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Review

Ecology and management of weeds under conservation agriculture: A review

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ABSTRACT

Tillage has been known to cause soil erosion and cost time and resources and this affects productivity and inflates the cost of production. Therefore, over the past few years in many countries, there has been a growing trend toward conservation agriculture (CA) to enhance sustainability without compromising land productivity. Three important pillars of CA are minimal tillage operations, permanent residue cover, and rotation of primary crops. Adoption of CA, however, influences weed populations differently from conventional agriculture. Weed control in CA is a greater challenge than in conventional agriculture because there is no weed seed burial by tillage operations and soil-applied herbicides are not incorporated, resulting in reduced efficacy. The behavior of weeds and their interaction with crops under CA tend to be complex and not fully understood. A large proportion of weed seed bank remains generally on or close to the soil surface after crop sowing under CA. Weed species, in which germination is stimulated by light, are likely to be more problematic in CA. In addition, in the absence of tillage, perennial weeds may also become more challenging in this system. On the other hand, weed seeds present on the soil surface are more prone to desiccation and greater predation activity of insects, especially ants. Crop residues, when uniformly and densely present, under CA could suppress weed seedling emergence, delay the time of emergence, and allow the crop to gain an initial advantage in terms of early vigor over weeds. Where pre-emergence herbicides are applied, crop residues may also intercept a considerable proportion of the applied herbicide and may result in lower herbicide efficacy. Approaches such as stale seedbed practice, uniform and dense crop establishment, use of cover crops and crop residues as mulch, crop rotations, and practices for enhanced crop competiveness with a combination of pre- and post-emergence herbicides could be integrated to develop sustainable and effective weed management strategies under CA systems.

1. Introduction

Conservation tillage, a practice that was introduced initially to reduce wind erosion was slowly transformed into conservation agriculture (CA). CA is defined as an agricultural management system that aims to minimize soil disturbance, permanent residue for soil cover, and rotation of main crops (FAO, 2012). Soil tillage is the most energy-consuming operation among all field operations. No-till fields act as a sink for carbon dioxide and CA could provide a major contribution to controlling air pollution in general and global warming in particular. Growers can save from 30% to 40% of time, labor, and, in mechanized agriculture, fossil fuels in CA as compared to conventional cropping (Hobbs and Gupta, 2004). A comparison of some issues between conventional tillage and CA is given in Table 1 (Hobbs et al., 2008). Soils under CA have very high water infiltration capacities, which reduces surface runoff and thus soil erosion significantly. In many areas, after some years of conservation farming, it has been observed that natural springs that had dried up many years ago started to flow again (Shrestha et al., 2003).

CA yields comparable with modern intensive agriculture but in a sustainable way. Conservation farming reduces the production costs, time and labor, and, in mechanized systems, it reduces the costs of investment in machinery in the long term. Compared with conventional systems, CA has been found to maintain or increase crop yields, improve soil fertility, and reduce soil erosion (Hobbs and Gupta, 2004; Hobbs et al., 2008; Kassam et al., 2009; Lal, 2004). However, unless CA technologies are properly developed, tested, and fine-tuned with adequate grower participation before widespread extension to growers, these benefits might not be equally suitable for all locations and agroecosystems. Important variability and system tradeoffs could limit the expansion and adoption of these technologies in smallholdings (Giller et al., 2009;

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Table 1
A comparison of some issues between conventional tillage and conservation agriculture (Hobbs et al., 2008).

Issues	Conventional tillage	Conservation agriculture
Soil disturbance	High	Minimum
Soil surface	Bare surface	Permanently covered
Erosion	High wind and soil erosion	Low wind and soil erosion
Water infiltration	Low	High
Weeds	Kill established weeds but also stimulate more weed seeds to germinate	Weeds are a problem in the early stages of adoption but decrease with time
Diesel use and costs	High	Low
Production costs	High	Low
Timeliness	Operations can be delayed	Timeliness of operations more optimal
Yield	Can be lower where planting is delayed	Same or higher if planting done more timely

Lahmar, 2010). In CA, diseases and insects may propagate from one season to another through crop residue and therefore, it may warrant increased use of pesticides.

Crop yields can be similar for conventional and no-till systems if weeds are controlled and crop stands are uniform (Mahajan et al., 2002; Norwood, 1994). Weeds, however, are one of the biggest constraints to the adoption of CA. Tillage affects weeds by uprooting, dismembering, and burying them deep enough to prevent emergence, by moving their seeds both vertically and horizontally, and by changing the soil environment and so promoting or inhibiting weed seed germination and emergence (Clements et al., 1996; Hartzler and Owen, 1997; Swanton et al., 2000). Any reduction in tillage intensity or frequency may therefore have an influence on weed management. As the density of certain annual and perennial weeds can increase under CA, effective weed control techniques are required to manage weeds successfully (Moyer et al., 1994). The main reason for increased weed density is the absence of tillage in CA, as tillage has been used to control weeds in agriculture since time immemorial. In CA, tillage is greatly reduced, which may allow weeds to grow and flourish.

Crop yield losses in CA due to weeds may vary, depending on weed community and intensity (Koskinen and McWhorter, 1986). Weed species shifts and losses in crop yield as a result of increased weed density have been cited as major hurdles to the widespread adoption of CA (Buhler et al., 1994; Derksen et al., 1993). In the past, attempts to implement CA have often caused a yield penalty because reduced tillage failed to control weed interference. However, the recent development of post-emergence broad-spectrum herbicides provides an opportunity to control weeds in CA and this may increase growers' interest in CA in the near future.

Past experience of implementation of CA in the northwestern Indo-Gangetic Plains revealed that weeds germinate less in CA in the rice-wheat system because of less soil disturbance and less exposure of weed seeds to light than in conventional agriculture (Singh, 2007). The cropping system, however, plays an important role in influencing weed flora in CA. There is also evidence of allelopathic properties of cereal residues in inhibiting weed germination (Jung et al., 2004; Lodhi and Malik, 1987; Steinsiek et al., 1982). Weeds under CA may also be controlled when the cover crop is harvested or killed by herbicides. Farming practices that maintain soil microorganisms and microbial activity can also lead to weed suppression (Kennedy, 1999). The aim of this paper is to define strategies for improved weed management in the context of CA.

2. Weed seed ecology in conservation agriculture

Seed dormancy and germination are important survival mechanisms of weeds. The seed bank in the soil builds up through seed production and dispersal, while it depletes through germination, predation, and decay. With adequate knowledge of the germination requirement of weeds, situations can be identified in CA in which very low germination should occur or in which high germination should be stimulated at times when seedlings can be easily killed (Chauhan and Johnson, 2010b).

2.1. Vertical weed seed distribution

As tillage is reduced under CA, only the depth of sowing and the type of seeding machine (with tines or discs or other kinds of sowing points) influence vertical weed seed distribution in the soil profile. In no-till wheat in Australia, the distribution of surface weed seeds through the soil profile was associated with the amount of soil disturbance during sowing operations (Chauhan et al., 2006b). In that study, the low-soil-disturbance single-disc system retained more than 75% of the weed seeds in the top 1 cm soil layer, whereas the high-soil-disturbance seeding system buried more than 75% of the seeds to a depth of 1–5 cm. The latter system left only 11% of the seeds in the top 1 cm soil layer. These results suggest that, under low-soil-disturbance systems, a large proportion of the weed seed bank will be left on the soil surface after sowing in CA. In another study, 60–90% (depending upon soil type) of the weed seeds were located in the top 5 cm of the soil in no-till systems (Clements et al., 1996; Swanton et al., 2000).

Differential vertical distribution of seeds in the soil has the potential to affect seedling emergence and weed population dynamics, as different soil depths differ in availability of moisture, diurnal temperature fluctuation, light exposure, and activity of predators (Chauhan et al., 2006b, 2007). Some studies have compared vertical weed seed distribution between conventional tillage and no-till systems; however, very limited information is available on vertical seed distribution by different no-till seeders under CA. Therefore, vertical seed distribution patterns caused by different seeders, attached with discs and tines, need evaluation under different amounts of residue.

2.2. Weed seed predation

As mentioned earlier, due to minimal soil disturbance in CA, most of the weed seeds remain on the soil surface after crop planting. Such conditions may also be more favorable for granivore fauna, such as ants and other insects. Weed seeds present on the soil surface in CA are most vulnerable to surface-dwelling seed predators and burial makes seeds largely unavailable (Hulme, 1994). Therefore, seed predation could be important in systems where newly produced weed seeds remain on the soil surface, for example, in no-till systems (Baraibar et al., 2009; Chauhan et al., 2010). On the other hand, tillage can damage the nests of harvester ants and redistribute the weed seeds stored in superficial chambers (Baraibar et al., 2009; Díaz, 1991). Only a small percentage of the weed seeds produced emerge as seedlings in the crop and seed predation may be responsible for the larger part of these losses (Westerman et al., 2003). When combined with other methods of weed control, seed predation may help to minimize herbicide use, risk and costs, and labor demand.

Predation of *Abutilon theophrasti* Medik. and *Setaria faberi* Herrm. seeds was found in corn-soybean crop rotations in the U.S. (Heggenstaller et al., 2006). Likewise, post-dispersal predation of *Echinochloa crus-galli* (L.) Beauv. reduced seed input from 2000 to 360 seeds m^{-2} (Cromar et al., 1999). In Western Australia, Jacob Spafford et al. (2006) reported an average of 48% seed predation and slightly higher predation for *Lolium rigidum* Gaudin than for *Raphanus raphanistrum* L. and *Avena fatua* L. The authors suggested that seed size and ease of consumption were the factors influencing the preference of the granivores, particularly the ants. Predators have preference for certain kinds of seeds. Vertebrate and large invertebrate predators usually prefer larger seeds. An ant species, *Solenopsis geminata*, prefers grass weed seeds over broadleaf weed seeds (Risch and Carroll, 1986). If *S. geminata* is the main seed predator in a field, broadleaf weed species may have an advantage. Such selectivity in seed consumption may result in shifts in weed population (Risch and Carroll, 1986).

These results suggest that seed predation can substantially reduce the size of the weed seed bank. Weed seed predation in CA can be encouraged by the management of bunds and dryland areas around fields. Crop residue can be retained in the field rather than removing or burning and this may provide forage to seed predators (e.g., Chauhan et al., 2010). Since such approaches are possible with no additional costs to growers, they can be integrated in existing practices. Weed seed predation is only one component of a potential package of integrated weed management practices (Chauhan et al., 2010); therefore, future research should evaluate how this component can best be combined in CA and intensive systems where insecticides and other chemicals are used widely.

3. Weed management in conservation agriculture

As the use of CA has been increasing in recent years due to the economics of crop production (Hobbs, 2007) and regulatory mandates concerning environmental problems (Locke et al., 2002), there is a need to gain understanding on weed management in CA crop production systems. Various approaches, including the use of preventive measures, crop residue as mulches, intercropping, competitive crop cultivars, herbicide-tolerant cultivars, and herbicides, are needed to manage weeds in a CA system.

3.1. Weed-preventive measures

Preventing invasive and alien weeds in fields is usually easier and less costly than controlling them after severe infestation, as it is difficult to control weeds once they are established. Some weed-preventive measures include the use of clean crop seeds, the use of clean agricultural implements, and managing weeds on bunds or levees and roads, etc. A study in Montana State University showed that a vehicle driven through a *Centaurea biebersteinii* DC. infestation picked up about 2000 seeds of *C. biebersteinii*, of which 90% dropped within 10 miles (Sheley et al., 2002). The study also suggested that minimizing disturbance of soil by vehicles, machinery, wildlife, and livestock is central to preventing noxious weed establishment.

Seeds of most crops are contaminated with weeds, especially where weed seeds resemble the shape and size of crop seeds. Contamination usually happens during the time of crop harvesting when weeds having life cycles similar to those of crops set seeds. The presence of even a small quantity of weed seeds may be enough for stinting a serious infestation in the next season. To obtain weed-free crop seeds, cultural and mechanical measures need to be adopted. The idea should be to minimize the weed infestation area and decrease the dissemination of weed seeds from one area to another or from one crop to another. Control of weed species is achieved by reducing plants and propagules to the point at which their presence does not seriously interfere with an area of economic use. The planning of post-infested weed control programs should be done in such a way that the build-up of weed seeds is reduced drastically within a short period of time. Proper care should be taken to restrict the weed seed bank size in the area by using integrated methods of weed control. In undisturbed or no-till systems, seeds of weeds and volunteer crops are deposited in the topsoil (Locke et al., 2002; Lyon et al., 1996; Swanton et al., 1999). Therefore, an appropriate strategy is needed to avoid high weed infestations and to prevent unacceptable competition with the emerging crop (Lyon et al., 1996).

L. rigidum and *R. raphanistrum* reach maturity at a time similar to wheat, lupins, and canola. As the majority of the seeds are retained on the plant, they enter the harvester. Up to 80% of *R. raphanistrum* seeds were collected in grain samples, while more than 95% of *L. rigidum* seeds that entered the harvester exited with the chaff (Walsh and Newman, 2007). Therefore, seed cleaning and chaff carts or direct bailing of chaff offer alternative methods to reduce the amount of weed seeds entering the seed bank. Chaff collected by chaff carts is generally burned or used as livestock feed. Destroying weed seeds by burning requires exposure to temperatures of 400 °C (for *L. rigidum*) to 500 °C (for *R. raphanistrum*) for 10 s. In wheat stubbles of 3–6 Mg ha^{-1}, soil surface temperatures between 300 and 400 °C were recorded for 30–50 s (Walsh and Newman, 2007). These temperatures and durations increased with increases in stubble quantity. Concentrating stubble and weed seeds into windrows increases the effective biomass. Burning windrows is more effective for *R. raphanistrum*, for which trials found 80% of seeds destroyed compared with only 20% in burned standing stubble (Walsh and Newman, 2007). For *L. rigidum*, 99% of the seeds were destroyed by windrow burning compared with 80% in standing stubble. Burning windrows can be time consuming but results in only about 10% of the field area being burned, thereby reducing the risk of soil erosion (Walsh and Parker, 2002; Walsh and Newman, 2007).

3.2. Tillage systems and time of crop sowing

In CA systems, stale seedbed practice can be a valuable way of reducing weed pressure. In this practice, a light irrigation or shower encourages weed seeds to germinate and emerged seedlings are killed by the use of non-selective herbicides. As most of the weed seeds remain in the topsoil layer in CA and weed seeds mostly germinate and emerge from the top 3 cm of the soil layer, a flush of weed seedlings will appear within a week after irrigation. These weed seedlings can be destroyed with non-selective herbicides glyphosate or paraquat. The stale seedbed practice was found very effective in zero-till wheat in the northwestern Indo-Gangetic Plains (Mahajan et al., 1999). The main advantage of the stale seedbed practice is that the crop emerges in weed-free environments and it will have a competitive advantage over late-emerging weed seedlings.

Tillage has been used to control weeds since the origin of agriculture; however, a reduction in tillage may dramatically increase weeds. Several studies suggested a small difference in weed populations between conventional and zero-till fields (Derksen et al., 1993) and, in some cases, fewer weeds were observed in zero-till conditions (Hobbs and Gupta, 2001; Malik et al., 2002; Singh et al., 2001). Mulugeta and Stoltenberg (1997) noticed a several-fold increase in weed seedling emergence due to tillage.

In CA, time of sowing can be manipulated in such a way that ecological conditions for the germination of weed seeds are not met. In the northwestern part of the Indo-Gangetic Plains, for example, growers advanced wheat seeding by 2 weeks to get a head start over noxious weed *Phalaris minor* Retz. (Singh et al., 1999). Earlier seeding of spring crops can improve their ability to compete with weeds. If weeds can be controlled, earlier seeding of winter wheat and other fall-seeded crops can also be advantageous for yield potential. However, other management options must be considered for the control of early seeding-related diseases (Karlen et al., 1994). In addition, herbicide application should be considered for the weeds emerging after an early seeding. If a field has a history of high infestation of *Bromus tectorum* L., some farmers delay fall seeding until fall rains stimulate weed germination (Froud-Williams, 1983). Late seeding, however, may reduce crop yield potential.

One of the pillars of CA is ground cover with dead or live mulch, which leaves less time for weeds to establish during fallow or a turnaround period. Often, in dryland fallow, the area becomes covered with weeds and uses residual soil moisture, which otherwise could be used by a succeeding crop. Adoption of no-till technology has proved beneficial for growers in the rice–wheat cropping system, and is the single largest factor in mitigating herbicide-resistant *P. minor* in Haryana, India. No-till systems had been tried unsuccessfully in the past in India, but herbicide resistance in *P. minor* forced growers to re-evaluate this tillage regime even though they held a strong traditional belief in intensive cultivation for field preparation. This practice not only reduced the cost of field preparation to compensate for the use of costly herbicides (clodinafop, sulfosulfuron, and fenoxaprop), but early planting also gave an advantage to wheat over *P. minor*. Reduced emergence of the weed due to minimum soil disturbance reduced the extent of crop-weed competition. Franke et al. (2001) showed that no-till resulted in reduced emergence of *P. minor*, irrespective of weed seed bank density. Variation in the amount of moisture in the no-till system (versus conventional tillage) might be a factor in the lower emergence of *P. minor* in no-till sown fields. *P. minor* emerges in two to three major flushes; the first flush is more important from herbicide point of view. Delayed herbicide application may result in reduced efficacy and a non-persistent herbicide may not control late-emerging weed seedlings effectively.

Some other common problems under CA include emergence from recently produced weed seeds that remain near the soil surface, lack of disruption of perennial weed roots, interception of herbicides by thick surface residues, and change in timing of weed emergence (Bullied et al., 2003). The information of weed species shifts under CA, however, are inconsistent in the literature. An earlier study reported an increase in dicot weeds with tillage intensity (Cussans, 1976). Another study found similar broadleaf weeds in both no-till and conventional tillage systems (Wrucke and Arnold, 1985). Swanton et al. (1999) reported that *Chenopodium album* L. and *Amarathus retroflexus* L. were associated with a conventional tillage system, whereas *Digitaria sanguinalis* L. was associated with a no-till system. In a later study, Shrestha et al. (2002) concluded that long-term changes in weed flora are driven by an interaction of several factors, including tillage, environment, crop rotation, crop type, and the timing, and type of weed management practice.

3.3. Crop residues

In CA, crop residues present on the soil surface improve soil and moisture conservation, and soil tilth (Locke and Bryson, 1997). In addition, the residues can influence weed seed germination and seedling emergence. However, the germination response of weeds to residue depends on the quantity, position (vertical or flat and below or above weed seeds), and allelopathic potential of the residue and the weed biology (Chauhan et al., 2006c). In some areas, cover crops are grown between the two main crops in order to reduce soil erosion and enhance soil fertility. The cover crop is then killed by using non-selective herbicides, such as glyphosate. In CA, the dead mulch of the cover crop on the surface suppresses weed germination by exhibiting allelopathic effects and decreasing light transmittance to the soil surface. A number of cover crops, including legumes (alfalfa, sesbania, sunhemp, clover, soybeans, lupins, and cowpeas) and non-legumes (sunflower, rapeseed, rye, buckwheat, and sudan grass), have been found to suppress and smother various weeds by crop competition or allelopathic interaction. In India, cover crops such as sesbania can produce a green biomass of 17–25 Mg ha^{-1} within 60 days and control most of the weeds, leaving fields almost weed-free (Mahapatra et al., 2004).

Emergence of some weed species declines monotonically in response to increasing residue amounts whereas emergence of other weed species increases at low residue amount before declining at high residue amount (Mohler and Teasdale, 1993). The residue of Russian vetch and rye reduced total weed density by more than 75% compared with the treatments with no residue (Mohler and Teasdale, 1993). Similarly, the presence of rye mulch reduced weed biomass in corn (Mohler, 1991). In another study, a rye mulch in corn significantly reduced weed emergence of *C. album*, *D. sanguinalis*, and *Portulaca oleracea* L. (Mohler and Calloway, 1992). Hairy vetch residue suppressed weeds early in the growing season without herbicide use, but it was necessary to use herbicide to achieve season-long weed control (Teasdale, 1993). The densities of *Ipomoea* spp., *Sida spinosa* L., and *Cassia obtusifolia* L. were also reduced by crop residues (Liebl and Worsham, 1983).

In addition to reducing weed emergence, high amounts of residue may prolong or delay emergence, which may have implications for weed management in CA. Delayed weed emergence may allow the crop to take competitive advantage over weeds, and these weed seedlings are likely to have less impact on crop yield loss and weed seed production. Plants emerging earlier produce a greater number of seeds than the later emerging ones (Chauhan and Johnson, 2010a). On the other hand, later emerging weed seedlings may escape the application of early post-emergence herbicides.

In some cases, the presence of crop residue may stimulate weed seed germination. Wheat residues, for example, promoted germination and growth of *A. fatua* and *Avena sterilis* subsp. *ludoviciana*. Organic matter may increase the moisture amount on the surface layer and decrease the soil temperature and these conditions may increase the germination of some weed species (Young and Cousens, 1999). There were a few instances in the literature where stubble retention, compared with stubble burning, resulted in a greater weed problem. This may be because the wide use of herbicides is effective in controlling any weed that resulted from sustained stubble retention. *B. tectorum* has also been a problem in stubble-retained systems in North America. Wicks (1983) suggested that *B. tectorum* flourished with stubble mulching due to reduced evaporation providing a favorable site for germination.

In northern India, straw management is a major factor in weed management in wheat grown after rice. Burning of straw has been practiced by many growers to reduce thatch and also to burn weed seeds, notably those of *P. minor* dispersed on the soil surface after the puddling process in rice. However, due to environmental pollution, straw burning has been banned in many states in India. In isoproturon-treated plots, *P. minor* density was 1.9 and 2.8 times greater where 6 and 12 Mg ha^{-1} of rice straw, respectively, was burned compared with its removal (Singh, 1996).

Overall, germination of various weed species can be reduced in the presence of crop residues; however, a higher quantity than normally found in dryland fields is needed to substantially suppress weed germination and growth (Chauhan and Johnson, 2010b; Chauhan et al., 2006c). The quantity of crop residues also varies with the type of crop grown, for example, oilseeds and pulses produce less biomass than cereals. In rainfed areas, the crop biomass will also depend on the amount and pattern of rainfall. Therefore, depending on the region, crop, and rainfall, the effects of crop residue on the weed population are likely to be dynamic. There is a need to integrate herbicide use with residue retention to achieve season-long weed control. In high-residue situations, it will also be important to determine that this amount of residue does not hinder crop emergence.

3.4. Intercropping

Currently, intercropping is practiced where farmers seek the highest combined yield of two or more crops per unit of land area or risk not meeting income requirements (Liebman et al., 2001). Intercropping implies growing two or more crops of different growth habits simultaneously on the same piece of land, which offers early canopy cover and seedbed use resulting in reduced weed growth by competition for resources among component crops. Intercrops can be more effective than sole crops in pre-empting resources used by weeds and suppressing weed growth because complementary patterns of resource use and facilitative interactions between intercrop components can lead to a greater capture of light, water, and nutrients (Liebman et al., 2001).

Intercropping offers potential advantages for increasing sustainability in crop production. Intercropping of short-duration, quick-growing, and early-maturing legume crops with long duration and wide-spaced crops leads to covering ground quickly and suppressing emerging weeds effectively. Corn-legume intercropping led to a higher soil canopy cover and decreased light availability for weeds, which resulted in a reduction in weed density and dry matter compared with sole crops (Kumar et al., 2010). Weed suppression by crops was also greater at a low-productivity site than at a high-productivity site (Bilalis et al., 2010). Compared with sole cropping, a leek-celery intercrop decreased relative soil cover of weeds by 41%, reduced the density of *Senecio vulgaris* L. by 58%, and increased total crop yield by 10% (Baumann et al., 2000). Improvement in yield and weed suppression has also been demonstrated in many environments for cereal–legume intercrops (Ofori and Stern, 1987).

Around two decades ago, Liebman and Dyck (1993) suggested that significant advances in the design and improvement of weed-suppressive intercropping systems are most likely to occur if important areas of research are addressed; however, such information is still limited under CA. The suggested research areas include attention to the study of weed population dynamics and crop-weed interference in intercropping systems, systematic manipulation of specific components of intercropping systems to isolate and improve elements important for weed control, and assessing the weed-related impacts of combining intercropping strategies. A resource-based approach for weed study in intercropping systems under CA can provide information on why certain crop combinations are more weed-suppressive than others (Liebman et al., 2001).

3.5. Crop rotations and diversification

Yields from rotation systems are often higher than from continuous monocultures because crop rotation improves soil characteristics and reduces pest problems (Liebman et al., 2001). The benefits of crop rotation depend on the selection of crops and their sequence in the system. Continuous cultivation of a single crop or crops having similar management practices allows certain weed species to become dominant in the system and, over time, these weed species become hard to control. For example, in continuous cereal cropping in temperate regions, reduced tillage can cause the dominance of grass weed species, such as *Alopecurus myosuroides* Huds and *Bromus* spp. (Froud-Williams, 1983). Therefore, it is very important to rotate cereals with crops having a different growing period. A long fallow period between two crops can be exploited to stimulate the emergence of problem weeds, which are then destroyed by non-selective herbicides. Differentiation of crops grown over time in the same field is a well-known primary means of weed control. Different crops require different management practices, which may help in disturbing the growing cycle of weeds and, may prevent selection of the weed flora toward increased abundance of problem species (Karlen et al., 1994).

Rotating to another crop may prevent one particular weed species from becoming unmanageable; however, it may also increase weed diversity (Locke et al., 2002). Malik and Singh (1995), for example, found fewer resistance cases in *P. minor* where growers included sugarcane, sunflower, and vegetables in rotation than in a rice-wheat cropping system. Some crops can suppress weed growth significantly through their ability to grow faster. Crop rotation is an effective practice for management of *P. minor* because selection pressure is diversified by changing patterns of disturbances (Bhan and Kumar, 1997; Chhokar and Malik, 2002). Diversification of the area under a rice–wheat cropping system changes weed spectrum and makes soil conditions unfavorable for *P. minor* emergence and growth. When replacing wheat with other crops such as berseem clover, potato, sunflower, and oilseed rape for 2–3 years in a rice–wheat cropping system, the population of *P. minor* decreased significantly (Brar, 2002).

Intensive cropping systems with shorter turnaround periods in CA can increase the competitive ability of crops, thereby reducing weed pressure. Bringing fodder crops such as Egyptian clover or alfalfa in cereal-based systems can drastically reduce weed densities. Crop rotation also allows growers to use new herbicides and this practice may control problematic weeds. Weedy rice (*Oryza sativa* L.) is becoming a serious weed problem in rice monoculture in Southeast and South Asia (Chauhan and Johnson, 2010c). This may become even a more problematic weed species when farmers attempt to adopt CA in rice. Rotating one rice crop in rice–rice–rice or rice–rice cropping systems with an upland crop in the dry season may significantly help in reducing the seed bank of weedy rice in the soil. Very encouraging results have been found in reducing the weedy rice seed bank in a rice–rice–rice cropping system in Vietnam when dry-season rice was replaced by corn, sesame, or mungbean (Chauhan et al., unpublished data). In these upland crops, it is easy to recognize weedy rice (and volunteer rice) seedlings and they can be pulled out or killed easily by using herbicides. In addition to reducing weed populations, crop rotation may also result in improved yield. Reddy et al. (2002), for example, reported a 10% increase in cotton yield following rotation with corn compared with continuous cotton. The adoption of rotational crops, however, will depend on the market price of the crops.

3.6. Chemical weed management

Weed management using herbicides has become an integral part of modern agriculture. Herbicides offer great flexibility of operation, are effective, and are often cost effective compared with any other method of weed management. Control of weeds using herbicides is becoming popular in many parts of the world mainly because herbicide application requires less human effort, can tackle difficult-to-control weeds, and allows flexibility in weed management. Nevertheless, injudicious and continuous use of a single herbicide over a long period of time may result in the development of resistant biotypes, shifts in weed flora, and negative effects on the succeeding crop and environment.

As the effect of no-till systems on weed control varies with weed species and herbicides used, choosing an appropriate herbicide and appropriate timing is very critical in CA systems (Buhler, 1995; Chauhan et al., 2006c). Weeds that are present when crops are planted in a CA system may need to be controlled with a non-selective herbicide such as glyphosate, paraquat, or glufosinate. For example, *Stellaria media* (L.) Vill., *Capsella bursa-pastoris* (L.) Medik., *Sisymbrium irio* L., *Erodium* spp., *Brassica* spp., and *Amsinckia* spp. are common annual weeds that are present on the fallow beds in CA systems, and these need to be controlled with non-selective post-emergence herbicides (Vargas and Wright, 1994). Non-selective burn-down herbicides can be applied before or after crop planting but prior to crop emergence (Hartzler and Owen, 1997). Since these herbicides lack residual activity, application should be scheduled as close as possible to crop planting in order to minimize further weed emergence prior to crop emergence.

In conventional tillage systems, crop residues generally are not present at the time of pre-emergence herbicide application. However, in CA systems, residues are present at the time of herbicide application and may decrease the herbicide's effectiveness as the residues intercept the herbicide, thus reducing the amount of herbicide that can reach the soil surface and kill germinating seeds (Hartzler and Owen, 1997). The level of herbicide by residue interaction, however, is hard to evaluate because of variable distribution of residue over the soil. Organic matter present on the soil surface in CA is the major soil component influencing the performance of most soil-active herbicides (Chauhan et al., 2006c; Peter and Weber, 1985). Crop residues can intercept from 15% to 80% of the applied herbicides and this may result in reduced efficacy of herbicides in CA systems (Banks and Robinson, 1982, 1984; Buhler, 1995; Chauhan et al., 2006c; Sadeghi et al., 1998; Sorenson et al., 1991; Streit et al., 2003).

In a study, metribuzin was applied with a high-volume boom spray application (280 L ha^{-1} of water) and around 30% of the herbicide reached the soil surface under 2.25 Mg ha^{-1} of wheat straw, declining to less than 15% under 4.5 Mg ha^{-1} of straw, and to less than 5% under 9 Mg ha^{-1} of straw (Banks and Robinson, 1982). However, subsequent irrigation (with 50 mm of simulated rainfall) increased these estimates to 45%, 39%, and 35% under 2.25, 4.5, and 9 Mg ha^{-1} of straw, respectively. In another study, a spray application of atrazine to wheat stubble resulted in only 40% of the herbicide reaching the soil surface, with the stubble retaining about 60% of the applied herbicide (Ghadiri et al., 1984). The stubble (a total amount of 6.4 Mg ha^{-1}) consisted of 3 Mg ha^{-1} of standing stubble and 3.4 Mg ha^{-1} of flattened stubble. Three weeks after herbicide application and 50 mm of rainfall, 75% of the original atrazine applied was in the top 4 cm of the soil surface, and 14% remained in the stubble.

The efficacy of herbicides may also depend on the herbicide formulations under CA systems. For example, pre-emergence herbicides applied as granules (alachlor, cyanazine, and metolachlor) provided better weed control than liquid-formations in no-till systems (Johnson et al., 1989). The granules are assumed to move to the soil surface through the stubble more effectively than a liquid applied herbicide, likely aided by sowing or cultural disturbances. In another study also, the granules of trifluralin were more effective (57% vs. 22% control) than the liquid formulation in controlling *Setaria viridis* L. and *S. glauca* L. in a no-till system having 7.5 Mg ha^{-1} of stubble with 84% ground cover (Endres and Ahrens, 1995).

Depending on the herbicide chemical properties and formulations, some herbicides intercepted by crop residues in CA systems are prone to volatilization, photodegradation, and other losses. Herbicide persistence under CA systems also depends on climatic conditions and herbicide application methods such as pre-plant incorporation by zero-till sowing tines or post-sowing pre-emergence, in which there is no incorporation by sowing tines (Curran et al., 1992). Herbicides with high vapor pressure, for example, trifluralin and pendimethalin, are susceptible to volatilization loss from the soil surface (Chauhan et al., 2006a). With no incorporation, only 2% of the initial amount of trifluralin was present 12 weeks after herbicide application, whereas 26% and 40% of the applied trifluralin remained following incorporation to 2.5–5 cm and 7.5–10 cm, respectively (Savage and Barrentine, 1969).

In a recent study, within different no-till systems, low-soil-disturbance sowing systems retained most of the trifluralin on the soil surface even after the sowing operation, so the herbicide was susceptible to loss through volatilization and photodecomposition (Chauhan et al., 2006a). On the other hand, the loss of bioavailable trifluralin was lowest with high-soil-disturbance seeding equipment because of greater soil coverage of the herbicide in the inter-rows, which would have reduced losses because of volatilization and photodecomposition in these systems. Similarly, pendimethalin was less persistent in the field when the herbicide was surface applied than when it was incorporated (Walker and Bond, 1977). Such high losses of herbicides under CA systems could have serious implications for the control of weeds that have a protracted emergence pattern (Chauhan et al., 2006a). In such situations, there may be insufficient herbicide remaining to control late-emerging weeds in the crop. As the amount of soil disturbance decreases, particularly with disc seeding systems, the level of control offered by pre-emergence herbicides, having high vapor pressure, can be expected to decrease. These studies suggest that there is a need to evaluate the performance of different pre-emergence herbicides under CA, which can provide effective weed control.

The effectiveness of post-emergence herbicides may also be reduced by the presence of weeds and cover crop residues. In a study, the quantity of spray lodged on *Amaranthus hybridus* L. was reduced by standing wheat stubble by 38% at a spray travel speed of 8 km h^{-1}, and by 52% at 16 km h^{-1} (Wolf et al., 2000). Hartzler and Owen (1997) suggested that growers wait until weeds become established and then control them with post-emergence herbicides since the timing of weed emergence is less uniform in CA systems than in conventional-tilled systems.

If growers use non-selective herbicides, almost all weeds can be removed in a single application. Previously, non-selective herbicides were used only when a crop was not growing in the field (e.g., before crop sowing), making control of some serious weeds very difficult. The important contribution of biotechnology has been the development of herbicide-tolerant crops for effective weed management. Herbicide-tolerant crops provide growers with a very important and useful tool in managing weeds and these crop cultivars are compatible with CA systems. Common crops tolerant of glyphosate (*Roundup Ready*™) and glufosinate (*Liberty Link*™) are soybean, corn, canola, and cotton.

Compared with the use of selective herbicides, the use of non-selective herbicides in a herbicide-tolerant crop offers several potential advantages, including the application of fewer herbicides to a crop, reduced use of fuel (when spraying is done by an engine- or tractor-mounted sprayer) because of less spraying, reduced soil compaction because of less spraying by tractors, ability to control weeds that previously could not be controlled in a particular crop because of the absence of a suitable selective herbicide or because the weeds have become resistant to certain herbicides, higher yields through the elimination of herbicide damage to the crop due to drought or low temperatures, and more environmentally benign and safer use than some other herbicides currently available. However, there could be potential disadvantages of herbicide-tolerant crops, such as the potential evolution of herbicide-resistant weeds because of over-reliance on a single herbicide or a group of closely related herbicides; gene-drift to similar species (e.g., from herbicide-tolerant rice cultivars to weedy rice), which would confer the resistance to the weedy population; poor application of herbicides can cause serious damage to non-herbicide tolerant crop cultivars in adjoining areas; and escape of herbicide-tolerant cultivars' seed as volunteers can become serious weed problems in the crop.

The potential for weed resistance to specific herbicide is always a concern with herbicide programs, and the concern increases with herbicide-tolerant crops in CA systems. Because of effective weed control and cost effectiveness of glyphosate-tolerant crop technology, growers rely solely on glyphosate herbicide for weed control. Continuous use of glyphosate may result in shifts in some problematic weed species or the development of glyphosate-resistant weeds in herbicide-tolerant crop fields and growers may lose this important tool for weed management. *Conyza canadensis* (L.) Cronq., for example, was reported to develop resistance against glyphosate in zero-till *Roundup Ready* corn–soybean rotations in the United States (Mueller et al., 2003). Therefore, herbicide-tolerant crop cultivars should not be considered as a stand-alone component of weed management. An integrated weed management strategy should be used to ensure that this important weed management tool remains profitable and environmentally sound over a long period of time.

3.7. Integrated weed management

Any single method of weed control cannot provide season-long and effective weed control. Therefore, a combination of different weed management strategies should be evaluated for widening the weed control spectrum and efficacy for sustainable crop production. The use of clean crop seeds and seeders and field sanitation (irrigation canals and bunds free from weeds) should be integrated for effective weed management. Combining good agronomic practices, timeliness of operations, fertilizer and water management, and retaining crop residues on the soil surface improve the weed control efficiency of applied herbicides and competitiveness against weeds. In Canada, for example, integrating superior cultivars with a high seeding rate and the earliest time of weed removal led to a 40% yield increase compared with the combination of a weaker cultivar, the lowest seeding rate, and the latest time of weed removal (Harker et al., 2003).

4. Conclusions

Weed management problems in CA systems range from the control of the pre-plant fallow vegetation to the management of plant residues, the choice of herbicides, problems with insects and pests, and lack of seed drills. Ineffective weed control is a major deterrent to the adoption of CA. Reducing or eliminating the tillage from crop production systems has a profound effect on an environment where weeds survive and reproduce. Weed populations are highly plastic and respond quickly to changing cropping practices. Therefore, restricting tillage also reduces weed control options and increases reliance on herbicides. The higher content of organic matter and crop residues in zero-till systems lowers the herbicide efficacy, especially of soil-active herbicides. There is a poor understanding of weed dynamics in CA and non-availability of effective weed control measures often result in increased herbicide use.

In addition to these suggested research areas, some future research in CA may focus on:

1. *Crop cultivars with high seed vigor:* Seeds with high vigor and improved canopy architecture of crop cultivars, including hybrids, can strengthen the weed competitiveness of a crop under CA systems. Research is needed to find cultivars that are not only suitable for CA but also have an ability to form an early dense canopy, leaving less space and light for weeds. Reduced light availability at the soil surface can restrict germination and subsequent growth of weed seedlings.
2. *Herbicide-tolerant crop cultivars:* Herbicide-tolerant crop cultivars are very effective options to effectively manage weeds in CA; however, there is a strong need to evaluate the risk management strategies for gene-flow from herbicide-tolerant crops to their wild relatives and the development of herbicide-resistant biotypes of weeds.
3. *Herbicide application technologies:* Low-cost and high-efficiency herbicide application technologies, including spray equipment and nozzles, herbicide carriers, adjuvants, etc., are important to reduce the cost of weed management and improve the efficacy of applied herbicides. In addition, we need to understand better how retained crop residues interact with soil-applied herbicides under CA. Similarly, further research on herbicide mixtures for delaying resistance, reducing the cost of weed management, and improving the weed control spectrum is needed.
4. *Tillage and crop establishment practices:* Harmonizing tillage and crop establishment systems with cultural practices to reduce crop losses due to weeds is needed. There is a need to evaluate the possibility of mechanical weeding in CA systems, such as permanent raised beds and wide-spaced crops. Mechanical weed control is important considering herbicide resistance and the limited availability of new herbicides.

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References

Banks, P.A., Robinson, E.L., 1982. The influence of straw mulch on the soil reception and persistence of metribuzin. Weed Science 30, 164–168.
Banks, P.A., Robinson, E.L., 1984. The fate of oryzalin applied to straw-mulched and non-mulched soils. Weed Science 32, 269–272.
Baraibar, B., Westerman, P.R., Carrión, E., Recasens, J., 2009. Effects of tillage and irrigation in cereal fields on weed seed removal by seed predators. Journal of Applied Ecology 46, 380–387.
Baumann, D.T., Kropff, M.J., Bastiaans, L., 2000. Intercropping leeks to suppress weeds. Weed Research 40, 359–374.
Bhan, V.M., Kumar, S., 1997. Integrated management of *Phalaris minor* in rice-wheat ecosystems in India. In: Proceedings of International Conference on Ecological Agriculture: Towards Sustainable Development, Chandigarh, India. pp. 400–415.
Bilalis, D., Panayiota, P., Aristidis, K., Sotiria, P., Anestis, K., Aspasia, E., 2010. Weed-suppressive effects of maize-legume intercropping in organic farming. International Journal of Pest Management 56, 173–181.
Brar, L.S., 2002. Current status of herbicide resistance in Punjab and its management strategies. In: Proceedings of International Workshop on Herbicide Resistance and Zero Tillage in Rice–Wheat Cropping System. CCSHAU, Hisar, India, pp. 6–10.
Buhler, D.D., Stoltenberg, D.E., Becker, R.L., Gunsolus, J.L., 1994. Perennial weed populations after 14 years of variable tillage and cropping practices. Weed Science 42, 205–209.
Buhler, D.D., 1995. Influence of tillage systems on weed population dynamics and management in corn and soybean in the central USA. Crop Science 35, 1247–1258.
Bullied, W.J., Marginet, A.M., Van Acker, R.C., 2003. Conventional- and conservation-tillage systems influence emergence periodicity of annual weed species in canola. Weed Science 51, 886–897.
Chauhan, B.S., Johnson, D.E., 2010a. Implications of narrow crop row spacing and delayed *Echinochloa colona* and *Echinochloa crus-galli* emergence for weed growth and crop yield loss in aerobic rice. Field Crops Research 117, 177–182.
Chauhan, B.S., Johnson, D.E., 2010b. The role of seed ecology in improving weed management strategies in the tropics. Advances in Agronomy 105, 221–262.
Chauhan, B.S., Johnson, D.E., 2010c. Weedy rice (*Oryza sativa* L.) I. Grain characteristics and growth response to competition of weedy rice variants from five Asian countries. Weed Science 58, 374–380.
Chauhan, B.S., Gill, G., Preston, C., 2006a. Tillage systems affect trifluralin bioavailability in soil. Weed Science 54, 941–947.
Chauhan, B.S., Gill, G., Preston, C., 2006b. Influence of tillage systems on vertical distribution, seedling recruitment and persistence of rigid ryegrass (*Lolium rigidum*) seed bank. Weed Science 54, 669–676.
Chauhan, B.S., Gill, G., Preston, C., 2006c. Tillage system effects on weed ecology, herbicide activity and persistence: a review. Australian Journal of Experimental Agriculture 46, 1557–1570.
Chauhan, B.S., Gill, G., Preston, C., 2007. Effect of seeding systems and dinitroaniline herbicides on emergence and control of rigid ryegrass (*Lolium rigidum*) in wheat. Weed Technology 21, 53–58.
Chauhan, B.S., Migo, T., Westerman, P.R., Johnson, D.E., 2010. Post-dispersal predation of weed seeds in rice fields. Weed Research 50, 553–560.

Chhokar, R.S., Malik, R.K., 2002. Isoproturon-resistant littleseed canary grass (*P. minor*) and its response to alternate herbicides. Weed Technology 16, 116–123.
Clements, D.R., Benoit, D.L., Murphy, S.D., Swanton, C.J., 1996. Tillage effects on weed seed return and seedbank composition. Weed Science 44, 314–322.
Cromar, H.E., Murphy, S.D., Swanton, C.J., 1999. Influence of tillage and crop residue on postdispersal predation of weed seeds. Weed Science 47, 184–194.
Curran, W.S., Liebl, R.A., Simmons, F.W., 1992. Effects of tillage and application method on clamazone, imazaquin and imazethapyr persistence. Weed Science 40, 482–489.
Cussans, G.W., 1976. The influence of changing husbandry on weeds and weed control in arable crops. In: Proceedings of British Crop Protection Conference-Weeds, Brighton, UK. pp. 1001–1008.
Derksen, D.A., Lafond, G.P., Thomas, A.G., Loeppky, H.A., Swanton, C.J., 1993. Impact of agronomic practices on weed communities: tillage systems. Weed Science 41, 409–417.
Díaz, M., 1991. Spatial patterns of granivorous ant nest abundance and nest site selection in agricultural landscapes of Central Spain. Insectes Sociaux 38, 351–363.
Endres, G.J., Ahrens, W.H., 1995. Fall-applied trifluralin granules in conservation-till spring wheat (*Triticum aestivum*). Weed Technology 9, 703–709.
FAO (Food and Agriculture Organization), 2012. Available online at: http://www.fao.org/ag/ca/doc/FLYER_Conservation_Agriculture.pdf (verified 23 January 2012).
Franke, A.C., McRoberts, N., Marshall, G., Malik, R.K., Singh, S., Nehra, A.S., 2001. The contribution of zero tillage for the management of *Phalaris minor* in the Indian rice–wheat system. Brighton Crop Protection Conference-Weeds 2, 901–906.
Froud-Williams, R.J., 1983. The influence of straw disposal and cultivation regime on the population dynamics of *Bromus sterilis*. Annals of Applied Biology 103, 139–148.
Ghadiri, H., Shea, P.J., Wicks, G.A., 1984. Interception and retention of atrazine by wheat (*Triticum aestivum*) stubble. Weed Science 32, 24–27.
Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and small holder farming in Africa: the heretics' view. Field Crops Research 114, 23–34.
Harker, K.N., Clayton, G.W., Blackshaw, R.E., O'Donovan, J.T., Stevenson, F.C., 2003. Seeding rate, herbicide timing and competitive hybrids contribute to integrated weed management in canola (*Brassica napus*). Canadian Journal of Plant Science 83, 433–440.
Hartzler, R.G., Owen, M.D., 1997. Weed Management in Conservation Tillage System. Iowa State University, Ames. Available online: www.extension.edu/Publications/PM1176. pdf.
Heggenstaller, A.H., Menalled, F.D., Liebman, M., Westerman, P.R., 2006. Seasonal patterns in post-dispersal seed predation of *Abutilon theophrasti* and *Setaria faberi* in three cropping systems. Journal of Applied Ecology 43, 999–1010.
Hobbs, P.R., Gupta, R., 2001. Resource Conserving Technologies for Wheat in Rice–Wheat Systems. http://apps.cimmyt.org/Research/NRG/map/developing_world/res_con/res_cons.htm.
Hobbs, P.R., Gupta, R.K., 2004. Problems and challenges of no-till farming for the rice–wheat systems of the Indo-Gangetic Plains in South Asia. In: Lal, R., et al. (Eds.), Sustainable Agriculture and the Rice–Wheat System. Ohio State University and Marcel Dekker, Inc., Columbus, Ohio, and New York, USA, pp. 101–119.
Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philosophical Transactions of the Royal Society B 363, 543–555.
Hobbs, P., 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? Journal of Agricultural Science 145, 127–137.
Hulme, P.E., 1994. Post-dispersal seed predation in grassland: its magnitude and sources of variation. Journal of Ecology 81, 645–652.
Jacob Spafford, H., Minkey, D.M., Gallagher, R.S., Borger, C.P., 2006. Variation in postdispersal weed seed predation in a crop field. Weed Science 54, 148–155.
Johnson, M.D., Wyse, D.L., Lueschen, W.E., 1989. The influence of herbicide formulation on weed control in four tillage systems. Weed Science 37, 239–249.
Jung, W.S., Kim, K.H., Ahn, J.K., Hahn, S.H., Chung, I.M., 2004. Allelopathic potential of rice (*Oryza sativa* L.) residues against *Echinochloa crus-galli*. Crop Protection 23, 211–218.
Karlen, D.L., Varvel, G.E., Bullock, D.G., Cruse, R.M., 1994. Crop rotations for the 21st century. Advances in Agronomy 53, 1–45.
Kassam, A., Friedrich, T., Shaxson, F., Pretty, J., 2009. The spread of conservation agriculture: justification, sustainability and uptake. International Journal of Agriculture Sustainability 7, 292–320.
Kennedy, A.C., 1999. Soil microorganisms for weed management. Journal of Crop Production 2, 123–138.
Koskinen, W.C., McWhorter, C.G., 1986. Weed control in conservation tillage. Journal of Soil and Water Conservation 41, 365–370.
Kumar, R., Gopal, R., Jat, M.L., Gupta, R.K., 2010. Conservation Agriculture Based Strategies for Sustainable Weed Management in Maize (*Zea mays*). Training Manual, Maize for Freshers. Directorate of Maize Research, New Delhi, India.
Lahmar, R., 2010. Adoption of conservation agriculture in Europe: lessons of the KASSA project. Land Use Policy 27, 4–10.
Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627.
Liebl, R.A., Worsham, A.D., 1983. Tillage and mulch effects on morningglory (*Ipomoea* spp.) and certain other weed species. In: Proceedings of the Southern Weed Science Society, pp. 405–414.
Liebman, M., Dyck, E., 1993. Crop rotation and intercropping strategies for weed management. Ecological Applications 3, 92–122.
Liebman, M., Mohler, C.L., Staver, C.P., 2001. Ecological Management of Agricultural Weeds Cambridge University Press, Cambridge.
Locke, M.A., Bryson, C.T., 1997. Herbicide-soil interactions in reduced tillage and plant residue management systems. Weed Science 45, 307–320.
Locke, M.A., Reddy, K.N., Zablotowicz, R.M., 2002. Weed management in conservation crop production systems. Weed Biology and Management 2, 123–132.
Lodhi, M.A.K., Malik, K.A., 1987. Allelopathy in agroecosystems: wheat phytotoxicity and its possible role in crop rotation. Journal of Chemical Ecology 13, 1881–1891.
Lyon, D.J., Miller, S.D., Wicks, G.A., 1996. The future of herbicides in weed control systems of great plains. Journal of Production Agriculture 9, 209–215.
Mahajan, G., Brar, L.S., Sardana, V., 1999. Effect of tillage and time of sowing on the efficacy of herbicides against *Phalaris minor* in wheat. In: The Proceeding of 17th Asian Pacific Weed Science Society Conference, Bangkok, Thailand. pp. 193–198.
Mahajan, G., Brar, L.S., Walia, U.S., 2002. *Phalaris minor* response in wheat in relation to planting dates, tillage and herbicides. Indian Journal of Weed Science 34, 213–215.
Mahapatra, B.S., Mishra, A., Kumar, A., 2004. Green manuring: a basic concept and its role in weed control. In: Training manual: Advances in Weed Management. G.B. Pant University of Agriculture and Technology, Pantnagar, India.
Malik, R.K., Singh, S., 1995. Littleseed canarygrass (*Phalaris minor*) resistance to isoproturon in India. Weed Technology 9, 419–425.
Malik, R.K., Yadav, A., Singh, S., Malik, R.S., Balyan, R.S., Banga, R.S., Sardana, P.K., Jaipal, S., Hobbs, P.R., Gill, G., Singh, S., Gupta, R.K., Bellinder, R., 2002. Herbicide Resistance Management and Evolution of Zero Tillage-A Success Story. Chaudhary Charan Singh Haryana Agricultural University, Hisar, India.
Mohler, C.L., Calloway, M.B., 1992. Effects of tillage and mulch on the emergence and survival of weeds in sweet corn. Journal of Applied Ecology 29, 21–34.
Mohler, C.L., Teasdale, J.R., 1993. Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereale* L. residue. Weed Research 33, 487–499.
Mohler, C.L., 1991. Effects of tillage and mulch on weed biomass and sweet corn yield. Weed Technology 5, 545–552.
Moyer, J.R., Rosman, E.S., Lindwall, C.W., Blackshaw, R.E., 1994. Weed management in conservation tillage systems for wheat production in North and South America. Crop Protection 13, 243–259.
Mueller, T.C., Massey, J.H., Hayes, R.M., Main, C.L., Stewart Jr., N.C., 2003. Shikimate accumulates in both glyphosate-sensitive and glyphosate-resistant horseweed (*Conyza canadensis* L. Cronq.). Journal of Agricultural and Food Chemistry 51, 680–684.
Mulugeta, D., Stoltenberg, D., 1997. Increased weed emergence and seed bank depletion by soil disturbance in a no-till system. Weed Science 45, 234–241.
Norwood, C., 1994. Profile water distribution and grain yield as affected by cropping system and tillage. Agronomy Journal 86, 558–563.
Ofori, F., Stern, W.R., 1987. Cereal-legume intercropping systems. Advances in Agronomy 41, 41–90.
Peter, C.J., Weber, J.B., 1985. Adsorption and efficacy of trifluralin and butralin as influenced by soil properties. Weed Science 33, 861–867.
Reddy, K.N., Locke, M.A., Zablotowics, R.M., 2002. Yield and weed control in conventional and roundup ready cotton–corn rotated under conservation tillage in the Mississippi Delta. In: Proceedings of the Beltwide Cotton Conference, Atlanta. pp.
Risch, S.J., Carroll, C.R., 1986. Effects of seed predation by a tropical ant on competition among weeds. Ecology 67, 1319–1327.
Sadeghi, A.M., Isensee, A.R., Shelton, D.R., 1998. Effect of tillage age on herbicide dissipation: a side-by-side comparison using microplots. Soil Science 163, 883–890.
Savage, K., Barrentine, W., 1969. Trifluralin persistence as affected by depth of soil incorporation. Weed Science 17, 349–352.
Sheley, R., Manoukian, M., Marks, G., 2002. Preventing Noxious Weed Invasion Extension Bulletin. Montana State University.
Shrestha, A., Knezevic, S.Z., Roy, R.C., Ball-Coelho, B.R., Swanton, C.J., 2002. Effect of tillage, cover crop and crop rotation on the composition of weed flora in a sandy soil. Weed Research 42, 76–87.
Shrestha, A., Vargas, R., Mitchell, J.,J.,L., 2003. Initial experience in transition from conventional to conservation tillages. A farming system perspective. In: Proceedings of Conservation Tillage. The Californa Experience. Oct. 7–9, Tulare, Five points, Davis, California.
Singh, S., Kirkwood, R.C., Marshall, G., 1999. A review of the biology and control of *Phalaris minor* Retz. (littleseed canarygrass) in cereals. Crop Protection 18, 1–16.
Singh, R.G., Singh, V.P., Singh, G., Yadav, S.K., 2001. Weed management studies in zero till wheat in rice-wheat cropping system. Indian Journal of Weed Science 33, 95–99.
Singh, S., 1996. Effect of rice straw burning, nitrogen and herbicides on wheat and *Phalaris minor*. PhD Thesis, CCS Haryana Agricultural University, Hisar, India.
Singh, S., 2007. Role of management practices on control of isoproturon-resistant littleseed canarygrass (*Phalaris minor*) in India. Weed Technology 21, 339–346.
Sorenson, B.A., Shea, P.J., Roeth, F.W., 1991. Effects of tillage application time and rate on metribuzin dissipation. Weed Research 31, 335–345.
Steinsiek, J.W., Oliver, L.R., Collins, F.C., 1982. Allelopathic potential of wheat (*Triticum aestivum*) straw on selected weed species. Weed Science 30, 495–497.

Streit, B., Rieger, S.B., Stamp, P., Richner, W., 2003. Weed populations in winter wheat as affected by crop sequence, intensity of tillage and time of herbicide application in a cool and humid climate. Weed Research 43, 20–32.

Swanton, C.J., Shrestha, A., Roy, R.C., Ball-Coelho, B.R., Knezevic, S.Z., 1999. Effect of tillage systems, N, and cover crop on the composition of weed flora. Weed Science 47, 454–461.

Swanton, C.J., Shrestha, A., Knezevic, S.Z., Roy, R.C., Ball-Coelho, B.R., 2000. Influence of tillage type on vertical seed bank distribution in a sandy soil. Canadian Journal of Plant Science 80, 455–457.

Teasdale, J.R., 1993. Interaction of light, soil moisture, and temperature with weed suppression by hairy vetch residue. Weed Science 41, 46–51.

Vargas, R.N., Wright, S.D., 1994. Staple, Plant Back Studies. Cotton Weed Management Research Progress Report. University of California, Cooperative Extension, Madera and Tulare Counties.

Walker, A., Bond, W., 1977. Persistence of the herbicide AC 92,553 [N-(1-ethylpropyl)-2,6-dinitro-3,4-xylidine] in soils. Pesticide Science 8, 359–365.

Walsh, M., Newman, P., 2007. Burning narrow wind rows for weed seed destruction. Field Crops Research 104, 24–30.

Walsh, M., Parker, W., 2002. Wild Radish and Ryegrass Seed Collection at Harvest: Chaff Carts and Other Devices. Agribusiness Crop Updates, Department of Agriculture, Western Australia, Perth, Australia, 37–38 pp.

Westerman, P.R., Hofman, A., Vet, L.E.M., Van Der Werf, W., 2003. Relative importance of vertebrates and invertebrates in epigaeic weed seed predation in organic cereal fields. Agriculture, Ecosystem and Environment 95, 417–425.

Wicks, G.A., 1983. Integrated systems for control or management of downy brome (*Bromus tectorum* L.). In: Meeting of the Weed Science Society of America. Abstracts, pp. 22–23.

Wolf, T.M., Harrison, S.K., Hall, F.R., Cooper, J., 2000. Optimizing postemergence herbicide deposition and efficacy through application variables in no-till systems. Weed Science 48, 761–768.

Wrucke, M.A., Arnold, W.E., 1985. Weed species distribution as influenced by tillage and herbicides. Weed Science 33, 853–856.

Young, K.R., Cousens, R.D., 1999. Factors affecting the germination and emergence of wild radish (*Raphanus raphanistrum*) and their effect on management options. In: Bishop, A.C., et al. (Eds.), Proceedings of 12th Australian Weeds Conference. Tasmanian Weed Society, Tasmania, Hobart, pp. 179–182.