot applications in a field to deal with a localized infestation of noxious weeds [95]. Currently, no bioherbicides based on specific plant pathogens are available commercially. In maize, growing cowpea as an intercrop for fodder or green manure has been found to suppress the weeds significantly. In mustard, better weed control and higher total productivity can be obtained by intercropping with berseem. Incorporation of *Sesbania* grown as an intercrop (brown manuring) in upland direct-seeded rice can be adopted for managing weeds and obtaining higher productivity. Enhancing a crop's competitive ability by integrating both cultural and mechanical weed control methods is a key strategy in organic systems, but the relative efficacy of different cultural and mechanical strategies and their interactions and additive effects when combined is not well known [50]. There is ample scope of developing system-based approaches and mechanical tools as part of IWM strategies in organic farming systems.

Obnoxious Weeds

Invasive weeds are an important problem for natural and agronomic systems and a major threat to global biodiversity [96]. According to the evolution of increased competitive ability (EICA) hypothesis, plants in invasive range allocate more to growth than to defense [97], and consequently the invasive plants perform better than plants of the same species from the native range. Abela-Hofbauerová and Münzbergová [98] observed that the plants from the invasive range have higher ability to use resources and are thus able to perform well even in nutrient-poor conditions. Further, the invasive potential of some alien invasive weed species may be enhanced due to absence of natural enemies [99, 100].

Obnoxious weeds, such as *Lantana, Parthenium, Ageratum, Chromolaena, Mikania,* and *Mimosa,* have invaded vast areas of forest, grasslands, wastelands, orchards, and plantation crops across the world. *Parthenium,* one of the seven most difficult weeds of the world, was previously a problem on roadsides and non-cultivated areas in India and is now entering into the field crops. *Chromolaena odorata was* earlier restricted to the north-eastern region and Western Ghats but it is now fast spreading to other areas. Similarly, *Mikania micrantha,* which is popularly called mile-a-minute weed on account of its rapid growth, is a big nuisance in forestry and plantation crops in northeast and south India [101]. *Lantana camara* has invaded large areas of non-crop lands in the north-western Himalayan region. *Ag-*

Table 16.2 World's major weeds that have not yet been recorded in India. (Source: Holm et al. [103])

Country	No. of weed species
Australia, New Zealand	195
African countries	181
SE Asia, Far East	150
Middle East	118
South America	102
Europe	90
Central America	86
North America	33
Former Soviet Union	20
Total	*975*

eratum has become a big nuisance in both crops and non-cropped areas. Widespread infestation of these weeds has threatened not only agricultural production systems but also biodiversity and human and animal health.

There are several barriers to the effective control of obnoxious weeds. For instance, a lack of public awareness about the invasiveness and ill effects of these weeds lead to limited public and legislative support; this consequently leads to insufficient human and fiscal resources to contain the weed problem. Due to insufficient resources, weed control efforts often lack planning and monitoring for effectiveness. Preventing the spread of these weeds before the situation gets more serious requires a great deal of money and people's participation.

Globalization and New Weed Problems

Weeds are spread internationally as contaminants through trade, travel, and illegal activities. For example, *Chromolaena odorata,* introduced from the West Indies in the ballasts of cargo boats [102], and *M. micrantha,* from Central and South America after the Second World War to camouflage airfields, have become great problems for plantations and forests in eastern and southern parts of India. Similarly, *Parthenium,* a menace in civic amenities, and *P. minor,* a major weed in wheat along the Indo-Gangetic Plains, were introduced in India through imported wheat grain from the USA.

Although the risk of entry is minimized by quarantine arrangements, an increased exchange of grains and seeds following globalization of agricultural trade is expected to further enhance the probability of entry of weeds in a new territory. For example, there are several weeds of invasive nature existing in different parts of the world, but they are not in India (Table 16.2) [103]. Increasing trade and globalization coupled with liberalization policies will, however, increase the risk of invasion by these weeds in India. The sanitary and phytosanitary agreement of the World Trade Organization (WTO) suggests that the countries should not only update their quarantine laws but also incorporate the elements of pest-risk analysis for making regulatory decisions for both import and export. Therefore, there is an urgent need to analyze the risk factor associated with different exotic weeds to design safeguards and to lower the risk of their entry. Many countries like Australia, New Zealand, and the USA have developed strong protocols for weed risk analysis and for identification of quarantine weeds. Similarly, other countries of the world should strengthen their capacity on weed risk analysis and develop more stringent guidelines and standards for prevention of introduction of alien, invasive weeds into the respective countries.

Dissemination of Weed Management Technologies

Improved weed management technologies have not reached the Indian farmers and elsewhere at the same pace as it happened in case of high-yielding varieties, fertilizers, and insecticides. Compared to the other improved agricultural practices in cereals, adoption of chemical weed management technologies by farmers is very dismal in India [104]. Similarly, adoption gap of sugarcane technologies was more in weed control followed by plant protection measures, time of sowing, irrigation, sowing methods, high-yielding varieties, and seed rate [105]. Lack of awareness and technical know-how among the farming community are the reasons for poor adoption of weed management technologies. Sometimes, extension agents and other traditional information dissemination mechanisms, such as using community decision leaders, neighbors, and seminars, are largely ineffective in the dissemination of weed management technologies [106]. The use of weeds as livestock feeds, fuel wood, construction material, and as medicines is also one of the deterrents toward non-adoption of new weed management technologies. In some places, the herbicides are not available locally to those farmers who are interested in using use them. Intensive training programs [107] and TV programs [108, 109] could be the effective extension techniques to enhance adoption of chemical weed control practices. Information about safe use of herbicides, herbicide application technology for higher efficacy, and integrating chemicals with other methods of weed management are also to be disseminated. However, overcoming the challenge of lesser attention of the growers toward adoption of new weed management practices than other production technologies, viz. seeds and fertilizers, is a matter of concern.

Site-Specific Weed Management

The concept of site-specific agriculture [110] is applicable to weed management, owing to the spatial and temporal heterogeneity of weed populations across agricultural fields [54, 111]. The uniform application of herbicides over heterogeneously distributed weed populations may lead to inefficiency in weed management [51]. Site-specific weed management may result in savings of herbicides and ecological and economical benefits.

Site-specific management of weeds involves locating specific areas of infestation and identification of weeds in a field for necessary herbicide treatments depending on the weed species present [112]. This will require a more precise application of weed management principles and biology to determine where, when, and what control practices are to be applied. Patchy weed distributions are the result of efforts made to manage weeds uniformly; it will also be important to notice whether site-specific management will change the nature of weed populations in fields.

Opportunities

With the advent of chemical weed control in the early 1940s, the contribution of weed science has been immense in increasing and sustaining the global food production. Herbicides became the mainstay for management of weeds more particularly in developed countries. In view of the changing climate, new cropping systems, weed shifts, changing land use, and environmental concerns, new opportunities in weed science exist that need to be exploited at a faster pace. The emerging problems could only be addressed when weed science works hand-in-hand with other disciplines on complex issues in vegetation management, viz. ecological weed management, molecular biology and physiology of weedy traits, invasion biology, and ecosystem restoration.

The following opportunities in weed science need to be exploited for efficient and safer weed management in future:

- Safer low-dose synthetic molecules of various modes of action will be introduced to replace more conventional herbicides. New formulations and spraying technologies of herbicides will be developed.
- Alternate weed control strategies involving mechanical, cultural, and biocontrol will also be given importance. A search for bioactive botanicals and microbial metabolites, which may act as lead molecules for herbicide development, is important.
- Breakthroughs made in biotechnology could be taken to advantage, leading to development of new HTCs and strains of bio-agents for specific weed control.
- The changing global climate may create new opportunities for the introduction of alien, invasive weed species. Immediate action to thwart their introduction to newer areas will help in protecting the biodiversity of native species.
- Climate change research would provide further insights into crop–weed association, herbicide, and bio-agent efficacy for developing effective weed management technologies.
- Research on nano-composite-based controlled release formulation is essential for precision weed management. The controlled release of herbicide molecules in application zones provides long-term control of weeds, avoiding repeated application of herbicides. These formulations minimize herbicide residues in the

environment, increase the efficacy and longevity of the herbicide by protecting it from environmental degradation, and decrease the application cost.

- Using remote sensing technologies for site-specific weed monitoring and their management under precision agriculture will greatly help in avoiding wastage of herbicides and minimizing residue hazards.
- A growing demand for cheap and effective non-chemical weed control measures, i.e., mechanical, cultural, bioherbicides, and biocontrol agents in the era of environmental awareness is observed.
- Innovative production systems such as CA are being developed for enhancing resource-use efficiency, crop productivity, and environmental sustainability. Weed management in such systems would require greatly enhanced knowledge and application. New-generation machines for tillage, sowing, interculture, spraying, harvesting, and residue management are being developed, which will provide cost-effective means of weed management.
- New tools aimed at more effective transfer of technology for weed management are available in the era of ICT. Management Information Systems (MIS) are required for researchers and farmers to obtain quick access of weed management technology.
- Efficient diagnostic techniques for monitoring herbicide residues would lead to safer chemical weed control and a cleaner environment. Effective decontamination techniques for active and transformation products will provide opportunities for mitigation of residue hazards.
- Solar energy-aided microwave-generating device may be helpful for the control of target weeds. The success of it may reduce herbicide consumption manifold. This device coupled with sensor technology may become the part of precision and automated weed control technology.
- Robotic science may also come in aid of weed science for environmentally safe weed management.
- Weed utilization techniques are available for effective conversion of weed biomass into enriched compost, medicinal use, bioremediation, and industrial application.

Conclusion

The dynamic nature of weed populations makes them a never-ending problem in crop fields. The cropping environment and the production practices—viz. crop rotation, tillage, fertilization, crop spacing, herbicides, irrigation, etc.—together dictate the nature and intensity of weed infestation. Accordingly, various approaches of weed management have evolved in the history of weed science. Because of the complexity and diversity of weed communities, application of a given control tactic leads to a weed population shift, thereby compelling the grower to use another tactic, and the cycles go on. This situation demands the use of integrated approaches involving more than one control tactic to favor the crop in its competition over weeds for natural resources.

The growing demand for food grains and other agricultural products on one hand and the shrinking availability of agricultural land on the other hand are already the burning problems being faced by agriculture. Further, climate change is predicted to affect precipitation rates and patterns, which will consequently affect temperature, growing season, soil moisture levels, and other critical agricultural production factors. All these developments are expected to force the growers to shift toward highly intensive production systems using newer production technologies. Weeds, being highly complex and competitive, and due to their wild and dynamic nature, are expected to adapt and remain a problem in the future production systems, and will necessarily create demand for newer integrated control tactics. Moreover, the way in which the interaction of weeds with crops and other pests will move under the changing climate is yet a domain of unknown probabilities. Developing innovative and economical weed management tactics to make more diverse and integrated approach of weed management for the future cropping systems is a great challenge and a continuous process for weed scientists.

Availability of herbicides simplified the weed management and benefitted the agricultural community in many ways, viz. timely weeding, overcoming the problem of labor shortage, reducing production cost, etc. However, the over-reliance on herbicides has already shown its consequences in the form of weed resistance to herbicides, and adoption of HTCs may further exuberate such a situation. Hence, the challenge is to manage herbicides in a manner that prevents adapted weed species from reaching troublesome proportions. Development of site-specific weed management systems is another challenge to be sorted out to reduce herbicide consumption and also to reduce the environmental impact of herbicides by preventing herbicide load where it is not required.

Present-day agriculture is also facing the problem of transborder movement of weed seeds being accompanied by the growing international trade of agricultural produce. It is of greater concern if the alien species are obnoxious and invasive in nature. Risk assessment and developing management tactics for such weeds in a newer environment are always a challenge.

Technology dissemination is as important as technology development. Minimum attention has been paid by the growers toward adoption of new weed management practices as compared to the adoption of other production technologies (viz. seeds and fertilizers), which is a matter of concern for the weed scientists.

References

1. UNPD (2011) United nations population division, department of economic and social affairs. World population prospects: the 2010 revision. New York: United Nations. http://esa.un.org/unpd/wpp/Excel-Data/population.htm. Accessed 24 May 2014
2. Von Braun J (2007) The world food situtation: new driving forces and required actions. International Food Policy Research Institute, Washington, DC

3. Reijinders L, Soret S (2003) Quantification of the environmental impact of different dietary protein sources. Am J Clin Nutr 78(suppl):664–668
4. Pimentel D, Pimentel M (2003) Sustainability of meat-based and plant-based diets and the environment. Am J Clin Nutr 78(suppl):660–663
5. World Bank (2007) World development report 2008: agriculture for development. World Bank, Washington, DC
6. WSSA (2002) Herbicide handbook. Weed Science Society of America, Lawrence, 462 pp
7. Buhler DD (2002) Challenges and opportunities for integrated weed management. Weed Sci 50:273–280
8. Buhler DD (1996) Development of alternative weed management strategies. J Prod Agric 9:501–505
9. Zimdahl RL (1991) Weed science—a plea for thought. US Department of Agriculture, Cooperative State Research Service, Washington, DC, 34 pp
10. Radosevich SR, Holt JS, Ghersa CM (1997) Weed ecology, implications for management. Wiley, New York, pp 3–4, 37–40
11. Purdue University Weed Science (2013) https://ag.purdue.edu/btny/weedscience/Pages/default.aspx. Accessed 24 Oct 2013
12. Hamill AS, Holt JS, Mallory-Smith CA (2004) Contributions of weed science to weed control and management. Weed Technol 18:1563–1565
13. Sutherland S (2004) What makes a weed a weed: life history traits of native and exotic plants in the USA. Oecologia 141:24–39
14. Ward SM, Gaskin JF, Wilson LM (2008) Ecological genetics of plant invasion: what do we know? Invasive Plant Sci Manage 1:98–109
15. Timmons FL (2005) A history of weed control in the United States and Canada. Weed Sci 53:748–761
16. Appleby AP (2005) A history of weed control in the United States and Canada—a sequel. Weed Sci 53:762–768
17. Das TK (2008) Weed science—basics and applications. Jain Brothers, New Delhi
18. Stephenson GR, Solomon KR, Frank R, Hsiung T, Thompson DG (2001) Pesticides in environment, section 3. University of Guelph, Guelph, pp 1–12
19. Ross MA, Lembi CA (1999) Applied weed science, 2nd edn. Prentice Hall, Upper Saddle River
20. Green JM, Hazel CB, Forney DR, Pugh LM (2008) New multiple herbicide resistance and formulation technology to augment the utility of glyphosate. Pest Manage Sci 64:332–339
21. Walker RH (1995) Preventative weed management. In: Smith AE (ed) Handbook of weed management systems. New York: Marcel Dekker, pp 35–50
22. Mohler CL (1996) Ecological bases for the cultural control of annual weeds. J Prod Agric 9:468–474
23. Litterick AM, Redpath J, Seel W, Leifert C (1999) An evaluation of weed control strategies for large-scale organic potato production in the UK. In: Proceeding of the 1999 Brighton Conference—Weeds, Brighton, UK, pp 951–956
24. Sindhu PV, George CT, Abraham CT (2013) Plant population and SRI management on crop-weed competition in rice in the humid tropics of Kerala, India. Indian J Agric Res 47:288–295
25. Rasmussen K, Rasmussen J (2000) Barley seed vigour and mechanical weed control. Weed Res 40:219–230
26. Lemerle D, Verbeek B, Orchard B (2001) Ranking the ability of wheat varieties to compete with *Lolium rigidum*. Weed Res 41:197–209
27. Benvenuti S, Macchia M (2000) Role of durum wheat (*Triticum durum* Desf.) canopy height on *Sinapis arvensis* L. growth and seed production. In: Proceeding of XIème Colloque International sur la Biologie des Mauvaises Herbes, Dijon, France, pp 305–312
28. Olofsdotter M (2001) Rice—a step toward use of allelopathy. Agron J 93:3–8
29. DiTomaso JM (1995) Approaches for improving crop competitiveness through the manipulation of fertilization strategies. Weed Sci 43:491–497
30. Kirkland KJ, Beckie HJ (1998) Contribution of nitrogen fertilizer placement to weed management in spring wheat (*Triticum aestivum*). Weed Technol 12:507–514

31. Anderson RL (1991) Timing of nitrogen application affects downy brome (*Bromus tectorum*) growth in winter wheat. Weed Technol 5(3):582–585
32. DeLuca TH, DeLuca DK (1997) Composting for feedlot manure management and soil quality. J Prod Agric 10:235–241
33. Teyker RH, Hoelzer HD, Liebl RA (1991) Maize and pigweed response to nitrogen supply and form. Plant Soil 135:287–292
34. Karssen CM, Hillhorst HWM (1992) Effect of chemical environment on seed germination. In: Fenner M (ed) Seeds: the ecology of regeneration in plant communities. CAB International, Wallingford, pp 327–348
35. Karlen DL, Varvel GE, Bullock DG, Cruse RM (1994) Crop rotations for the 21st century. Adv Agron 53:1–45
36. Liebman M, Gallandt ER (1997) Many little hammers: ecological management of crop-weed interactions. In: Jackson LE (ed) Ecology in agriculture. Academic, San Diego, pp 291–343
37. Ballare CL, Casal JJ (2000) Light signals perceived by crop and weed plants. Field Crops Res 67:149–160
38. Harper JL (1977) The limiting resources in the environment. In: The population biology of plants. Academic, London, pp 305–346
39. Baumann DT, Kropff MJ, Bastiaans L (2000) Intercropping leeks to suppress weeds. Weed Res 40:359–374
40. Teasdale JR (1998) Cover crops, smother plants, and weed management. In: Hatfield JL, Buhler DD, Stewart BA (eds) Integrated weed and soil management. Ann Arbor, Chelsea, pp 247–270
41. Bàrberi P, Mazzoncini M (2001) Changes in weed community composition as influenced by cover crop and management system in continuous corn. Weed Sci 49:491–499
42. Liebman M, Davis AS (2000) Integration of soil, crop, and weed management in low-external-input farming systems. Weed Res 40:27–47
43. Temperini O, Bàrberi P, Paolini R, Campiglia E, Marucci A, Saccardo F (1998) Solarizzazione del terreno in serra-tunnel: effetto sulle infestanti in coltivazione sequenziale di lattuga, ravanello, rucola e pomodoro. In: Proceeding of XI SIRFI Biennial Congress, Bari. 12–13 November. (Italian), Italy, pp 213–228
44. Brust GE, House GJ (1988) Weed seed destruction by arthropods and rodents in low-input soybean agroecosystems. Am J Altern Agric 3:19–25
45. Buhler DD (1995) Influence of tillage systems on weed population dynamics and management in corn and soybean in the central USA. Crop Sci 35:1247–1258
46. Mishra JS, Singh VP (2012) Effect of tillage sequence and weed management on weed dynamics and productivity of dry-seeded rice (*Oryza sativa*)-wheat (*Triticum aestivum*) system. Indian J Agron 57:14–19
47. DeBach P (1964) The scope of biological control. In: De Bach P (ed) Biological control of insect pests and weeds. Chapman and Hall, London, pp 3–20
48. McFayden RE (1998) Biological control of weeds. Ann Rev Entomol 43:369–393
49. Mortensen K (1988) The potential of an endemic fungus, *Colletotrichum gloeosporioides*, for biological control of round-leaved mallow (*Malva pusilla*) and velvetleaf (*Abutilon theophrasti*). Weed Sci 36:473–478
50. Benaragama D, Shirtliffe SJ (2013) Additive weed control by integrating cultural and mechanical weed control strategies in an organic cropping system. Agron J 105:1728–1734
51. Cardina J, Johnson GA, Sparrow DH (1997) The nature and consequences of weed spatial distribution. Weed Sci 45:364–373
52. Hartzler RG (1996) Velvetleaf (*Abutilon theophrasti*) population dynamics following a single year's seed rain. Weed Technol 10:581–586
53. Zanin G, Sattin M (1988) Threshold level and seed production of velvetleaf (*Abutilon theophrasti*) in maize. Weed Res 28:347–352
54. Cardina J, Sparrow DH, McCoy EL (1996) Spatial relationships between seedbank and seedling populations of common lambsquarters (*Chenopodium album*) and annual grasses. Weed Sci 44:298–308

55. Wiles LJ, Wilkerson GG, Gold HJ, Coble HD (1992) Modeling weed distribution for improved post-emergence control decisions. Weed Sci 40:546–553
56. Buhler DD, Liebman M, Obrycki JJ (2000) Theoretical and practical challenges to an IPM approach to weed management. Weed Sci 48:274–280
57. Duncan LW, Noling JW (1998) Agricultural sustainability and nematode integrated pest management. In: Barker KR, Pederson GA, Windham GL (eds) Plant and nematode interactions. Agronomy monograph 36. ASA, Crop Science Society of America, Soil Science Society of America, Madison, pp 251–287
58. Grönberg L, Andersson B, Yuen J (2012) Can weed hosts increase aggressiveness of phytophthora infestans on potato? Phytopathology 102:429–433
59. Boydston RA, Mojtahedi H, Bates C, Zemetra R, Brown CR (2010) Weed hosts of *Globodera pallida* from Idaho. Plant Dis 94:918
60. Lee H, Ullrich SE, Burke IC, Yenish J, Paulitz TC (2012) Interactions between the root pathogen *Rhizoctonia solani* AG-8 and acetolactate-synthase-inhibiting herbicides in barley. Pest Manage Sci 68:845–852
61. Norris RF, Kogan M (2000) Interactions between weeds, arthropod pests, and their natural enemies in managed ecosystems. Weed Sci 48:94–158
62. Thomas SH, Schroeder J, Murray LW (2005) The role of weeds in nematode management. Weed Sci 53:923–928
63. Sage RF, Kubien DS (2007) The temperature response of C3 and C4 photosynthesis. Plant Cell Environ 30:1086–1106
64. Yamori W, Hikosaka K, Way DA (2013) Temperature response of photosynthesis in C3, C4, and CAM plants: temperature acclimation and temperature adoption. Photosynth Res. doi:10.1007/s1 1120-013-9874-6
65. Rodenburg J, Meinke H, Johnson DE (2011) Challenges for weed management in African rice systems in a changing climate. J Agric Sci 149:427–435
66. FAO (2013) Food and agriculture organization of the United Nations, 2012. http://www.fao.org/ag/ca/6c.html. Accessed 24 May 2014
67. Malik RK, Gupta RK, Singh CM, Yadav A, Brar SS, Thakur TC, Singh SS, Singh AK, Singh R, Sinha RK (2005) Accelerating the adoption of resource conservation technologies in rice wheat system of the Indo-Gangetic plains. In: Proceedings of project workshop, directorate of extension education, Chaudhary Charan Singh Haryana Agricultural University, June 1–2, 2005, Hisar, India
68. RWC-CIMMYT (2005) Agenda notes. 13th regional technical coordination committee meeting. RWC-CIMMYT, Dhaka, Bangladesh
69. Jat ML, Gathala MK, Ladha JK, Saharawat YS, Jat AS, Kumar V, Sharma SK, Kumar V, Gupta R (2009a) Evaluation of precision land leveling and double zero-till systems in rice-wheat rotation: water use, productivity, profitability and soil physical properties. Soil Tillage Res 105:112–121
70. Gathala MK, Ladha JK, Saharawat YS, Kumar V, Kumar V, Sharma PK (2011b) Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice−wheat rotation. Soil Sci Soc Am J 75:1851–1862
71. Saharawat YS, Ladha JK, Pathak H, Gathala M, Chaudhary N, Jat ML (2012) Simulation of resource-conserving technologies on productivity, income and greenhouse gas emission in rice-wheat system. J Soil Sci Environ Manage 3:9–22
72. Jat ML, Malik RK, Saharawat YS, Gupta R, Mal B, Paroda R (2012) Proceedings of regional dialogue on conservation agricultural in South Asia, New Delhi, India, 1–2 November, 2011. APAARI, CIMMYT, ICAR, p 32
73. Gathala MK, Ladha JK, Kumar V, Saharawat YS, Kumar V, Sharma PK, Sharma S, Pathak H (2011a) Tillage and crop establishment affects sustainability of south asian rice-wheat system. Agron J 103:961–971
74. Pathak H, Saharawat YS, Gathala M, Mohanty S, Chandrasekharan S, Ladha JK (2011) Simulating the impact of resource conserving technologies in rice-wheat system on productivity, income and environment—part I. Green house gases. Sci Technol 1:1–17

75. Sidhu HS, Singh M, Humphreys E, Singh Y, Singh B, Dhillon SS, Blackwell J, Bector VM, Singh S (2007) The happy seeder enables direct drilling of wheat into rice straw. Aust J Exp Agric 47:844–854
76. Jat ML, Singh S, Rai HK, Chhokar RS, Sharma SK, Gupta RK (2005) Furrow irrigated raised bed planting technique for diversification of rice-wheat system of Indo-Gangetic plains. J Jpn Assoc Int Coop Agric For 28:25–42
77. Jat ML, Singh RG, Saharawat YS, Gathala MK, Kumar V, Sidhu HS, Gupta R (2009b) Innovations through conservation agriculture: progress and prospects of participatory approach in the Indo-Gangetic plains. In: Pub lead papers, 4th world congress on conservation agriculture, 4–7 February, 2009. India, New Delhi, pp 60–64
78. Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM (2011) Crop yield and weed management in rainfed conservation agriculture. Soil Tillage Res 117:172–183
79. Heap I (2013) The international survey of herbicide resistant weeds. http://www.weedscience.org. Accessed 21 Dec 2013
80. Busi R, Vila-Aiub MM, Beckie HJ, Gaines TA, Goggin DE, Kaundun SS et al (2013) Herbicide-resistant weeds: from research and knowledge to future needs. Evol Appl 6:1218–1221
81. O'Brien M, Mullins E (2009) Relevance of genetically modified crops in light of future environmental and legislative challenges to the agri-environment. Ann Appl Biol 154:323–340
82. Owen MDK, Zelaya IA (2004) Herbicide-resistant crops and weed resistance to herbicides. Pest Manage Sci 61:301–311
83. Beckie HJ, Warwick SI (2010) Persistence of an oilseed rape transgene in the environment. Crop Prot 29:509–512
84. Mueller TC, Massey JH, Hayes RM, Main CL, Stewart CN Jr (2003) Shikimate accumulates in both glyphosate-sensitive and glyphosate-resistant horseweed (*Conyza canadensis* L. Cronq.). J Agric Food Chem 51:680–684
85. Martinez-Ghersa MA, Worster CA, Radosevich SR (2003) Concerns a weed scientist might have about herbicide-tolerant crops: a revisitation. Weed Technol 17:202–210
86. Parker C (2009) Observations on the current status of *Orobanche* and *Striga* problems worldwide. Pest Manage Sci 65:453–459
87. Parker C (2012) Parasitic weeds: a world challenge. Weed Sci 60:269–276
88. EWRS (2014) Parasitic weeds working group. http://www.ewrs.org/parasitic_weeds_details.asp. Accessed 4 Jan 2014
89. Miller GT (2004) Sustaining the earth, 6th edn. Thompson Learning, Pacific Grove, pp 211–216
90. Barman KK, Varshney JG (2008) Impact of herbicides on soil environment. Indian J Weed Sci 40:10–17
91. Sumption P, Firth C, Davies G (2004) Observation on agronomic challenges during conversion to organic field vegetable production. In: Hopkins A (ed) Organic farming: science and practice of profitable livestock and cropping. Proceedings of the BGS/AAB/COR conference. British Grassland Society, pp 176–179
92. Romero A, Chamorro L, Sans FX (2008) Weed diversity in crop edges and inner fields of organic and conventional dry-land winter cereal crops in NE Spain. Agric Ecosyst Environ 124:97–104
93. Lundkvist A (2009) Effect of pre- and post- emergence weed harrowing on annual weeds in peas and spring cereals. Weed Res 49:409–416
94. Armengot L, Jos-Maria L, Chamorro L, Sans FX (2013) Weed harrowing in organically grown cereal crops avoids yield losses without reducing weed diversity. Agron Sustain Dev 33:405–411
95. Schonbeck M (2011) Principles of sustainable weed management in organic cropping systems, 3rd edn, September 2011. Mark Schonbeck, independent sustainable agriculture consultant. http://www.carolinafarmstewards.org/wp-content/uploads/2012/12/1-Schonbeck-Principles-of-Sustainable-Weed-Management-in-Organic-Cropping-Systems.pdf dt 08.01.2014
96. Wilcove DS, Rothstein D, Dubow J, Phillips A, Losos E (1998) Quantifying threats to imperiled species in the United States. BioScience 48:607–615

97. Blossey B, Notzold R (1995) Evolution of increased competitive ability in invasive non-indigenous plants: a hypothesis. J Ecol 83:887–889
98. Abela-Hofbauerová I, Münzbergová Z (2011) Increased performance of *Cirsium arvense* from the invasive range. Flora morphology, distribution. Funct Ecol Plants 206:1012–1019
99. Cappuccino N, Carpenter D (2005) Invasive exotic plants suffer less herbivory than non-invasive exotic plants. Biol Lett 1:435–438
100. Colautti RI, Ricciardi A, Grigorovich IA, MacIsaac H (2004) Is invasion success explained by the enemy release hypothesis? Ecol Lett 7:721–733
101. Yaduraju NT, Prasadbabu MBB, Gogoi AK (2003) Green invaders—a growing threat to agriculture and environment. In: Abstracts, national seminar alien invasive weeds in India, April 27–29, 2003, AAU, Jorhat, pp 1–9
102. Biswas K (1934) Some foreign weeds and their distribution in India and Burma. Indian For 60:861–865
103. Holm L, Pancho J, Herberger J, Plucknett D (1979) A global atlas of world weeds. Wiley, New York, 391 pp
104. Bala B, Sharma SD, Sharma RK (2006) Knowledge and adoption level of improved technology among rural women owing to extension programmes. Agric Econ Res Rev 19:301–310
105. Dashora P, Verma AK, Rokadia P, Punia SS (2011) Transfer of technology to bridge the yield gap in sugarcane of south east Rajasthan. J Progress Agric 2:59–62
106. Wanjala MJ, Lloyd DJ, Nichols JD (2003) Information sources and dispersal channels in the extension of pasture weed management technologies in southern eastern Kenyan rangelands. In: Proceedings from APEN National Forum 2003, 26–28 November, Hobart, Tasmania
107. Wijeratne M, AbeydeeraI RN (1994) Knowledge gap on agrochemical use in rice farming. Int Rice Res Notes 19(4):26–27
108. Chundi J, Srivastva A (1999) Role of media in dissemination of information in rural areas. Interaction 17(1, 2):82
109. Goswami G, Dhawan D, Bareth LS (2003) Impact of T.V. programme on rural women. Allahabad Farmer 57:21–27
110. Robert PC, Rust RH, Larson WE (1994) Preface. In: Robert PC, Rust RH, Larson WE (eds) Site-specific management for agricultural systems. American Society of Agronomy, Madison, p 3
111. Clay SA, Lems GJ, Clay DE, Forcella F, Ellsbury MM, Carlson CG (1999) Sampling weed spatial variability on a field-wise scale. Weed Sci 47:674–681
112. Swinton SM (2005) Economics of site-specific weed management. Weed Sci 53:259–263