Weed Management for Healthy Crop Production

13

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Abstract

This chapter deals with the potential, limitation, and impacts of the recent trend of changing agricultural practices induced by predicated climatic changes on weed management in crop production systems. Change in the agricultural practices from conventional to conservation agriculture has to some extent compromised the sustainability and productivity of cropping systems through the evolution of herbicide-resistant (HR) weed species, a shift in weed populations, and human and environmental hazards. The chapter assesses the potential challenges faced by regarding the overreliance of herbicides, with the introduction of herbicide-tolerant (HT) crops and possible recommendation of how healthy crop production can be achieved through sustainable weed management. The first section deals with the potential constraints associated with weed management in cropping system focusing the main driving factors, such as changing agricultural practices and climate change, socio-economic constraints. Possible strategies to improve weed management, focusing on the importance of promoting IWM strategies and best management practices for HT crops, have been discussed in the second section. The third section shares a series of recommendation for future research directions for sustainable and profitable weed management.

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Cropping production · Sustainable weed management · Changing agricultural practices · Climate change · Herbicide resistance

Abbreviations

A	ACCase inhibitors
B	ALS inhibitors
BMP	Best management practices BMP
C1	Photosystem II inhibitors
C2	PSII inhibitor (ureas and amides)
C3	PSII inhibitors (nitriles)
CO_2	Carbon dioxide
D	PSI electron diverter
E	PPO inhibitors
EPTC	Eptam
F1	Carotenoid biosynthesis inhibitors
F2	HPPD inhibitors
F3	Carotenoid biosynthesis (unknown target)
F4	DOXP inhibitors
FAO	Food and Agriculture Organization
G	EPSP synthase inhibitors
GM	Genetically modified
GMHT	Genetically modified herbicide-tolerant crops
GRDC	Grains Research & Development Corporation
H	Glutamine synthase inhibitors
HR	Herbicide-resistant
HT	Herbicide-tolerant
IWM	Integrated weed management
K1	Microtubule inhibitors
K2	Mitosis inhibitors
K3	Long-chain fatty acid inhibitors
L	Cellulose inhibitors
MOAs	Mode of actions
N	Lipid inhibitors
non-GM	Non-genetically modified
NSCT	Nonselective crop topping
O	Synthetic auxins
pK_a	Vapour pressure
SOA	Site of actions
SST	Selective spray-topping
Z	Antimicrotubule mitotic disrupter
Z1	Unknown
Z2	Cell elongation inhibitors
Z3	Nucleic acid inhibitors

13.1 Introduction

Food demands have doubled in recent times due to an ever-increasing world population and overconsumption. This increasing need for more food production is at its greatest in the least developed countries where the most dramatic expansion of population is occurring. The clear majority of the world's most hungry people belong to these developing countries, where about 13% of the population is undernourished with approximately 281 million of these people in Southern Asia. In addition, more recent projections suggest a rate of undernourishment of almost 23% in sub-Saharan African countries. For the next decade, more sustainable food production will be essential if these ever-growing demands on food production are to be met and for this to be done with judicious use of natural resources whilst moderating the deleterious impacts of an intensified agriculture on the environment (Yaduraju and Rao 2013).

Agriculture, the world's largest employer, provides a livelihood for 40% of the global population and is the largest generator of jobs and income for poor rural households. Available figures suggest that half a billion smallholder farmers globally produce up to 80% of the food consumed in developing countries (FAO 2018a). Another concern is that since the 1900s, about 75% of the diversity of crops planted has been lost from farmer's fields (FAO 2018b). Furthermore, climate change is putting pressure on the normally dependable resources required for agriculture, with the outcome being degraded soils, unstable supply of freshwater resources and biodiversity losses, etc., thus, increasing the susceptibility of agricultural systems to unfavourable events, such as drought, fire, and flood. Because of such changes, a profound change needs to follow in the global food and agricultural systems that we use to nourish the already 815 million hungry people and the additional 2 billion population expected by 2050. Better use of agricultural biodiversity would be one way to help create more nutritious diets and to enhance farmers' livelihoods, leading towards more resilient and sustainable farming systems.

Weeds are the main threat to world agriculture production, reducing crop and pasture yields and quality, interfering with crop harvesting and postharvest handling, affecting animal health, and hindering irrigation (Abouziena and Haggag 2016). According to a study, the annual world losses due to weeds are approximately 10–15% of the potential production of all the major food commodities or approximately USD $40 billion per year (Monaco et al. 2002). Despite the tremendous improvement in the way weeds are chemically controlled, especially with the advancement of genetically engineered crops with tolerance, both in the developed and developing countries, weeds remain an unmanageable threat to crop productivity and profitability (Nawaz et al. 2017; Banerjee et al. 2018). As one example, the cost of not managing agricultural weeds in maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) is estimated to be USD $43 billion per year in North America (Peter 2018).

Numerous socio-environmental constraints as the impact upon the damage weeds cause and impact the strategies employed for their control. For example, herbicide use worldwide has now risen 12-fold over that used in the period 1995 to

2014 (both in agricultural and nonagricultural applications), leading towards serious environmental and public health concerns (Drzyzga and Lipok 2018). In addition, the acute shortage of labour during peak periods and the absence of economically feasible and effective weed management techniques adapted for local conditions, all have influenced weed control in crop production systems (Sengxua et al. 2018). Thus, changes in land use, climate change factors, increasing food production demands, and the public-demanded increased environmental protection have all necessitated the move towards a more effective and reliable weed management approach. It is believed that by diversifying the weed management strategies used, the current and future challenges in weed control may be addressed more effectively (Liebman et al. 2016). These socio-environmental constraints have allowed the damage caused by weeds to become unchecked and have limited the kind of strategy that can be used to manage them. Therefore, new diversified ways of weed control are needed to manage weeds effectively under the growing demands for greater food production, to help counter the rapid shifts in land use and climate, and to meet the future expectations of environmental protection (Ehrenfeld 2010; Liebman et al. 2016).

In the next section (Sect. 13.2), several of the greatest challenges to food production are reviewed, and that when considered together will help in the development of an improved weed management approach that can support healthy and sustainable crop production. In the subsequent section (Sect. 13.3), further development of the components of the approach will be discussed, which will make the agricultural production system sustainable in the longer term by creating a healthful food supply that reduces the impact on natural resources and farmers' health without compromising crop yields.

13.2 Constraints Associated with Weed Management in Crop Production

13.2.1 The Results of Human-Induced Changing Agricultural Practices

13.2.1.1 Overuse of Herbicide: The Evolution of Herbicide-Resistant (HR) Weeds

Overuse of the same herbicide year after year, especially by farmers with less awareness, has dramatically increased the occurrence of herbicide-resistant (HR) weed populations, with the result that herbicide resistance has now become one of the major threats to global food security (Pacanoski 2017). Selection pressure due to the continuous use of the same herbicide or herbicides mode of action group is the main reason for this development (Manalil et al. 2011; Vencill et al. 2012; McElroy 2014). In addition, the increased use of herbicides, in general, has resulted in cases of multiple resistance developing, leaving limited or no herbicide options for farmers to control weeds in the future (Peterson et al. 2018).

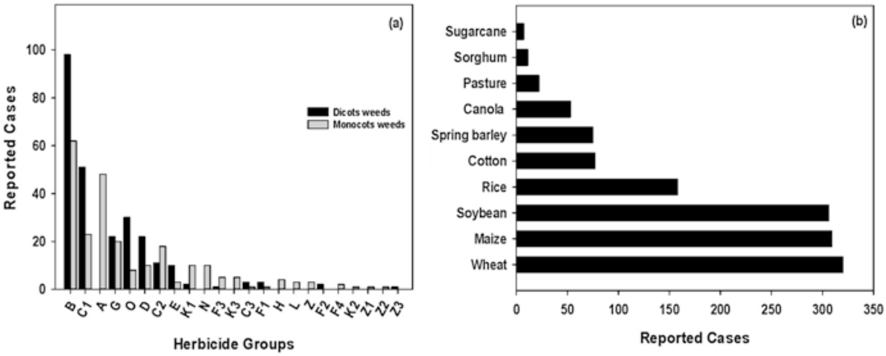

Fig. 13.1 Globally reported case of herbicide-resistant weeds on the basis of mode of action group (**a**) and crops (**b**). (Reference Heap 2018)

Of the 26 known herbicide mode of action groups, weeds have developed resistance to 23 of these, including resistance to 161 herbicide formulations (Fig. 13.1; Heap 2018). Currently, 495 unique cases of HR weed populations have been reported in 255 species (148 dicot and 107 monocot species) found in 92 crops grown in 70 countries, including all continents apart from Antarctica (Figure 13.1a, b; Heap 2018). Countries such as Australia and the USA have the highest number of HR cases, whereas many fewer have been reported from Asia and South America. Similarly, fewer cases have been reported from Africa, but this may be due to the limited area that is under intensive agriculture and where herbicides are routinely used. Based on the number of reported cases, HR is a problem of the developed countries (Peterson et al. 2018).

In countries with developing economies, significant human migration from rural to urban areas has taken place, and rural agriculture is already experiencing a shortage of labour due to this migration. This trend, if continued, will increase farmer's dependence on herbicides, leading to a greater selection pressure which will result in more HR weed populations and more cases of multiple resistance. Consequently, the evolution of HR weed populations will outpace those of the development of new herbicides with new sites of action (SOA), making it critical for farmers to employ diverse weed management option to maintain sustainable crop production (Peterson et al. 2018). It is highly likely that some countries will lose the use of certain herbicides to control particular weed species if the present trend in increasing HR continues. In developed countries, if the appearance of HR populations continues, this will result in the use of alternative herbicides and mixtures, and this may also result in the use of higher application rates (Peterson et al. 2018). For example, results from a national grower survey in Australia estimated that HR costs growers an additional AUD $135 million annually in addition to herbicide costs (Llewellyn et al. 2018).

The continued evolution of HR weed populations will reduce crop yield and the flexibility of cropping systems, thus restricting farmers to operate only certain kinds of cropping system in those areas that have become affected. Additionally, in cases where HR weed populations are present, a proactive approach that moves towards using a greater range of crops and tillage in combination with herbicides might result in a net profitability loss of between 4 and 24% as compared to cropping systems without resistance (Gerhards et al. 2016). In recent surveys in the USA, the proportion of respondent indicated that weed control costs of USD $50 per acre nearly doubled following the emergence of HR weeds on cotton farmers (Zhou et al. 2015). There have been reported yield losses of 15%, whilst in extreme cases, farmers have abandoned farming land entirely (100% yield losses; Carpenter and Gianessi 2010; Culpepper et al. 2010). Despite these costs due to HR weed populations, farmer's adoption of resistance management practices has been poor and insufficient to restrict the further development of HR weed populations (Lamichhane et al. 2017).

13.2.1.2 Introduction of Herbicide-Tolerant (HT) Crops

The introduction of genetically modified herbicide-tolerant (HT) crops has offered numerous benefits to farmers; however, this technology has reduced the diversity of herbicides used, resulting in the evolution of more HR weed populations and HT volunteers (HT crop plants emerging in the following season) as well as resulting in weed population shifts. The marketing of these HT crops, designed to tolerate specific broad-spectrum herbicides, has encouraged farmers to use more herbicide, thus increasing the chances of HR development in weed species (Fig. 13.2). For example, the high predominance of glyphosate-tolerant (GT) crops has greatly increased the development of glyphosate resistance (GR) in weed species, since their introduction in 1996. Ineffectiveness in the control of HR weed species in HT crops has called into question the long-term sustainability of these GMHT crops (Livingston et al. 2015). Promoters and supporters describe HT crops to be revolutionizing farming and to be bringing about considerable agro-economic and environmental

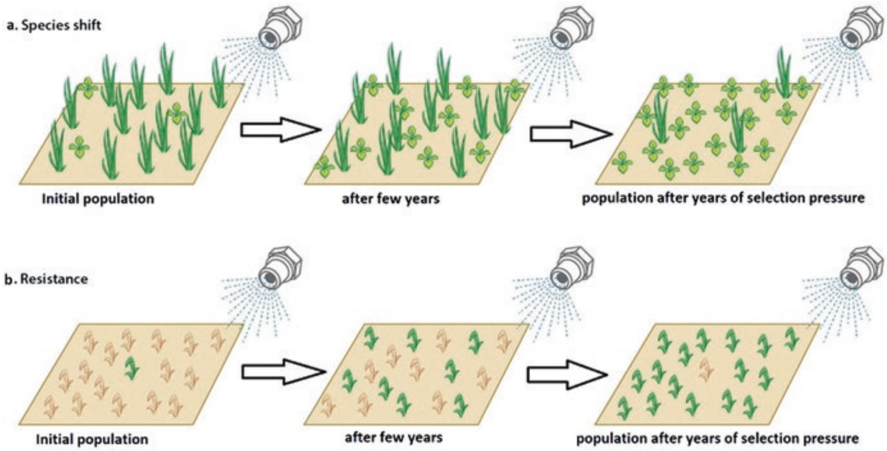

Fig. 13.2 Repeated herbicide uses impose selection pressure leading towards weed species shift (**a**) resulting in more tolerant/resistant species (**b**). (Adapted and modified from Orloff et al. 2009 with permission)

benefits. However, sceptics challenge this by citing the considerable rise of more HR weed populations (Bonny 2016).

Increased adoption of HT crops, particularly GT crops, has increased the use of glyphosate for weed control (Benbrook 2016). In addition, this has promoted the adoption of conservation tillage practices, which in turn reduced further the use of other herbicides and facilitated glyphosate overreliance (Travlos and Chachalis 2010). The widespread use of glyphosate has now resulted in heavy selection pressure linked to the adoption of GT crops and the concomitant reduction in the tillage, thus contributing to weed species shifts. Studies have demonstrated that an increase in the annual grassy and perennial weed species has been associated with the use of reduced tillage practices and are now becoming the predominant weeds in conservation tillage production systems (Buhler 2002). Though the use of reduced tillage practices, there has been a change in weed species present, their distribution, densities, as well as weed community composition, and these different weed communities respond differently in conservation tillage systems and need to be treated accordingly (Bajwa 2014).

HT crops are reported to exert significant influence on growth and yield in many crops as HT volunteers in succeeding crops (Lopez-Ovejero et al. 2016). These HT crop volunteers are emerging as a major threat due to their seed characteristics (i.e. production, dormancy, and persistence), resulting in depletion of available resources, interfere with weed management, and reduced herbicide efficacy, as herbicide fails to manage HT volunteer with same herbicide tolerance profile (Alms et al. 2016; Lopez-Ovejero et al. 2016). In addition, the flow of gene to GM or other non-GM cultivars result in adventitious presence or contamination of seed lots, exerting economic consequences or repercussions in the marketplace (Warwick et al. 2009; Dong et al. 2014). The potential of gene or pollen flow from GM HR crops to non-GM to other GM crop and to weedy relatives is seen to be a real risk in transgenic crops with a high degree of outcrossing, particularly with a large number of weedy relatives (Fig. 13.3; Warwick et al. 2009). The prevailing environmental conditions and agronomic technologies, most importantly the weed management strategies, harvest efficacies, and postharvest handling, significantly influence the pace at which the volunteer plants can acquire the status of major weeds in coming years, like herbicide-resistant weeds (Graef et al. 2007; Bond and Walker 2009).

13.2.1.3 Intensification of Agriculture: Impact on Human Health and Environment

Commercial crop production is highly dependent on the utilization of agricultural pesticides; in the top 25 pesticides used in the agricultural sector, 13 are herbicides, predominantly glyphosate (Grube et al. 2011). Exposure to the herbicide, either contact or inhalation, type of herbicide, duration of exposure, and the individual health status determined the possible health outcome. More emphasis is given widely to glyphosate, which is closely related to current agriculture (Baylis 2000). Continuous exposure from frequent use resulted in increased levels of this herbicide in foods, drinking water, and the atmosphere (Chang et al. 2011), although research

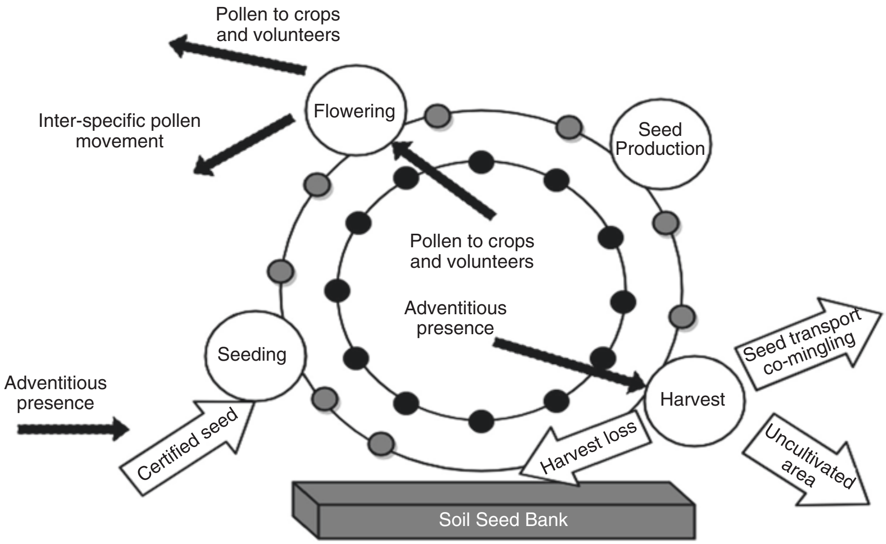

Fig. 13.3 Seed- and pollen-mediated gene flow in crop plants (○) and volunteers (●) through the annual crop cycle. (Reproduced from: Warwick et al. 2009)

on the risk assessment identifies glyphosate as one of the safest herbicides on human health.

In recent years, the World Health Organization's International Agency for Research on Cancer concluded that glyphosate is probably carcinogenic to humans. The half-life of glyphosate in water and soil is longer than previously recognized, and human exposure to this herbicide is rising; thus glyphosate is now authoritatively classified as a probable human carcinogen (Myers et al. 2016). Moreover, certain herbicides like acetochlor, imazaquin, imazethapyr, and pendimethalin have also been reported for causing lung cancer, bladder cancer, colon cancer, and asthma, respectively, in humans (Lerro et al. 2015; Koutros et al. 2015).

Besides intensifying problems of herbicide-resistant weeds, excessive use of herbicides has raised public concerns about their adverse impact on the soil and groundwater contamination (Kumar et al. 2013). One of the major drawbacks associated with chemical weed control is the excessive accumulation of residues in the soil, a serious environmental concern (Bzour et al. 2018). Soil enzymes, phosphates, and microorganisms mediate organic matter decomposition and organic chemical degradation, promote organic phosphorus mineralization, and improve soil quality and health (Abbas et al. 2015).

Herbicide contamination of the soil ecosystem leads to imbalances in the equilibrium between soil chemistry and microbes involved in nutrient cycling. Soil-applied herbicides adsorb to clay minerals, soil organic matter, and organoclay complexes, enhancing their concentration in the topsoil and affecting crops grown in the subsequent season (El-Nahhal and Hamdona 2015). Herbicides inhibit extra- and intracellular protein-synthesizing enzymes, leading to imbalances in the production of plant growth regulators (Abbas et al. 2014). Baboo et al. (2013) stated that herbicides, butachlor, pyrazosulfuron, paraquat, and glyphosate, at recommended field doses, caused a transient impact on the microbial population and enzymatic activities in agricultural soils of Burla, India.

13.2.2 The Results of Climate Change on Weed Management in Crop Production

Over the past few decades, significant transformations have been induced by changing climate in the weed flora of agroecosystems, worldwide (Peters et al. 2014; Varanasi et al. 2016), allowing thermophile, late-emerging weeds, and some opportunistic weeds to become more abundant in some cropping systems (Peters et al. 2014). These climatic variables, particularly precipitation and temperature, have ruled the composition of arable weed species directly or indirectly by enforcing adaptations of altered agronomic practices (Fleming and Vanclay 2010). In order to persist in a local habitat, arable weed species have responded to the change in climatic conditions, leading towards shifts at distinctive scales (Fig. 13.4; see Peters et al. 2014 for details).

Being principal determinants of species distribution, changing climate variables may increase the distribution range of weed species or might allow non-potential weed to dominate weed abundance in cropping systems (see Ramesh et al. 2017). It is believed that perennial weed species are more likely to take advantage in terms of their abundance and survival with the rise in CO_2 due to stimulated tuber and rhizome growth (Chandrasena 2009). On the other hand, weeds with less phenotypic plasticity will experience population decline under frequent extreme weather events, drought or cold spells (Peters et al. 2014). In addition, lack of vegetation cover and bare ground due to limited growth of crops and pastures as the result of a decline in

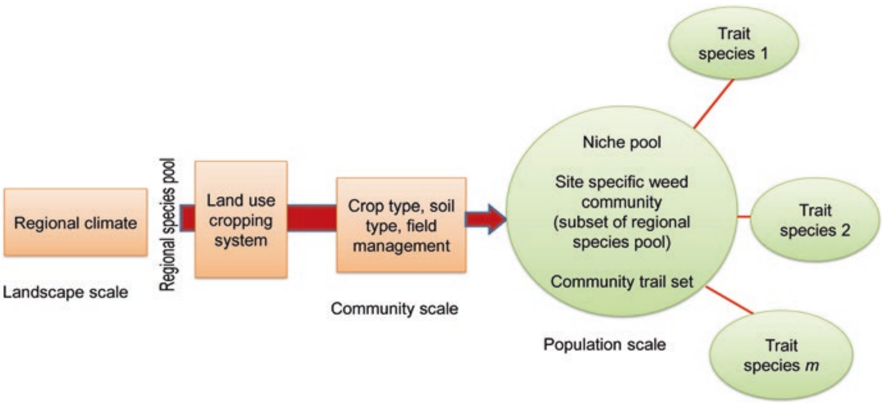

Fig. 13.4 Factors determining the species composition of the arable weed community in a particular area. (Adapted from Peters et al. 2014)

rainfall and prolonged drought will allow invasion of more resilient drought-tolerant weeds.

Due to the diverse genetic pool and great physiological diversity, weeds are more likely to show greater resilience and better adaptation to changes in climatic condition in competition with crops (Varanasi et al. 2016). However, weed with C_3 and C_4 photosynthetic pathways might exhibit a differential response to rising CO_2 and associated changes in global temperature and precipitation (Varanasi et al. 2016). In addition, reduced water availability, associated with unpredicted droughts, might alter the competitive balance between crops and some weeds, thus intensifying weed-crop competition, which will threaten to crop production (Ramesh et al. 2017). However, the interactive effect of this variable will affect weed-crop competition simultaneously or sequentially in a more complex and quite differential manner.

Despite affecting weed growth positively, changes in climatic conditions could influence the efficacy of many herbicides, making it a great challenge for farmers to manage weed effectively for sustainable crop production (Ziska 2016). Changes in environmental factors, such as CO_2 concentration, temperature, precipitation, light, and relative humidity, either alone or in combination, differentially affect the uptake, translocation, and activity of different herbicide chemistries (Varanasi et al. 2016). Morpho-physiological and anatomical changes in C_3 plants, such as a decrease in stomata number and conductance, increase in leaf thickness and starch accumulation on leaf surface under elevated CO_2, interfere with the foliar uptake of herbicides. Thus, stimulated vegetative growth to turn weeds into more noxious due to increased photosynthesis, which is expected to reduce herbicide efficacy due to dilution effect (Manea et al. 2011).

Unpredicted rainfall and drought spell also have an adverse effect on the persistence activity of soil-applied herbicides (Rodenburg et al. 2011). Prolonged drought spells to increase the volatilization of many herbicides thus reduce their rain-safe period available for herbicide application in the soil. For example, trifluralin and pendimethalin will be lost if remain on the soil surface for an extended period without rainfall (Curran 2016). Increased rainfall frequency and intensity promote leaching of many soil-applied herbicides, subsequently cause groundwater contamination, and lead towards additional weed pressure. Impact of these climatic changes on the efficacy or performance might be unpredictable among herbicides belonging from same MOA or within herbicide MOAs, thus making difficult to draw generalized assumptions for each MOA (see Ziska 2016; Varanasi et al. 2016).

The fate of pesticide, including herbicides, is more likely to be affected by changing climatic variables, such as temperature and precipitation (Lewan et al. 2009). These factors usually increase the volatilization of herbicide; thus, most volatile herbicides are incorporated into the soil to avoid losses (Table 13.1). Generally, an increase in temperature and soil moisture increased the degradation of herbicide due to chemical and microbial activity. In years following a drought, the carryover problems are always high, whereas if winter and spring receive mild to high rainfall following a previous dry summer, then the likelihood of herbicide carryover is low (Curran 2016).

Table 13.1 Soil and climatic conditions to increase the persistence of herbicide families

	Importance		
Herbicide families	Very important	Important	Less important
Clomazone	Low rainfall	High clay/organic matter	High or low soil pH
Dinitroanilines	Low rainfall	High clay/organic matter	High or low soil pH
Imidazolinones	Low rainfall	High clay/organic matter	Low soil pH
Pyridines	Low rainfall	High clay/organic matter	High or low soil pH
Sulfonylureas	High pH	High clay/organic matter	Low rainfall

Curran (2016)

13.2.3 Socio-economic Constraints: Inputs Unavailability to Farmer's Unawareness

Weed Dynamics and Uncertainty Current trends suggest that weed problems will worsen in the next 10–20 years, becoming an even more intractable barrier in efforts towards the sustainable intensification of agricultural production and the preservation of natural habitats (Neve et al. 2018). The uncertainties associated with the variations in demographic traits, weed impacts, and efficacy of control methods are highly relevant to weeds in agroecosystems. In general, some field held many weeds of a single species spread throughout the field in a diffuse, consistent pattern, whereas other fields show tight patches of multiple weed species. The difference among weed species in herbicide tolerance, life history, competitive ability, and other factors affects the relative abundance of individual species when management practices changes (Gibson et al. 2005).

For practical perspective, variations in seed production, dispersal, and persistence as well as weed recruitment and survival remain the sources of unpredictable variation in demographic traits under field conditions. Moreover, the uncertainty of occurrence of species and the uncertainty of their spread might result in irreversible crop losses. Recruitment of weeds from natural into agricultural ecosystems can be highly episodic due to possible associated risks, such as lack of effective control measures. It will take time for farmers to understand the sources of the diversity of weeds in their agricultural fields to develop successful long-term weed management approaches.

Herbicide Ban In recent years, there has been a call to limit the use of herbicides at national levels either through reducing application rates, restricting product ranges, or using alternative weed management strategies. In Europe, the proposed measure comprises banning specific herbicides (i.e. glyphosate) or introducing pesticide taxes (Finger et al. 2017). In most countries, farmers and researchers have expressed strong concerns with regard to potential negative impacts of the partial herbicide ban on the crop potential yield and food security (Wilson and Tisdell 2001; Foley et al. 2011). Herbicides are implicitly thought to improve crop yield by reducing weed biomass so reducing herbicide use would indirectly reduce the crop production (Gaba et al. 2016).

For example, ban on glyphosate use will stop farmers from growing GMHT crops, resulting in a significant effect on crop production as it will influence the production of major HT crops, such as cotton, soybean, corn (maize), rapeseed, and sugar beet (Table 13.2; Brookes et al. 2017). Globally, production of soybeans and rapeseed falls by 9.7 million tonnes and 0.45 million tonnes, respectively, but it will increase the production of oil palms and other oilseeds by 1.6 million tonnes and 2.3 million tonnes, respectively (Brookes et al. 2017). More likely, this ban on glyphosate use will increase the prices of rice, wheat, sugar crops, and other crops by 0.5%, worldwide. In short, cultivation of GMHT crops will no longer shock the cost of chemical, labour capital, and productivity of land, which will directly affect the costs of affected crops, will alter relative prices and will derive changes in the global economy (Brookes et al. 2017).

Table 13.2 Impact of the ban on glyphosate use on crop production

Data item	Crop	USA	EU	Brazil	Canada	South America	Others	World
Percent change	Rice	0.2	0.2	−0.1	0.5	−0.6	0.0	0.0
	Wheat	0.4	0.1	−0.4	0.6	−1.1	0.0	0.1
	Coarse grains	−2.3	0.1	−0.8	0.8	−1.6	0.2	−0.6
	Soybeans	−1.9	7.5	2.7	−5.6	−17.1	1.4	−3.7
	Palm fruit	6.8	3.1	3.6	9.8	4.8	0.5	0.7
	Rapeseed	−0.1	1.7	2.9	−5.6	1.6	0.0	−0.7
	Other oilseeds	3.3	2.3	2.7	2.8	2.5	1.1	1.4
	Sugar crops	0.0	0.0	−0.2	−0.6	0.0	0.0	−0.1
	Other crops	0.2	0.1	−0.5	0.4	−1.1	0.0	0.0
Change in 1000 metric tons	Rice	18.9	5.5	−18.1	0.0	−73.7	−2.9	−70.2
	Wheat	226.2	73.9	−19.9	143.2	−213.6	223.0	432.8
	Coarse grains	−7518.4	140.8	−482.3	170.3	−751.3	1258.9	−7182.0
	Soybeans	−1604.5	82.4	1988.3	−236.2	−10497.9	528.7	−9739.2
	Palm fruit	0.0	0.0	46.4	0.0	319.6	1272.1	1638.2
	Rapeseed	−0.6	330.0	1.5	−795.3	3.3	10.4	−450.6
	Other oilseeds	93.6	519.3	94.4	14.7	142.4	1484.0	2348.4
	Sugar crops	11.2	−56.5	−1812.1	−4.6	−45.3	−221.8	−2129.1
	Other crops	1605.8	498.1	−458.2	183.8	−2312.6	952.2	469.1

Brookes et al. (2017)

Weak Adoption of Integrated Weed Management (IWM) Practices Despite several decades of promotion, farmers have relatively weak adoption of integrated weed management (IWM) practices due to their complexity in contrast to the simplicity of regular pesticide application. Factors identified to act negatively upon the decision by farmers to invest in adopting IWM practices include the preference for returns in the short term over the long terms, expectations of new herbicide technology, and uncertainty as for whether weed problems will be prevented or delayed by adopting the practices. In addition, system's profitability and sustainability, heterogeneity of farm situations, time of benefits and costs, and social or institutional issues also influenced the adoption of new technology (Pannell et al. 2006).

Education programmes intended to promote IWM practices rely primarily on innovation diffusion methodology. This methodology has proven to be ineffective for the promotions regarding the adoption of prevention practices, which do not address farmers weed management problems in the short term. Though some of the members of the society lag behind for a considerable time before adopting the new practices and some will never change but this methodology has successfully been used to diffuse agricultural technologies to the farming communities (Rogers 2003). Instead, IWM tends to be a deterrent to adoption due to associated short-term complexities and learning costs (Swanton et al. 2008). In addition, the unintentional patronizing attitude of the researchers and extension educators towards influences the farmer's decision-making, contributing to a failure to adopt IWM practices.

Many IWM practices are perceived to be costly and unreliable relative to major selective herbicides; some of the extensively used practices do not offer high weed control efficacy (Llewellyn et al. 2004). In most cases, less attention has been paid to farmers' perceptions related to the efficacy and economic values of the IWM practices. The perceived value of the practice and subsequent adoption decisions are greatly influenced by the farmers' perception of various attributes of a practice.

Inappropriate Herbicide Use Herbicide application is considered a key factor in optimizing herbicide efficacy through maximizing herbicide deposition and minimizing spray drift (Kudsk 2017). It should be according to the three E's of spray application: economic, effective, and environment-friendly (Wolf 2009). Series of stages starting from the nozzle with droplet formation, travelling to plant surfaces, impacting the leaf surface, the formation of a deposit, uptake by the plant, and other biological responses are involved in the spraying process, which influences the herbicide use and performance (Ebert and Downer 2008). Spray performance can be affected if a change occurs at any stage interacts with the other application factors and subsequent stages (Creech et al. 2015).

Most common mistake associated with the inappropriate use of herbicide is the incorrect identification of weeds and using inappropriate herbicide product. Similarly, incorrect rate and/or water volume can frequently result in poor weed control and crop damage, causing a waste of money and time. Herbicide application below label rate or when the plant is stressed also result in application failure. In addition, if the chemical is not stored under the recommended conditions or maybe too old, it might also influences herbicide efficacy.

Farmers' Perceptions and Technical Unawareness Due to diversity and dispersal, the issues facing farmer communities with weed management are complex and varied. In most cases, farmers' perception "it would cause significant losses" or not considering it the main priority prevent them from controlling the overwhelming infestation, i.e. lack of motivation to spend money on controlling weeds. In other words, not everyone is aware of their responsibilities related to weed control, which resulted in continual seed rain from uncontrolled infestations. Some of the farmers are not fully aware of the consequences of not managing weed populations or may not have the knowledge or equipment to properly control weeds.

In the developing countries, lack of awareness in farmers and government organization is the major constraint limiting the implementation of efficient weed management causing significant losses caused by weeds and the methods to control them. Lack of information from agricultural extension services about weeds and their problems, ineffective links between agricultural research units and extension services and inappropriate or limited research on weed management are the possible reasons for the lack of technical awareness. In most of the countries, there is no adequate agricultural weed research programme due to lack of funds or lack proper research activities and are too weak, if exist, which results in the deficiency of well-trained weed scientists.

13.3 Weed Management Options for Healthy Crop Production

13.3.1 Planning Weed Control

The outcomes of weed management in cropping systems can substantially be improved by approaching the task with an efficient plan. A well-thought-out strategic plan can make weed management tasks much easier and more achievable and can result in significant savings of resources (time, effort, and money). Therefore, weed strategies must be built on a solid foundation of good agronomy in order to be effective enough to contribute to profitable and sustainable cropping systems. In addition, it should avoid heavy reliance on one or two control methods, especially herbicide with same MOA to avoid selection pressure. Overall steps involved in the development of the strategic plan are (see Fig. 13.5):

(i) Developing an effective plan is to be familiar with the weed species present and another management issue in the fields. Many resources are available to assist you in understanding how to identify and understand the behaviour of the weed species.

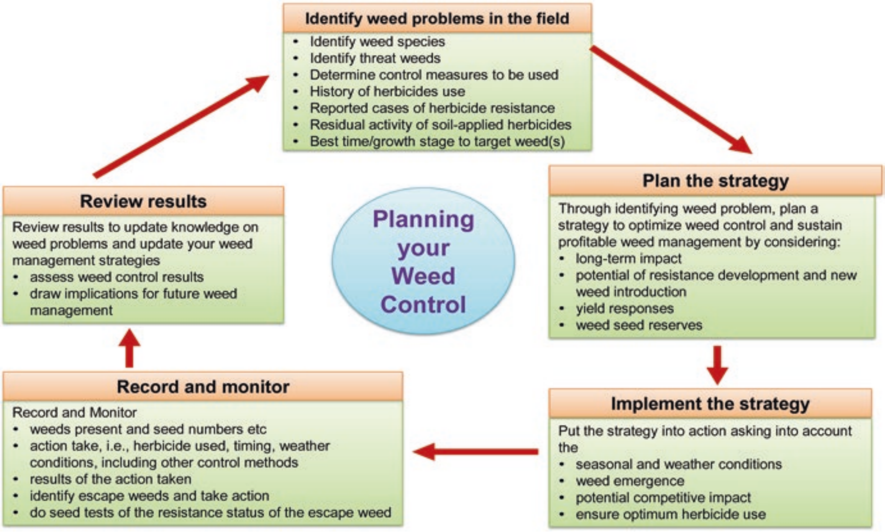

Fig. 13.5 The five-step process of on-farm weed management plan

(ii) The range of skills that are useful to define management zones, describing the current extent of weeds and identifying key land management practices, helps in preparing a property-wide weed management plan.

(iii) Prioritize the weed management options (i.e. herbicide, cultural, etc.) to ensure a high impact within the available resources.

(iv) Implement the plan taking into account the seasonal and weather patterns, weed emergence, potential impact, and increased efficacy.

(v) Monitor and review the results to realize at the outset that the plant will need to change as you progress, and these changes are based on the evidence gained whilst monitoring your results.

13.3.2 Preventing Weed Introduction

Globalization and World Trade Organization (WTO) regime resulted in a free flow of food grains another commodity across the borders that enhance the possibilities of movement of weed seeds along with grains to other countries (Duary 2014). Human-induced mechanisms seem to be more important in the rapid spread of weed seeds than the natural mechanisms (i.e. water, wind, or animals). Globally, human-induced mechanisms are now considered to be the main reason for new weed incursions (Adkins 2013). Survival of any weed species depends on the production of sufficient numbers of viable seeds, and therefore, prevention of entry of weeds seed is the key to eliminate future weed problems (Duary 2014).

Preventing weed establishment is the most effective way to minimize weed problems in crop fields (GRDC 2018). Farmers need to implement strategies to reduce and avoid the unnecessary introduction of weeds and their spread in order to reduce the likelihood of new weed species and also the risks of importing herbicide-resistant weeds. Following approaches will be helpful in preventing weed seed introduction:

- Preventing introduction through contaminated seed and feed through sowing weed-free seeds. If possible, seed lot sample should be analysed for both weed seed contamination and germination, the herbicide resistance status of weeds present on the source farm should be determined, and seeds should be graded to reduce weed.
- Restricting the movement of machinery to prevent weed seed introduction from one field to another field. Prior to entry on the farm, ensure machinery and vehicles are cleaned or are cleaned at a specially designed wash station.
- Avoid livestock grazing in weed-infested areas during flowering and seeding time period. If grazed, and then their movement should be restricted for 10 to 14 days before moving to weed-free ranges.
- Use well-decomposed farmyard manure/compost, otherwise many seeds of annual weeds will germinate and aggravate the weed problem.
- Cleaning the wastelands, public places, and irrigation channels.
- Avoid soil transplant from an area highly infested with weeds.
- Use appropriate weed control measures in the nurseries of rice and vegetables.
- Inspect farm on a frequent bases for any strange looking weed, and such patches should be destroyed by digging deep or by using suitable herbicides.
- Isolation of an area where a serious weed has established and prevented further movement of weeds into non-infested areas.
- Legal and quarantine measures should be followed whilst importing crop seeds, food grains, seedlings, etc.

13.3.3 Stopping Weed Seed Set

As an important weed management principle, prevention of weed seed production can dramatically reduce the number of seeds present in an area (GRDC 2018). Research has reported many cases in which a single weed plant can produce more than one million seed, which is eventually deposited either onto the soil adjacent to parent plant or transported to another area (Norris 2007). Therefore, preventing weed seed production provides an opportunity to control weed seed in the pasture, late fallow, late stubble, and in-crop phases. Techniques such as herbicide-topping, pasture spray-topping, crop desiccation and windrowing, wiper technology, grazing, silage and haymaking, manuring, and mulching have been observed to prevent weed seed set. Following techniques have been reported to stop weed seed setting in cropping systems:

- Spraying weeds at the reproductive stage with post-emergent selective herbicides, a technique is known *as* "selective spray-topping", prevent seed set of certain weed, thus reducing additions to the weed seedbank with minimal impact on the crop (Cook et al. 2014). This strategy can also be used to control "escapes" as a late post-emergent salvage treatment or for managing herbicide resistance (see Beckie 2006).

- Crop topping using nonselective herbicide like paraquat or glyphosate at flowering or early grain fill stage of weed, minimizing the production of viable weed seed and also reduced the crop yield losses (see Steadman et al. 2006). Efficacy of this technique in reducing weed seed set can be increased by using nonselective herbicide in conjunction with selective herbicides.
- Control of upright weeds by using herbicide wiper technology for the application of translocated herbicides on their foliage and stems above the height of surrounding vegetation. This technique ensures herbicide application with minimal damage to desired crops as well as saves herbicide up to 80% as compared to broadcast spraying (see Moyo et al. 2016).
- Strategic termination of crop growth using knockdown herbicides prevents seed set in weeds. This technique broadens the weed management tool in pulses and strengthens their role in crop sequences of southern farming systems (see Armstrong et al. 2015).
- Collection and/or destruction of weed seeds at harvest weed seed control (HWSC) system to prevent the spread of weed seeds across the fields and reduces seedbank inputs. This system includes narrow windrow burning, chaff lining, chaff tramlining, chaff carts, and Harrington Seed Destructor (HSD) to target weed species with a potential weakness of retaining a large portion of their seed at maturity (Walsh et al. 2013). This new method has been used to reduce the impact of HR weeds on Australian grain production.
- Incorporation of leguminous green manure suppresses weed growth through high biomass production, which ultimately results in preventing weed seed setting and dispersal (Koehler-Cole et al. 2017). Incorporation of brown manure crop into the rotation and employing the double-knock herbicide technique prior to weed seed set have bolstered in the battle against HR weeds through reducing seed viability.

13.3.4 Depleting Weed Seed Bank Reserves

Changes in crop rotations and weed management greatly influence the weed population in cropping systems; limited studies have characterized the effect of these crop management practices on weed seedbank dynamics (Kleemann et al. 2016). Use of diverse crop rotations, competitive crops, higher crop seed rates, specific timing and placement of fertilizer, crop mulches, and cover crops can effectively manage weed seedbank dynamics, especially when used in conjunction with limited but targeted use of herbicides (Ball 1992). Weed populations resulting from the seedbank comprised of many species with few dominant species. Therefore, effective management of these dominant weed species depends complete on the preventing weed seed production and exhaustion of the seedbank, influenced by the

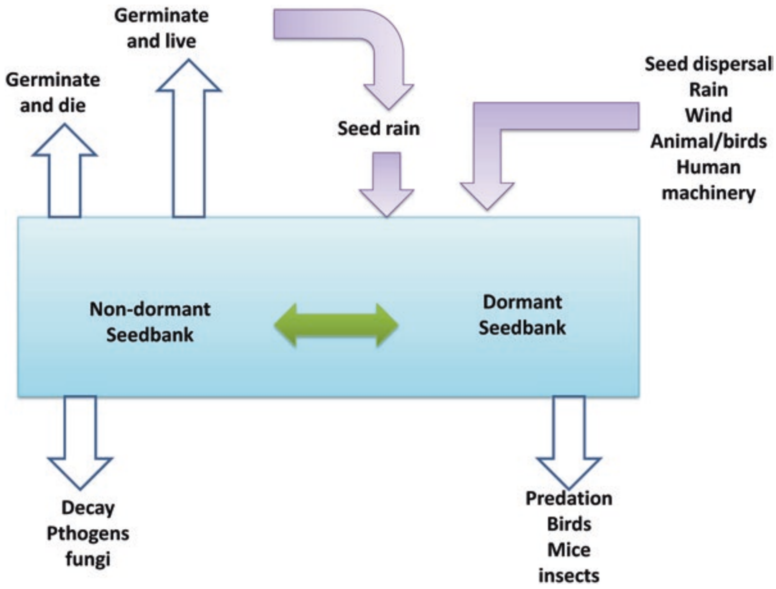

Fig. 13.6 The fate of weed seeds, showing inputs of seedbank (purple arrows) and losses (white arrows). (Adapted from Menalled and Schonbeck 2010 with permission)

persistence of weed seeds in the soil (Fig. 13.6). Techniques to deplete weed seedbank in soil involve:

- Stimulating weed germination and then destroying weeds deplete weed seedbank of certain species for a number of years. Shallow cultivation and delayed sowing are some techniques which change the moisture, temperature, or the amount of light to maximize weed emergence.
- Preventing new weed incursions between the fields by using clean seed and farm equipment.
- Inversion ploughing helps in placing weed seeds on or just below the soil surface deep into the depth from which seeds cannot germinate.
- Seed predation through pathogens increases the mortality rates of weed seeds, particularly in no-till systems in which weed seeds are left on the soil surface (see Li and Kremer 2006).
- Preventing harvest losses, particularly in the case of HT crops, will prevent volunteer crops to emerge as weed problems in future crops in subsequent years.
- Chaff collection will potentially reduce the weed seed return and possible will reduce the need for weed control.
- Clipping tall weed above crop canopy or terminating crop early, as green manure, will prevent weeds from seed production and returning it to weed seedbank.
- Manipulation of crop management practices such as narrow row spacing, competitive crop cultivars, and increased plant density could lower the weed seed production and ultimately soil seedbank (see Dyer 1995).

- Techniques like herbicide application, in-crop tillage, and the use of perennial or annual forages which are harvested prior to seed maturation will be effective strategies to stop weed seed set.
- Incorporation of succulent legumes or other cover crops stimulates weed seed germination by increasing soil nitrate (N) levels or promotes weed seed or seedling decay as a result of soil microbial organisms on the green manure residues (Kumari et al. 2018).

Depending upon the weed species, seedbank could be exhausted within a few years of effective weed control achieved consistently in the crop sequence (Chauhan et al. 2006). Despite the importance of numerous economically important weed species, limited information is available on their long-term seedbank dynamics in cropping systems. This information is more likely to contribute towards the development of cropping systems and weed management to achieve high productivity as well as to maintain weed populations at low levels (Kleemann et al. 2016).

13.3.5 Limiting Weed Seed Dispersal

Depending upon the dispersal mechanism, spatial distribution resulting from seed dispersal varies greatly within the weed species, ranging from a few centimetres to hundreds of kilometres (Benvenuti 2007). Reducing weed seed dispersal is extremely difficult as most of the weed species possess specific characteristics that allow their seeds and other reproductive parts to be easily transported over long distances (GRDC 2018). Techniques mentioned in 3.1 also helps in minimizing the weed seed dispersal within the fields and across the regions.

- Improved knowledge of weed biology to acquire an in-depth awareness of the factor involved in an agroecosystem population dynamics to achieve a trade-off between agricultural productivity and environmental protection (Benvenuti 2007).
- Investigation of the biotic, abiotic, or anthropic weed seed dispersal mechanism in integration with weed prevention strategies will help in developing a valid agronomic tool for long-term management of weed species in the agroecosystems (Benvenuti 2007).
- Refraining from driving vehicles and machinery through weed-infested areas during the seed production period.
- Reducing tillage practices, as in conservation systems, can restrict the weed seed spread both within and across the field.
- Washing the undercarriage of vehicles after driving through the weed-infested area.
- Using certified weed-free feed.
- Grinding and pelleting forage or grains.

13.3.6 Maximizing Crop Competitiveness

Over the time period, development of herbicide-resistant weed species and weed populations shifts; researchers have been highlighting the significance of cultural strategies for the management of weed species in different cropping systems (Peerzada et al. 2017). In the recent years, manipulation of cultural practices, such as altered row spacing, competitive crop cultivars, etc., is gaining rapid attention in many countries once again as a possible strategy to suppress weed competitiveness. The use of crop management practices has been reported to have the capability to suppress weed and their integration aid in the development of sustainable weed management strategy (Mishra et al. 2015). Crop competitiveness can be maximized through:

- Selection of crop cultivars with specific growth characteristics, such as rapid emergence, fast biomass accumulation, leaf characteristics, height, canopy structure, as well as allelopathic potential, can significantly affect the growth and population densities of weeds in cropping systems (Buhler 2002; Bhadoria 2011).
- Reduced row spacing and altered row orientation parallel to the sun direction minimizes the photosynthetic active radiation (PAR) availability to the weed species, thus reducing the weed germination, establishment, growth, and ultimately the seed production due to faster canopy closure (Scott et al. 2013).
- High seed rate or increased planting densities have proven to be an effective approach to increase crop competitiveness against weed and also facilitate rapid canopy closure, which helps in suppressing the weed emergence and growth effectively (Gibson et al. 2002).
- The use of different crop sequences creates varying patterns of resources competition, allelopathic interactions, soil disturbance, and mechanical damages that create an inhospitable and unstable environment, preventing the proliferation of particular weed species (Liebman and Dyck 1993). These temporal and spatial diversification strategies have been marked to reduce the weed population densities and biomass production in the published literature. Thus, proper understanding related to these dynamics is required for the manipulation of cropping systems to improve weed management.
- Better crop nutrient and irrigation management by manipulating fertilizer placement and irrigation timing can increase the nutrient and water availability to the crops instead of the weeds (Blackshaw et al. 2003).

Under the aforesaid circumstances, adoption of potential alternative ecological approaches like manipulated crop management practices could be more viable and sustainable strategies for suppressing weeds on large scale. With the increasing incidences of herbicide-resistant weeds, suppressing weed growth through improving crop competition will more likely impact the weed seed biology and thus can help in reducing the seed viability and might influence the seed dormancy as well in the next generations. Therefore, farmers need to adopt these strategies to increase crop competitiveness as a component of integrated weed management systems (Peerzada et al. 2017). Further researches on quantifying competitive effect and providing rules of thumb will facilitate farmers' decision for weed management, particularly in herbicide resistance scenario (Lemerle et al. 2016).

13.3.7 Optimizing Herbicide Use and Performance

Herbicide efficacy can greatly depend upon a number of factors, including plant physiology, environmental conditions, chemical properties of herbicides, and edaphic conditions (Cieslik et al. 2013; Matzenbacher et al. 2014). For optimization of herbicide, three-step-based improved decision-making is prerequisite: prevention, the timing of weed control and herbicide choice, and rate (Kudsk 2007). Under field condition, successful use of herbicide depends on the herbicide selection for the weed spectrum, correct application timing, rate, and method. Reliability of chemical weed control can be improved by:

- Understanding herbicide classification helps farmers, advisors, and researchers to choose herbicides best suited to combat specific weed problems in specific crops (Shaner and Leonard 2001). Herbicide classification will increase farmer's awareness of herbicide mode of action and provide more accurate recommendations for resistance management and will make it easier to keep records on which herbicide mode of actions are being used on a particular field from year to year.
- Identifying weed species correctly to prevent wastage of herbicide applied for controlling weed species and to prevent unnecessary chemical entering into the environment, a cash outlay for no return and a crop full of competitive weeds. In case of highly competent, persistent, and difficult-to-control weed species, possessing greater threat to compete with crop and reduce yield, correct identification ensures herbicides to be able to effectively control and to decide on an appropriate response.
- Maximizing crop competition through using cultural practices, such as competitive crops and cultivar, high seed rates, and optimum agronomic practices, and disease or insect control measures to effectively improve chemical weed management programmes in cropping systems (Christensen 1994).
- Diversifying crops to reduce the weed populations, directly or indirectly, through entailing the weed-competitive crop species and/or species with varied growth cycles and phonologies, enables herbicide diversity and enforces different sowing and harvesting dates which exert different selection pressures on weed communities (Beckie and Harker 2017).
- Rotating herbicide and/or using herbicide mixtures with different MOAs to avoid the selection of weeds with the ability to detoxify herbicide or to mitigate the oxidative stress (Waggoner et al. 2011; Camargo et al. 2012). This strategy safeguards the evolution of herbicide resistance (Anwar et al. 2012) and reduces the chances of ecological shifts in weed populations (Murphy and Lemerle 2006).

- Understanding the effect of weather conditions before and after herbicide application on the herbicide performance is essential to realize the influence of climate change on the herbicide efficacy (Bailey 2004).
- Considering temperature, humidity, and high irradiance during the herbicide application and their influence on the effectiveness of numerous herbicide groups. Consideration related to choosing the best application timing would be helpful in optimizing the herbicide efficacy, particularly for post-emergent herbicides (Cieslik et al. 2013; de Queiroz et al. 2013).
- Preventing spray drift by maintaining due care and attention at all times when spraying herbicide and also by knowing how to apply the product carefully. Violation of a specific user instruction on the label and incorrectly assessing the prevailing conditions at the time of spraying (wind direction and speed, etc.) is a common example of herbicide misuse, causing herbicide drift.

13.3.8 Strengthening Farmer's Knowledge

To get benefits from the technological innovation in weed management, institutes and research organizations need to create a capacity building of the farming community to mitigate the menace caused by ever-adapting dynamic weeds under the enormous challenges to crop production, including climate change, soil degradation, and resources scarcity. Thus, updating farmers' knowledge with timely, relevant, accurate technical information is an urgent need (see Adusumilli et al. 2014). In developing countries, the following ways need to be followed to strengthen farmer's knowledge and ability in managing weed effectively as:

- Farmer's need-based extension efforts, counselling assistance, high-calibre extension agents, proper information dissemination, and technical farming experts are the essential ingredients for effective extension (Adusumilli, et al. 2014). Effective extension activities ensure farmers are equipped with the knowledge of improved weed management technologies for optimized long-term agricultural productivity.
- Better linkage between farmers and agricultural researcher in order to couple the scientist subject expertise with farmers' location-specific experience. Farmer's participatory process in the technology development process will strengthen their knowledge and will increase the adoption rate of existing and new technologies.
- Farmers should be involved in the development of technologies, which will increase the chances of a farmer's adoption; this will strengthen their knowledge.
- Training approaches, like farmer field schools (FFS), involving active farmers' participation to share knowledge with other farmers and learning new concepts through the experiential learning cycle (i.e. learning from practical experience).
- Developing partnership between the public, private, and global scientific research organizations to achieve dissemination of new technologies to the end-users.

Partnerships with global institute led towards faster progress as well as changes behavioural/attitude among bureaucrats and policymakers.
- Due to women actively involved in both Asia and Africa, focus on gender during technology development and extension will greatly enhance the efficiency and research impact; also it reduces gender inequalities in access to technologies.
- Involvement of private sectors will ensure high production through effective weed control by ensuring the timely availability of different components of weed management, such as herbicide, competitive cultivars, mechanical implements, and other inputs.
- Advance information dissemination systems and existing communication systems have been effectively used for transferring technological information. Weed management technologies can be passed effectively to the farming communities, facilitated by the Internet, mobile phones, and other communication networks (Adusumilli et al. 2014).

13.3.9 Promoting IWM Practices

Redesigning crop systems in order to reduce the weed population's densities and interference capacity would be one step forward in proactively reducing the need for herbicides (Peerzada et al. 2017). Cropping systems employing IWM approaches produce competitive yields and realize profit margins on a long-term basis, which are comparable to that system that relies chiefly on herbicides (Liebman et al. 2008; Anderson 2015). For promoting IWM knowledge, the following researchers highlighted some important keys to be followed (Nord et al. 2011; Mortensen et al. 2012), such as:

- Integration of IWM complexities into user-friendly decision support systems to satisfy farmers' demands for simple, effective, and flexible methods of weed management with respect to increasing farm sizes.
- Estimation of risk of weed management methods used alone or in combination through statistical approaches, such as collective risk theory (see Cummins 1991) and/or examining crop yield variability over time, for the adoption and long-term viability of IWM strategies.
- Region-specific information on crop and weed ecology for the selection of planting date to optimize the trade-off between weed control and the shorter growing season.
- Locally adapted and ongoing public research, combined with effective extension education programmes to address current and future weed management challenges.
- Concrete policy steps to ensure that the new HT crops will be adopted as only one component of fully IWM systems to ensure negative consequences for food production and the environment.
- Improved farmers education programmes implemented through industry-university-government collaborations and environmental support payments, con-

necting IWM to broader environmental goals, such as on-farm efficiency, soil quality management, and agro-diversity conservation.

- Implementation of spatially explicit, area-wide management plants to reduce selection pressure at the landscape or regional scale, mandating carefully the defined herbicide rotation patterns or setting upper limits on the sale of specific herbicide active ingredient or seeds of HT variety within an agricultural country.

13.3.10 Best Management Practices (BMP) for HT Crops

The adoption of HT crops and their associated agronomic practices facilitate the achievement of effective weed management and overcome increasing HR weed problems and other environmental concerns associated with agricultural intensification (Lamichhane et al. 2017). Sustainable practices and measures should be integrated with diversified herbicide as a key tactic for weed control as weed control without herbicide use are presently not conceivable in intensive farming systems. Such practices might be costly for farmers on a short-term basis; they will be beneficial in the longer term, especially if appropriate policies and incentives are put in place. For the transition towards IWM with HT crops, five action plans have been recommended (see Lamichhane et al. 2017);

- Education programmes to maintain and improve knowledge of weed and their management.
- Revision of current stewardship programmes.
- Integration of socio-economic studies to understand and change farmers' attitude and behaviour.
- Development of adequate public policy.
- Regulatory revisions.

13.3.11 Reducing the Evolution of Herbicide-Resistant Weeds and Their Management

Herbicide resistance is threatening the crop production, and farmer's response varies across different countries, which are largely reactive rather than proactive (Llewellyn and Allen 2006; Wilson et al. 2008; Norsworthy et al. 2012). In developed countries, farmers are more focused on managing resistance through non-chemical methods and/or looking for alternative herbicide options due to the loss of many sites of action. To some extent, a similar situation exists in developing countries or countries with less number of herbicide resistance reports. Under such circumstances, diversification of weed control methods seems to be the only practical solution for managing herbicide resistance in weeds. Norsworthy et al. (2012) suggested 12 best management practices (BMPs) to be employed in herbicide-resistant management programmes, which consider all cultural, mechanical, and herbicide options available for effective weed control:

(i) Understanding weed biology to devise a strategy, targeting the life stage most sensitive to management.
(ii) Diversified weed management approaches focusing on reduced weed seed production and minimized seedbank reserve, which adds to short-term management costs as compared to long-term costs associated with future herbicide resistance management.
(iii) Keeping field weed-free as possible sing residual herbicide before or at planting, especially in conservation tillage systems.
(iv) Plant weed-free crop seeds prevent the spread of herbicide resistance into new areas.
(v) Routine weed scouting of the fields.
(vi) Use of multiple herbicide modes of actions (MOAs).
(vii) Herbicide application on the labelled rate at the recommended weed size.
(viii) Suppress weed growth through increased crop competitiveness.
(ix) Use of appropriate mechanical and biological management practices.
(x) Prevent field-to-field and within-field dispersal of weed seeds and vegetative propagules.
(xi) Management weed seed at harvest and after harvest to deplete weed seedbank.
(xii) Prevent an influx of weeds into the field by management field borders.

Minimizing the continuous use of herbicide with the same mode of action through rotations and combination of products could be the key step in herbicide resistance management. In addition, integration of chemical weed control with effective cultural, mechanical, and physical options could possibly delay the onset of resistance. Furthermore, selection of nozzle size, carrier volume, and spray angle or orientation will do the right job the first time and will avoid unnecessary repeat applications. Dissemination of information related to herbicide group classification to the farmers and farm advisors to understand will make it easier for them to understand which herbicide shares the same mode of action. Most of the herbicide labels now indicate the group number and active ingredients; thus alternation or sequencing products with different MOAs or limiting the total number of application per season could be included in resistance management programmes.

13.4 Recommendations

Despite the development of broad-spectrum post-emergent herbicides, weeds continued their journey as a big constraint towards the adaptation of conversation agriculture, requiring more effective and economically viable integrated technologies in diverse cropping systems. Therefore, the development of more resilient weed management is prerequisite under the highly diverse emerging agricultural scenarios for an economically sustainable future agricultural management system.

- Responses of most of the economically damaging weed species towards changing climate have been rarely investigated and, consequently, are not well understood. It necessitates the proper understanding of the weeds, their biology, and population shifts under changing crop management practices and the predicted climate change.
- Early detection, combined with an understanding of the ecology of the weed, would play a vital role in the prevention and successful elimination of the invasive weed species from the agroecosystems.
- Prevention of seed production during the fallow period is potentially a low cost and valuable approach in preventing the buildup of the seedbank or perennial vegetative structure.
- Farmer's knowledge of herbicide mode of action will deliver a practical approach for preventing, delaying, and managing herbicide resistance.
- Broad understanding related to these factors helps farmers in minimizing the negative impact of herbicide on agroecosystem and will increase herbicide performance.
- Collaborative approaches among farmers to optimize the extension of improved weed technologies give them an opportunity to modify agricultural technologies and add value to them.
- Creating awareness regarding modern technologies, balanced herbicide doses, and land preparation through farmer training and workshops are needed to benefit agriculture in developing countries.
- Studies on integrated approaches including site-specific weed management using precise herbicide delivery techniques, controlled release formulation of herbicides, and weed-competitive crop cultivars with allopathic potentials would be acceptable in future.
- Information on herbicide-environmental risk assessment, particularly related to IWM strategies and BMP in HT crops, will help in better understanding and adoption of these strategies.

13.5 Conclusion

The significance of integrated weed management as an integral component of crop production cannot be neglected if the sustainable and economic development of agricultural systems in changing agroclimatic scenarios is to be achieved. Under such changing trends, increased concerns of herbicide failure and weed population shift in arable lands pressurized weed scientists to develop environmentally sustainable and economically viable options for controlling weeds in crop production systems. Strategies for minimizing weed spread, reducing weed seed production, maximizing crop resources use, improving herbicide efficacy, and depleting weed seedbank reserves could potentially be helpful approaches for better weed management under these systems. Farmer's awareness regarding maximizing crop competitiveness through suppressing weed growth will reduce herbicide rates for controlling difficult to control weed species. Furthermore, their understanding related to biology and ecology has largely been ignored, which need encouragement as such studies contribute significantly to developing integrated weed management programmes. Therefore, development of best management practices manuals and dissemination of information regarding weed identification, herbicide selection, and possible control options using the latest information technologies would be helpful in developing sustainable weed management programmes.

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