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Research needs for improving weed management in rice

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ABSTRACT

Weeds are the most important biological constraints to increasing rice productivity in Asia. They are managed by using herbicides; however, reliance on herbicides alone is not sustainable in the long run. There is thus, a need to develop sustainable weed management strategies in different rice-based cropping systems. The development and adoption of improved weed management strategies must form an integral part of sustainable rice production. Improved weed management techniques in rice should focus on shifting the crop-weed balance in favour of rice by integrating possible cultural, physical, and biological weed management tools with judicious use of herbicides. Together, these approaches may be used as components of an integrated package in the future to slow down the evolution of new weed problems in rice production. The improved weed management approaches should aim to reduce the weed seed bank before crop sowing and reduce weed emergence and weed growth in rice.

Key words: Improved management, Research need, Rice, Weed management

Rice (*Oryza sativa* L.), the staple food of more than 60% population of the world, plays a crucial role in the economic and social stability of the world. The resources for rice production-land, water, nutrients, and labour-are becoming scarce. Therefore, meeting the rice demand of the burgeoning population is a great challenge in the future. In rice production, weeds are one of the major yield-limiting biological constraints worldwide. Losses caused by weeds in rice vary in different countries because the nature, extent, and intensity of weed problems depend on the ecology in which the crop is grown and situations such as hydrology, land topography, establishment methods, *etc.* Management practices of farmers to control weed also differ in different countries, and this explains the variation in losses caused by weeds in different countries. The dimension of the problem can be ascertained with the following examples. In India, about 33% of rice yield losses are caused by weeds (Mukherjee 2004), while in Sri Lanka, weeds accounted for 30-40% of yield losses (Abeysekera 2001). In world rice production, about 10% of the total yield is reduced by weeds (Oerke and Dehne 2004). Globally, pests have a potential to reduce rice yield by 40%, of which weeds account for 32%. Annually, 10 million tonnes of rice produce are lost in China due to weed competition. This quantity of rice is sufficient to feed at least 56 million people for a year. Weeds are the universal pests in rice, causing losses that exceed tolerable levels in all seasons (Moody and Cordova 1985). Therefore, it is imperative that investment in weed management practices be made to reduce yield losses caused by weed competition. Total loss caused by weeds are tied up with cultural practices pertaining to weed control, land preparation, weed control expenses, and reduction in yield quantity and quality. Rice is cultivated in various ecosystems from irrigated to shallow lowland, mid-deep lands, deep water to uplands. In most of the Asian countries, including India, rice is cultivated mainly by manual transplanting of seedlings in puddled conditions. Weed control in puddled transplanted rice is done by a combination of pre-emergence herbicides, hand weeding, and water management.

The increase in production cost, shortage of labour, increased wages, and decreased water availability resulted in a shift from transplanting to direct seeding in many Asian countries. In India, dry-seeded rice is extensively practiced in the northwest Indo-Gangetic Plains because dry-seeded rice in this region provides the highest opportunity to attain optimal plant density and high water and labour productivity (Chauhan *et al.* 2012b). However, weeds are a serious problem in dry-seeded rice because dry tillage practices and aerobic soil conditions are favourable for germination and growth of weeds, which can cause grain yield losses from 50 to 90% (Chauhan and Johnson 2011, Chauhan *et al.* 2011, Prasad 2011). With the adoption and development of dry-seeded rice, good crop growth can be obtained, but the lack of sustained flooding can cause great losses from weeds. Since weeds are a major constraint to dry-seeded rice cultivation, the success of dry-seeded rice warrants the

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intensive use of herbicides. Herbicides have been proven effective in many cases, but intensive herbicide use can cause environmental contamination and induce herbicide resistance in weeds (Heap 2012). Therefore, to sustain rice production, effective weed management strategies are required. Researchers are now taking an interest in exploring non-chemical (cultural) methods of weed control because of increased use of herbicides, risk of herbicide resistance, rising costs of production, and concerns about environmental pollution (Chauhan 2012a, b).

Rice and rice weeds have similar requirements for growth and development. They compete for limited resources such as nutrient, moisture, light, space, *etc*. Most of the weeds, being C_4 plants, have higher adaptability and faster growth than rice, a C_3 crop. Weeds dominate the crop habitat and rice yield potential is reduced. Proper weed control in rice, especially dry-seeded rice, is achieved by using both pre- and post-emergence herbicides. But the use of herbicides brings about environmental problems because farmers lack knowledge about the proper use of herbicides. Currently, herbicides with ALS inhibitors are used in dry-seeded rice, which have high selection pressure and may exacerbate the problem of herbicide-resistant species. The constant shift in weed population dynamics that goes with the introduction of new herbicides has always been a prelude to the development of new and more potent herbicides. When a particular herbicide is applied, susceptible weeds are controlled and their population decreases, but the number of tolerant weeds increases. Also, even in single weed species, intra-specific variation in ecological characteristics or herbicide susceptibility is often observed in rice fields, leading to a decrease in herbicide efficacy. This problem can be solved only by implementing integrated weed management (IWM) in rice, which can go a long way to sustain rice production.

In this review, we describe some of the present approaches and possible future strategies to manage weeds in rice. However, the main focus is on direct-seeded rice systems.

Knowledge of weed ecology and biology

Knowledge of the behaviour of weed species in a region, such as time of germination of weeds, period of fruit setting, emission of first vegetative organ, *etc.* is critical in weed management. In the present scenario, weed management strategies should focus on preventing the build-up of a weed seed bank. Because of the complexity of weed flora, this is not easy; however, knowing under what conditions weed seeds germinate and grow may help farmers improve their weed management practices. With adequate knowledge of the germination requirements of weed seeds, weeds can be controlled by stimulating germination at a time when seedlings can be easily killed or by providing an environment that induces very low germination (Chauhan and Johnson 2010b). The most important survival mechanisms of weeds are seed dormancy and germination. The seed bank in the soil builds up through seed production and dispersal; it is depleted through germination, predation, and decay. Seedling emergence and weed population dynamics are influenced by the differential vertical distribution of weed seed bank in the soil, the consequences of differences in availability of moisture, diurnal temperature, light exposure, and predator activities at different soil depths (Chauhan *et al.* 2006, 2007).

Cultural control

Flooding is commonly used as the primary cultural weed control method to suppress weeds in puddled transplanted rice; however, flooding effect on weeds is species-specific (Chauhan and Johnson 2010b, Singh 2010). Some weed species, such as *Leptochloa chinensis* (L.) Nees, *Eleusine indica* (L.) Gaertn., and *Eclipta prostrata* (L.) may be encouraged by alternate wetting and drying in puddled as well as dry-seeded rice. Sedges primarily compete for nutrients as their root systems are fibrous. Similarly, grass weeds also pose serious competition for soil water and nutrients, apart from that for CO_2 and light. Broad-leaved weeds have less competition for nutrients with rice because their deep root systems explore the deeper layer for minerals. *Echinochloa* species poses serious competition for light because of its height, whereas weeds with short stature [*e.g. Monochoria vaginalis* (Burm. f.) Kunth] offer little competition for light. Management and environmental factors greatly influence weed distribution in upland rice. Soil moisture content in the upper 0-15 cm soil layer affects the emergence patterns of weeds. All the weeds do not emerge at one time but rather in several flushes.

Weed seed bank in rice

Very limited information is available on the persistence of weed seed banks. For example, the long-term fate of the seeds that remain in the seed bank and the management practices that deplete the seed bank are not well understood. There is a need for research to address this key knowledge gap in our understanding of the ecology of important rice weeds, including weedy rice. To develop a viable weed management technology, a better understanding of weed ecology, the basis for competitiveness, phenology, physiology, and biochemistry, and threshold population is required, and it is toward this goal that the research programme needs to be reoriented.

Tillage reforms: Tillage influences weed growth by altering the soil conditions for germination and emergence through several ways: uprooting, dismembering, burying them deep enough to prevent emergence, and moving seeds both vertically and horizontally in the soil (Clements *et al.* 1996, Hartzler and Owen 1997, Swanton *et al.* 2000). Weed management is thus greatly influenced by any change in intensity or frequency of tillage. As tillage is reduced, the density of certain annual and perennial weeds can increase, so effective weed control techniques are required to manage weeds successfully (Moyer *et al.* 1994). Harrowing and puddling are done for a range of reasons, including weed control. Precision land levelling, obtained with laser-directed equipment, has made an important contribution to weedy rice management in European rice production (Ferrero and Videtto 2007). Level or regulatory sloping fields enable appropriate water management, which limits weed growth and guarantees uniform emergence of weeds. This in turn makes herbicide application more effective.

A large proportion of the weed seed bank remains on or close to the soil surface after crop planting in zero-till systems, which may promote greater emergence of weed species that require light to germinate (Chauhan *et al.* 2009). Weed seeds present on the soil surface after crop sowing may be more favourable for granivore fauna, such as ants and other insects. Hulme (1994) suggested that weed seeds remaining on the soil surface are most vulnerable to surface-dwelling seed predators, while burial makes seeds largely unavailable. Therefore, seed predation could be used as an important tool in weed management systems where newly produced weed seeds remain on the soil surface as in, for example, zero-till systems (Baraibar *et al.* 2009, Chauhan *et al.* 2010). In contrast, tillage redistributes the weed seeds stored in superficial chambers by destroying the nests of weed seed predators (Baraibar *et al.* 2009). Westerman *et al.* (2003) reported that germination and emergence of weed seeds are reduced and seed predation may be responsible for the larger part of these losses. Thus, herbicide use, risk, and cost and demand for labour can be reduced by integrating seed predation with other weed control methods. These results suggest that the size of the weed seed bank can be reduced significantly by seed predation. Weed seed predators can be encouraged by retaining crop residues in the field as they serve as forage to them (Chauhan *et al.* 2010). Since no additional cost is required to apply such approaches, these can be combined with existing practices as a component of an IWM package (Chauhan *et al.* 2010). Future research may look into ways of integrating weed seed predation in existing weed management systems where chemical herbicides are used widely.

Climate change and weeds in rice

In the wake of climate change, weed communities in rice may also be affected. Weed species distribution and prevalence within weed and crop communities will be influenced by changes in atmospheric CO_2, rainfall, and temperature. Competitiveness in rice over C_4 weeds (*e.g., Echinochloa glabrescens* Munro ex Hook. F.) could be increased with elevated CO_2 alone (Alberto *et al.* 1996). However, the simultaneous increase in CO_2 and temperature favours the C_4 species. Climate change can also influence the chemical and mechanical weed management operations in rice. Under high-temperature conditions, C_4 plants (mostly weeds) have a competitive advantage over C_3 plants (rice) (Yin and Struik 2008). The increased concentration of CO_2 may have positive effects on rice competitiveness over C_4 weeds (Fuhrer 2003, Patterson 1995). But this is not always true. Potvin and Strain (1985) reported that, in several weed species, elevated CO_2 has been found to increase tolerance for low temperature. At the Directorate of Weed Science in Jabalpur, India, studies on the effect of CO_2 enrichment on weed species revealed that some weeds, such as *Echinochloa colona* (L.) Link, responded to elevated CO_2, but others, such as *Cyperus rotundus* L. and *Eleusine indica*, did not.

Ziska *et al.* (2010) reported that weedy rice responds more strongly to increasing levels of CO_2 than does cultivated rice. The authors suggest that weedy rice may become a more problematic weed in the future. In field conditions, the rate of emergence of weed seedlings increased with increases in CO_2 concentrations (Ziska and Bunce 1993). Under erratic rainfall conditions also, a similar change in weed flora can be expected because of climate change. Any type of environmental stress on a crop due to a sudden change in climate may increase its susceptibility to attacks by insects and pathogens; it thus becomes less competitive with weeds. These aberrant weather conditions not only increase weed competitiveness but also enhance weed seed germination in several flushes, making weed management more difficult. An increase in CO_2 level in the atmosphere may increase the tolerance of weeds for glyphosate (Ziska *et al.* 1999), a pre-plant herbicide used to kill weeds before crop sowing. Such information suggests that glyphosate efficiency in the future may decrease with increase in CO_2, thereby posing a threat in areas where weeds are controlled with the stale seedbed technique.

Rotation of establishment methods, crops and herbicides

There are three different kinds of direct-seeded rice systems: dry-seeded, wet-seeded, and water-seeded. Dry-seeded rice can be sown after tillage or under zero-till conditions. Because of the availability of rice cultivars tolerant of anaerobic conditions, it is possible to increase the area under water seeding also, as in eastern India. In water-seeded rice systems, however, aquatic weeds are likely to be problematic. Because of the availability of transplanters, mechanical rice transplanting is being practiced in zero-till and non-puddled (tillage in dry soil conditions) conditions in India (Kamboj *et al.* 2013). In such conditions, however, weed infestation may increase faster than in puddled conditions. Rice establishment methods affect the level of weed infestation and the species composition in the crop. However, such information on weed shifts, as a result of the adoption of a particular establishment method, is limited in different cropping systems. Knowledge on the shifts in principal weeds under a particular establishment method could help reduce the buildup of seed banks by using other establishment methods.

Crop rotation is an important tool of IWM. The long-term weed population dynamics is affected by the choice and sequencing of crops. Consequently, weed management is affected. The key component of weed management in traditional farming was the rotation of different crops with different life cycles. Plant establishment or seed production by weeds can be prevented by different planting and harvest dates of these crops, which provide more opportunities for farmers to control weeds (Rao 2011). Grasses and sedges in the rice-wheat cropping system can be controlled to a great extent by sequences involving summer cowpea for fodder or *Sesbania* for green manure, resulting in significantly lowest weed populations (Singh *et al.* 2008).

Continuous growing of a single crop or different crops having similar management practices give certain weed species the chance to become dominant in the cropping system. With passage of time, these weed species become hard to control (Chauhan *et al.* 2012b). For instance, grass weed species, such as *Alopecurus myosuroides* Huds and *Bromus* species, dominate in continuous cereal cropping with reduced tillage in temperate regions (Froud-Williams 1983). Crops with different management practices may help in disrupting the growth cycle of weeds (Chauhan 2013). When there is a fallow period in any crop rotation, it can be exploited to stimulate the emergence of problem weeds. These weeds are then controlled by non-selective herbicides. Different crops have different management practices, which is a key weed management tool: disturbing the growth cycle of weeds and thus preventing selection of weed flora toward increased abundance of problem species (Karlen *et al.* 1994). One particular weed species cannot become unmanageable when different crops with different management practices are grown in crop rotation (Locke *et al.* 2002).

With crop rotation, growers can use new herbicides and this practice helps to control problematic weeds in rice. In Southeast and South Asia, weedy rice is becoming a serious weed problem in rice monoculture systems (Chauhan and Johnson 2010c, Chauhan 2013). This may even become a more problematic weed species when rice is grown with conservation agricultural techniques. In rice-rice-rice or rice-rice cropping systems, rotating one rice crop with an upland crop, such as maize, soybean, sesame, mungbean *etc.* in the dry season may significantly help in reducing the seed bank of weedy rice in the soil. In these upland crops, the emerged seedlings of weedy rice can be killed by using a combination of different herbicides, which otherwise would not be used in a rice crop because of the non availability of selective herbicides to control weedy rice in the conventional rice system (Chauhan 2013). Greater herbicide effectiveness may be achieved when crops as well as herbicides are rotated. Combining herbicides and sequential treatment and herbicide mixture with cultural, mechanical, and bio-control methods will reduce the chance of undesirable ecological shifts to tolerant weed species, minimize the chance of an accumulation of herbicide residue in the soil, and reduce the weed seed population in the soil. To make the approach most effective, preventive weed control must precede and accompany standard weed control practices. Information on the role of crop rotation in suppressing the build-up of weed populations in rice monoculture systems is very limited in India.

Agronomic approaches

Plant geometry: Weed flora can be smothered by making changes in plant arrangement with bidirectional sowing. In a thin crop stand, weeds get a favourable environment and so they flourish well. This results in grain yield reduction and also an increase in the soil weed seed bank, paving the way to weed infestation during the following season. In most parts of India, broadcasting is still commonly used to sow dry-seeded rice or wet-direct-seeded rice (Chauhan 2013). However, with this seeding method, it is difficult to recognize weedy rice seedlings from cultivated rice seedlings until the plants reach flowering stage. In such a situation, use of row-seeded rice will be a better option than use of broadcast rice as weedy rice seedlings emerging between the rows can be easily distinguished. Manual and mechanical weeding is much easier to perform in row-seeded rice than in broadcast rice.

In a crop-weed ecosystem, by maintaining narrow row spacing, the crop provides a more smothering effect on weeds as less space is available for weeds to flourish. The light regime created at the ground level by the thick crop canopy is also low. With the help of high crop density per unit area, weeds can be suppressed by maintaining the dominant position of crop plants over weeds through a modification in canopy structure. Sunyob *et al.* (2012) reported that weed dry matter production was significantly affected by plant spacing of rice at different stages. Narrow plant spacing decreased weed biomass, increased weed suppression, and ultimately, increased the rice yield. Phuong *et al.* (2005) reported that favourable conditions for the crop are produced with higher plant density and narrow row spacing in rice, enabling it to compete with weeds and to give higher yield. Twin planting in rice reduced the weed biomass in dry-seeded rice and resulted in an increase in yield (Mahajan and Chauhan 2011). More weed biomass was produced using a row spacing of 30 cm as compared with that produced in 15 cm or 10-20-10-cm paired rows (Chauhan and Johnson 2011). Grain yield remained similar at different row spacing (20 cm or 30 cm) in weed-free environments (Chauhan 2012a). However, in weedy or partially weedy conditions, narrow row spacing provided a significantly higher grain yield than did wider row spacing. Besides, in crops planted in narrow rows, the critical period for weed control was usually less than that for crops planted in wider rows. The rice crop's ability to compete against weeds for light can be increased with cultural management practices, such as reduced crop row spacing (Chauhan and Johnson 2010c).

In India, the agronomic aspects (crop geometry, row, *etc*.) of crop competitiveness are yet to be exploited as a component of IWM in direct-seeded rice systems. Narrower row spacing, for example, improves the competitiveness of crops with weeds by developing faster canopy cover and allowing less light penetration through their leaves. In transplanted rice, seedlings are usually transplanted in a random manner or in squares. Changes in plant geometry (*e.g.*, transplanting in a triangular manner or in paired rows) may help cultivars suppress weeds more effectively. Different rice genotypes (including hybrids), depending on their architectural traits, may perform differently at different plant geometry. However, such information is not available and there is a need to evaluate the performance of rice cultivars planted using different geometric schemes in different environments. Results from such research may guide the design of better transplanters and sowing drills.

Seeding rate: The impact of weeds on crops can be reduced by increasing crop density. Increasing crop competitiveness through the use of high crop density is a possible technique for weed management, especially in low-input and organic production systems or when herbicide resistance develops in weeds. At low crop density, crop cover early in the growing season is usually low and a large amount of resources is available for the weeds. These conditions enable weeds to establish and grow quickly. In a previous study in India and the Philippines, increases in seeding rate of rice from 15 to 125 kg/ha decreased weed biomass significantly (Chauhan *et al.* 2011). It was due to rapid canopy closure and reduced weed competition. Thus, high seeding rate could partly control weeds. However, the effectiveness of high seed rates in controlling the weed problem is dependent on the biology of weeds and rice cultivars present in the field. Moody (1977) reported that biomass of broadleaved weeds, grasses, and sedges significantly decreased as seeding rate increased from 50 to 250 kg/ha. Grain yield may not be influenced with increasing or decreasing seed rate in a weed-free environment (Chauhan 2012a, b).

In many Asian countries (e.g., Vietnam and Sri Lanka), high seeding rates (up to 150 kg seeds/ha) are used mainly in a broadcast rice crop but, in other parts of the world (e.g., South America), growers use high seeding rates in a mechanized row-seeded rice crop also. In weedy rice-infested areas (e.g., in Malaysia), the use of high seeding rates helped to reduce the problem of weedy rice (Chauhan 2013). Weed growth is encouraged with low plant density and high gaps and, in many cultivars, it also results in less uniform ripening and poor grain quality. Therefore, it can be concluded that high seeding rates may help control weeds and reduce yield losses caused by weeds if no or partial weed control is expected (Mahajan *et al.* 2010). However, such information on the use of high seeding rate in managing weeds is very limited in Indian conditions. In some situations, the very high plant density tends to reduce productive tillers, increase lodging, minimize full benefits from nitrogen (N) application, and increase the chances of rat damage. Therefore, there is a need to evaluate the effect of high seeding rates on weed management and rice productivity, especially where herbicide use is limited or less effective.

Fertilisation: Crop fertilization can be used as an important component of IWM. It is observed that N fertilisation plays a vital role in establishing the competitive balance between weeds and rice (Raun and Johnson 1999, Camara *et al.* 2003). Weed growth in rice fields is affected by fertilisation. Some sedges, such as *Eleocharis kuroguwai* Ohwi dominated on low-fertility soils (Guh 1974). A lower population of *Cyperus iria* L. in transplanted rice was obtained at higher N rates (80-120 kg/ha) than at lower (40 kg/ha) (Mishra *et al.* 2001). N application has a negative effect on the germination and growth of *Striga* seeds in the soil. On the other hand, the susceptible host is favourably affected by N application as N enables the host plant to tolerate or avoid the effect of *Striga*. Kayeke *et al.* (2007) reported that the number of *Striga* seedlings was reduced by 100% in the 6^{th} and 12^{th} weeks with application of N at the rates of 25 or 50 kg/ha. Under good N fertilisation, the rice plant grew vigorously and thus an unfavourable environment was created for *Striga* germination and development. It enabled the host plant to avoid the effect of *Striga* probably by delayed haustorium attachment and by poor production of germination stimulants.

Nitrogen application without proper weed management, however, provides a favourable environment to enhance the vigour and competitive ability of weeds. Although improved nutrient status may improve crop competitiveness, some weeds become more successful than crops in utilizing the available excess nutrients (Raun and Johnson 1999). Other authors also report that nutrient absorption is faster and higher in weeds than in crop plants (Iqwal and Wright 1997, Ali *et al.* 2003, Blackshaw *et al.* 2005), suggesting that, in the presence of high weed density, crop growth may be suppressed by increased weed growth due to fertilisation. Therefore, manipulation of crop fertilisation is an important agronomic practice that can be used in weed management (Cathcart *et al.* 2004, Blackshaw *et al.* 2005, Mahajan and Timsina 2010). However, the effect of fertilisation, especially N, on weed interference with crop growth is not fully understood (Zoschke and Quadranti 2002), especially in the newly emerged direct-seeded rice systems.

Rice cultivars

Weed-competitive cultivars: The selection of cultivars plays a vital role in crop-weed competition because of the differential morphological characters of cultivars. The competitive ability of rice cultivars is associated with light interception-related traits (Chauhan 2012a, b). Variation in many crops, including rice, in terms of ability to compete with weeds, has been documented (Gibson and Fischer 2004, Zhao 2006). Therefore, the use of competitive cultivars may be an important IWM strategy (Mahajan *et al.* 2013). The rice plant characteristics associated with weed competitiveness are plant height, together with high canopy cover at the early stage of growth, high tiller density, droopy leaves, high biomass accumulation at the early crop stage, high leaf area index and high specific leaf area during vegetative growth, rapid canopy ground cover, and early vigour.

Generally, weed competitiveness in tall plants is higher but they tend to lodge and often have low yield potential. Semi-dwarf cultivars also have the same ability to compete with weeds. These cultivars have higher yield potential than tall cultivars. Therefore, intermediate height may be a more desirable trait for direct seeding in suppressing weeds (Fischer *et al.* 2001, Fukai 2002). Fischer and Gibson (2001) examined the competitive ability of rice cultivars with *Echinochloa colona*, *E. phyllopogon* (Stapf) Koss, *E. oryzoides* (Ard.) Fritsch, and *Brachiaria decumbens* Stapf. It was observed that, to achieve a high level of competitiveness, it is not necessary to develop highly erect cultivars (normally susceptible to lodging); modern high-yielding, semi-dwarf cultivars are also able to compete with weeds efficiently. Gibson *et al.* (2001) reported that *E. oryzoides* and *E. phyllopogon* infestation was effectively suppressed by competitive rice cultivars in California and such cultivars may thus help reduce herbicide dependency and decrease selective pressure for resistance. Early-maturing rice cultivars and rice hybrids also have a smothering effect on weeds due to their improved vigour and early canopy cover (Chauhan and Johnson 2010a). The effectiveness of competitive cultivars in weed suppression can be increased with agronomic manipulations. Changing the plant spacing pattern and the time of sowing, for example, might be helpful in providing supplemental weed control when herbicide inputs are reduced (Mahajan and Chauhan 2011).

There are two components of weed competitiveness: weed tolerance and weed-suppressive ability (Jannink *et al.* 2000, Zhao 2006). Weed tolerance is the crop's ability to maintain high yield despite weed competition, whereas weed-suppressive ability is the ability of the crop to suppress weed growth through competition. Since yield stability and the prevention of weed seed production and subsequent seed bank build up are desirable in crops growing in association with weeds, both components are important (Jordan 1993). Because the use of weed-competitive cultivars is a cost-effective method with minimum environmental pollution, more attention has been given by researchers to the use of competitive cultivars for weed management in direct-seeded rice systems (Chauhan 2012a, Mahajan and Chauhan 2011). However, in transplanted rice, there was less emphasis on weed-competitive traits in as much as seedling size advantage and puddling, followed by stagnation of water, provide effective weed control (Mahajan and Chauhan 2013). In dry-seeded rice crops, this type of environment is not available; therefore these crops face crop-weed competition at the early stages and suffer from heavy yield losses, if weeds were not controlled. In summary, the development of weed-competitive cultivars is a useful tool in managing weeds in rice. This could prove to be a cost-effective component of an overall IWM program in rice, especially in newly emerging direct-seeded systems. There is a strong need to evaluate rice traits responsible for weed-competitiveness in favourable as well as unfavourable environments in India.

Allelopathic cultivars: Crop allelopathy refers to the process of releasing chemical compounds, called allelochemicals, by living and intact roots of crop plants, which adversely affect the growth of other plant species (Belz 2007, Farooq *et al.* 2011). Allelopathy holds promise as a possible component in IWM. Some crops such as sorghum, pearl millet, and maize have the ability to reduce the weed population by allelopathy, thereby reducing weed biomass. For example, pearl millet shows residual weed suppression in the following crop. Therefore, these fodder crops can be grown before the rice crop in some cropping systems (Narwal 2000).

Rice plants release toxic allelochemicals (either as root exudates or sourced from decaying plant materials) that can suppress and kill weeds. *Heteranthera limosa* (Sw.) Willd. and other aquatic weeds are controlled by these allelochemicals. Dilday *et al.* (1991) reported that, out of 10,000 rice accessions tested in the United States, approximately 4% exhibited some allelopathic activities. Weed suppressiveness and allelopathy, however, may be confounded and they may coexist in the same cultivar. Progress has been significant in isolating rice allelochemicals (Rimando *et al.* 2001) and locating genes controlling allelopathic effects of rice (Jensen *et al.* 2001). Olofsdotter (2001) reported that both monocot and dicot weed species can be suppressed by allelopathic rice. The potential of some allelopathic rice cultivars to inhibit weed growth is up to 40% and this has been shown by planting *Echinochloa crusgalli* (L.) Beauv. together with various allelopathic rice varieties in the greenhouse (Mattice *et al.* 1999). Quantitative trait loci, which are associated with rice allelochemicals against *E. crus-galli,* have been identified (Jensen *et al.* 2001). This is an important step toward breeding allelopathic rice cultivars. Many studies suggest that farmers in rice-cultivating countries would be benefited by the success in breeding new rice cultivars with high weed-suppressing ability and this will play a vital role in sustaining agricultural production (Khanh *et al.* 2007, Jamil *et al.* 2011). However, more research is needed along this area.

Herbicides

Herbicides, being one of the most important tools for weed management, are a must in rice cultivation. Azmi *et al.* (2005) reported that unavailability and increasing cost of labour and the pressing need to raise yield and maintain profits on a progressively limited land base have forced farmers to seek substitutes for manual weed control. Herbicides proved to be one such alternative, as they provide superior weed control and are more energy- and labour-efficient than manual or mechanical methods of weed management. Farmers consider several factors, such as weed control spectrum, lack of crop injury (selectivity), cost, environmental impacts, *etc.* before selecting a weed management system using herbicides. Because cultural and mechanical weed control methods are time-consuming, cumbersome, and laborious, farmers rely more on herbicides. In addition, weeds tend to regenerate from roots or rhizomes that are left behind during manual or mechanical weeding, and these can be controlled only by the use of herbicides.

Direct seeding provides a favourable environment for the growth of sedges, such as *Cyperus difformis* L., *C. iria, C. rotundus,* and *Fimbristylis miliacea* (L.) Vahl (Azmi and Mashor 1995, Mortimer and Hill 1999, Gressel 2002). Some weed species, such as *E. colona* and *E. crus-galli*, escape from hand weeding as they are difficult to distinguish from rice at the early stage, thus reducing rice yield in the current season and producing weed seeds that can infest crops in subsequent seasons (Chauhan 2012a,b). Singh (2008) reported that these weeds severely affected rice growth, sometimes resulting in complete crop failure of the crop. It is important to include systematic herbicide in weed management options with this changing scenario of weed composition in dry-seeded rice systems.

Available are several pre-emergence herbicides that reportedly provide a fair degree of weed control when applied alone or supplemented with hand weeding (Chauhan 2012a, Mahajan and Chauhan 2011, Chauhan and Opeña 2013). These herbicides include butachlor, thiobencarb, pendimethalin, oxadiazon, oxyfluorfen, and nitrofen. However, with pre-emergence herbicides, some difficulties are encountered: application duration is limited and at the time of application, adequate soil moisture is required. The use of post-emergence herbicides was better option in these situations. Singh *et al.* (2006) suggested that both pre- and post-emergence herbicides can effectively suppress weeds in dry-seeded rice, if these are properly used.

In dry-seeded rice systems, the sequential spray of pre-emergence application of pendimethalin (1 kg/ha), followed by bispyribac-sodium (30 g/ha) at 15 days after sowing was found effective for weed management (Mahajan *et al.* 2009). In direct-seeded systems, especially in aerobic rice systems where a broad range of weeds is present, there is a need to use mixtures of different compatible herbicides (Chauhan 2012b). However, some weed species are not controlled effectively even after using herbicide mixtures. Moreover, some weed species [e.g., *Rottboellia cochinchinensis* (Lour.) W.D. Clayton] keep emerging throughout the crop season because of their high degree of seed dormancy. In such situations, other weed management strategies, such as high seeding rates or hand weeding should be integrated with herbicide use to control them.

In spite of the aforementioned advantages of herbicide use, 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 the environment (Chauhan *et al.* 2012a). Several issues, such as food safety, groundwater and atmospheric contamination, increased weed resistance to herbicides, destruction of beneficial organisms, and concerns about endangered species, have also been related with the indiscriminate use of herbicides. In India, due to the continuous use of butachlor and anilofos in rice, particularly in northwest India, the weed flora is shifting to sedges, such as *Cyperus* sp., *Scirpus* sp., *Fimbristylis* sp., and *Eleocaris* sp., and broadleaved weeds, such as *Caesulia auxillaris* Roxb. Such information suggests the need to rotate herbicides and integrate herbicide use with other weed management strategies.

Herbicide-resistant rice

The evolution of herbicide resistance is now a common and undesirable feature of most cropping systems; around 310 herbicide-resistant (HR) biotypes across 183 weed species have been reported (www.weedscience.org). Herbicide-resistant weed species have been reported in countries with high herbicide adoption rates, including the Philippines, Malaysia, Japan, Sri Lanka, Thailand, Korea, Colombia, Costa Rica, Italy, Portugal, Spain, France, Greece, North and Central America, and Australia (Rao 2011).

Biotechnology plays a vital role in the genetic engineering of plants for herbicide tolerance. In direct-seeded rice systems, the development of HR rice cultivars is essential as herbicides are continuously used in these systems. The development of a non-transgenic HR cultivar would be a classical, safe, and yet novel and effective means of weed management through the application of new-generation herbicides that are highly effective, non-toxic, and rapidly biodegradable (Mahajan and Chauhan 2013). In direct-seeded rice systems, HR rice can solve the problem of weeds, especially weedy and wild rice. The main benefits from introducing HR rice are as follows: (1) it solves the problem of managing weeds, specifically those associated with rice(weedy rice); (2) it provides an alternative to currently used herbicides, with new ones having better environmental profiles and greater efficiency; (3) it provides the solution to the problem of controlling weeds that have already developed resistance to current herbicides; and (4) it enables the adoption of resource conservation technologies by improving weed management options.

In direct-seeded systems, weed problems can be controlled dramatically with the use of HR rice and it will reduce the need to puddle soils and keep them continuously submerged (Malik *et al.* 2003). Three HR rice systems have been developed: imidazolinone-, glufosinate-, and glyphosate-resistant cultivars (Gealy *et al.* 2003). Glufosinate- and glyphosate-resistant rice cultivars were developed through transgenic technologies. Imidazolinone-resistant rice was developed through chemically induced seed mutagenesis and conventional breeding. Growing rice containing transgenes that impart resistance to post-emergence, nonselective herbicides such as glyphosate and glufosinate allows farmers use of no-till cultural practices, which may potentially reduce the total amount of herbicide released in the environment while controlling nearly the entire spectrum of weed species (Duke 1999). These properties make these herbicides safer and environmentally compatible. Therefore, HR rice offers a new way of conferring selectivity and enhancing crop safety and production (Chauhan *et al.* 2012b, James 2011). The use of non-transgenic HR rice cultivars developed by seed mutagenesis could be used as an effective weed management strategy in direct-seeded systems.

HR rice can be used to control weeds that proliferate in conservation (minimum) tillage systems, for example, perennial weeds, such as *Cyperus* spp. Some weeds (parasitic broomrapes and witchweeds) cannot be controlled by herbicides or there are no readily usable selective herbicides for their control. Such problems can be controlled by the use of HR rice cultivars. Therefore, HR rice should be part of IWM to improve our agricultural ecosystems.

Integrated weed management

Several weed management strategies have been discussed in the previous section. However, the use of any single strategy cannot provide effective, season-long, and sustainable weed control as different weeds vary in dormancy and growth habits. Effective and sustainable weed management involves the combined use of preventive, cultural, mechanical, chemical, and biological weed control techniques in an effective and economical way. Aside from this, herbicide use moves the agroecosystem to low species diversity with the possibility of new problem weeds occurring. There is a need for an ecological approach to control weeds instead of relying totally on chemical control methods. The use of clean crop seeds and seeders and field sanitation (irrigation canals and bunds free from weeds) can be included as a component of IWM for effective weed management.

The efficiency of applied herbicides and competitiveness against weeds can be improved by integration of improved agronomic practices, timeliness of operations, optimum fertilisation and water management, and incorporation of crop residues in the soil (Chauhan *et al.* 2012b). Brar and Walia (2001) revealed that high N rate (180 kg/ha), along with a plant density of 44 plants/m^2, provided superior weed control. A pre-emergence spray of pendimethalin at 1 kg/ha plus one hand weeding at 25 days after sowing in rice + green gram intercropping provided effective weed control and caused a significant improvement in yield in both crops (ICAR 2007). Aulakh and Mehra (2006) recorded effective control of *L. chinensis* with increased crop density from 22 to 44 plants/m^2, coupled with pyrazosulfuron at 0.015 kg/ha. Sharma and Singh (2008) reported that, among different weed control treatments, IWM including criss-cross sowing plus one hand weeding plus herbicide provided better results than those obtained from only one weed control method, that is, two hand weedings and no weeding. It is imperative that IWM strategies be evaluated, considering available resources and locations.

Decision-making tools

Decisions for weed control must be made on the basis of knowledge of the biology and phenology of weeds in the field in order to design rotation scheme where each crop naturally suppresses weeds in the subsequent crop. Herbicide use and application rate must be decided based on what weeds are expected in the field (for pre-emergence herbicides) or are present in the field (for post-emergence herbicides). Progressive farmers now understand that the more varied the control mechanisms used in a rotation, the longer the duration of each desired effect would be. Research is needed to develop effective decision-making tools for weed management in rice.

The trend of replacing transplanted rice by direct-seeded rice is increasing because of water and labour scarcity. This change removes the suppressive advantage of standing water. In these situations, problems of weed management may become more important because of the emergence of new weeds and consequently the change in composition of the weed flora. To achieve effective, long-term, and sustainable weed control, IWM strategies that target the prevention of weed invasion, recruitment, and reproduction need to be developed. These strategies may include stale seedbed practice, crop rotation, weed seed predation, use of crop residue as mulch, combination of optimal fertilizer schedule, summer ploughing, land preparation, modifying plant geometry, planting time, seeding rate, and use of weed-competitive cultivars. Knowledge of weed ecology and biology can prove to be very effective tools for IWM.

Future issues and strategies

Although herbicide-based weed management systems have been proven to be beneficial to the agricultural community in many ways, continuous use of herbicides creates an environment that encourages weed resistance to herbicides, weed population shifts, and off-site movement of herbicides. Therefore, rice producers face the challenge of using herbicides and other inputs in such a way that prevents adapted species from reaching troublesome proportions. Other major areas for future IWM research are further described.

Rice cultivars with high competitive ability: India needs rice cultivars that can form an early dense canopy, leaving less space and light for weeds. In this case, germination and subsequent growth of weed seedlings is reduced due to restricted light availability at the soil surface. Although the vigorous, early vegetative growth of a cultivar has been identified as the key characteristic for increasing crop competitiveness, there is still a need to learn about the characteristics that impart competitiveness, the component traits of vegetative vigour, possible trade-offs, and the relative importance of these in different cropping environments and management systems. Many scientists think that root competition has a vital role in the interaction between rice and weeds, which suggests the need to study root characteristics of rice cultivars in relation to weed competition, especially in nutrient- and water-stressed environments.

Herbicide-resistant rice cultivars: Herbicide-resistant rice cultivars are an effective option in the IWM program. However, there are risks of gene flow from HR rice to their wild relatives (e.g., weedy rice) and of HR biotypes of weeds. Risk management strategies must therefore be seriously considered. Equally critical is the development of stewardship guidelines for the use of HR rice cultivars.

Exploiting the potential of biocontrol: The bioherbicide approach of weed control is based on the ability of natural enemies to cause sufficient damage to weeds to reduce their adverse effects on crop yield. In some developed countries, including the USA, Canada, and the UK, several biocontrol agents have been successfully patented and commercialized, Collego Devive, Elgo, Casst, Anisomycin, Bialophos, and AAL toxin. Foliar application of conidial suspensions of *Curvularia tuberculata* Jain and *Cyperus oryzae* Bugnicourt is used to kill *C. difformis*, *C. iria*, and *F. miliacea*. However, there is very low abundance of these natural enemies at the particular time required to control the weed in a specific agricultural situation. This explains why their potential has not been harnessed to support weed management strategies. There is a need to explore the role of biocontrol in IWM systems in rice as it provides a cheaper and more effective eco-friendly means for addressing the prevalent weed problems in agriculture as well as in other ecosystems.

Herbicide application technologies: To improve the efficacy of applied herbicides and to reduce the cost of weed management, low-cost and highly efficient herbicide application technologies should be adopted. These may include spray equipment and nozzles, herbicide carriers, adjutants, and the like. Moreover, further research is needed on herbicide mixtures for delaying resistance, reducing the cost of weed management, and providing more options in the weed control spectrum. There is a need to develop decision tools for different IWM options, including the choice of herbicide use and establishment methods.

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Weedy rice: problems and its management

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ABSTRACT

Weedy rice belongs to the same genus and species as cultivated rice but with different forms. It appears as hybrid swarms due to introgression of genes between wild and cultivated species in nature. In Asian rice, it is known as *Oryza sativa* var. *spontanea* whereas in African context it is said as *O. sativa* var. *stapfii*. It grows faster; produces more tillers, panicles and biomass; makes better use of available N; shatters earlier; has better resistance to adverse conditions; and possesses longer dormancy in soil. Because of its high competitive ability, it becomes a serious threat to rice growers worldwide. Great morphological variability, similar growth behavior and high biological affinity with cultivated varieties make its control difficult. No single management technique can effectively control weedy rice. An appropriate combination of preventive, cultural, mechanical and chemical control measures is essential.

Key words: Distribution, Origin, Traits, Weedy rice, Weedy rice management, Weedy rice problem

Weedy rice, an introgressed form of wild and of cultivated rice (*Oryza sativa* L.), is native of Asia (Londo *et al.* 2006) but was first documented in North Carolina, USA in 1846 (Smith 1981). A century after, it was considered a noxious weed in Arkansas, USA (Vincenheller 1906). Weedy rice infests rice fields in most of the rice growing areas in the tropics, and is particularly a problem in the direct-seeded rice systems of the Americas, the Caribbean and South and South-East Asia (Mortimer *et al.* 2000). The spread of weedy rice infestations have been reported to 40-75% of the total rice area in Europe (Ferrero 2003), 40% in Brazil (De Souza 1989), 55% in Senegal (Diallo 1999), 80% in Cuba (Garcia de la Osa and Rivero 1999) and 60% in Costa Rica (Fletes 1999). The extent of infestation was found 5-60% in different states of India, whereas it was observed in the range of 11.32 to 44.28% in cultivators' field and 0.78 to 2.40% at research farm of DWSR. Ten types of weedy rice (known as Sada or Sadwan) found in the farmers' field and other two types found in water ponds/tanks (called as Pasai Dhan in Madhya Pradesh) were identified and characterized (Varshney and Tiwari 2008). Different hypotheses were proposed to explain its origin (Kane and Baack 2007). It evolved from wild forms of *Oryza* or it may have originated through natural hybridization of cultivated and wild species (Azmi and Karim 2008) or from escaped domesticated rice seeds, which then evolved weedy traits.

In the United States, weedy rice (called red rice) has been a persistent problem for many decades (Goss and Brown 1939). In Asia, however, weedy rice is an emerging problem in Malaysia, Thailand, India, Republic of Korea, Philippines, Vietnam and Srilanka (Delouche *et al.* 2007). Its infestation was first reported in Malaysia in 1988, in the Philippines in 1990, and in Vietnam in 1994 (Mortimer *et al.* 1999, Mortimer *et al.* 2000, Wahab and Faimi 1991). Weedy rice aggressively competes with rice crop, increases production cost and reduces farmers' income quantitatively through yield reduction and qualitatively through lowering the value of cultivated rice in markets as grains of cultivated rice at harvest get contaminated with weedy rice grains having coloured pericarps (Mortimer *et al.* 2000**,** Chauhan 2013). The growth and competitive ability of weedy rice may vary considerably due to differences in plant height, tiller and leaf area producing capacity (Estorninos *et al.* 2002). Labrada (2003) stated two major weeds of particular concern to rice production; one is *Echinochloa* species, and the other is weedy rice. In Asia, rice yield losses due to weedy rice infestation were reported to be from 16-74% (Azmi *et al.* 1994 Chin, 2001). Smith (1988) reported that 5 to 10 plants/m^2 of barnyard grass, *Echinochloa crusgalli* (L.) P. Beauv. were threshold infestation to prevent yield losses of rice, whereas the corresponding density for weedy rice was only 1 to 3 plants/m^2. Serious infestation of weedy rice in Malaysia caused a maximum yield loss of 74% in direct-seeded rice (Azmi *et al.* 1994). In a later study, it was estimated that infestations represented by about 35 weedy rice panicles/m^2 would cause a yield loss of about 1 tonne rice grains/ha (Azmi *et*

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al. 2005). In the United States, low weedy rice infestations (5 plants/m^2) caused severe yield and quality losses in dry seeded rice, and also contaminated field with shattered grains of weedy rice (Diarra *et al.* 1985a). The threshold infestation of weedy rice to prevent yield losses of rice was 1-3 plants/m^2 (Smith 1988). Weedy rice at densities of 35 to 40 plants/m^2 can reduce yields of tall rice cultivars by 60% and short cultivars by 90%, which are much greater yield losses than with other grassy weeds such as bearded sprangletop [*Leptochloa fascicularis* (Lam.) Gray] (Smith 1983, Kwon *et al.* 1991). In India, infesaton was ranged from 5-60% in different states, therefore, considering mean of 10% infestation, the average loss in rice production in India was assessed to the extent of 9.15 million tones (Varshney and Tiwari 2008)

The spread of weedy rice became significant over the last 30 years due to large scale cultivation of semi-dwarf indica-type rice varieties. The spread has further aggravated due to use of commercial seeds that contain seeds of the weedy rice and through the machines used in rice cultivation specially the tillage implements and mechanical harvesters. The increase in weedy rice infestation in South-east Asia is closely associated with the increase in area under direct seeded rice (Delouche *et al.* 2007) and is a growing problem as this establishment method spreads in entire tropical Asia (Rao *et al.* 2007). Infestation of weedy rice is also reported to be higher in the no-till fields compared to the cultivated fields (Pyon *et al.* 2000).

The physical and physiological similarities of weedy rice to cultivated rice, adoption of direct seeded rice systems and the absence of standing water at the time of crop emergence in direct-sown rice fields, makes weedy rice infestation one of the most serious problems that farmers encounter during recent times (Azmi and Karim 2008, Chauhan and Johnson 2010, Chauhan 2012). Due to that reason, in some countries where direct seeding is already a common practice, farmers are reverting to mechanized transplanting to manage weedy rice. Selective herbicides to control weedy rice in conventional rice cultivation are not available and therefore, managing weedy rice is a challenging problem for farmers in Asia (Chauhan 2013). For farmers, it becomes a difficult-to-control, aggressive weed that increases the costs of production, reduces yield, lowers the market value of their crop and, where not controlled properly, can render the infested land unfit for rice production. Due to difficulties in controlling, it has been posing cancerous threat to the rice farmers of many South-east Asian countries (Karim *et al.* 2010).

Origin, sources and distribution of weedy rice

The phylogenetic origin of the weedy forms is closely related to that of cultivated rice. Many weedy plants share most of the features of the two cultivated species *i.e.*, Asian rice (*Oryza sativa)* and African rice (*O. glaberrima)*. Wild species like *O. nivara*, *O. rufipogon* and *O. longistaminata* share the same genome 'AA' as cultivated rice and can easily be crossed with the cultivated *O. sativa* and *O. glaberrima* species. The wild *O. barthii* species (*O. breviligulata*) is considered to be the progenitor of African rice. In the distant past, different types of weedy rice were generated primarily through natural crossing between wild and cultivated rice species in areas where they grew (or still grow) sympatrically (Vaughan and Morishima 2003). While this type of crossing is still important in a few areas in Africa and Asia, most types of weedy rice elsewhere now arise from much closer crosses between the plants of cultivated varieties and those of the weedy rice that infest the crop. *Oryza rufipogon*, a wild perennial rice with a red pericarp, is endemic to South and Southeast Asia and both the weedy and cultivated rice are believed to have evolved from this wild species (Khush 1997, Londo *et al.* 2006). It is considered to be an ancestor of the *sativa* (AA) group of cultivated rice, *i.e. indica, japonica* and *javanica* types, and the likely donor of the red pericarp that is the common characteristic of the weedy red rice as well as selected red-pericarp lines of rice that have been and still are cultivated. In fact, some red rice accessions in the southern USA belong to the same genotypic cluster as its progenitor *O. rufipogon* (Vaughan *et al.* 2001).

The main sources of weedy rice are the contaminated seed stocks. However**,** several "delivery systems" other than seed stocks have been implicated in the spread of weedy rice. Harvesting equipment is a significant source of contamination of rice seed lots and rice fields with seeds of weedy rice (De Souza 1989, Smith 1992). Weedy rice seeds are also spread within fields and to other fields with mud adhering to the hooves and legs of animals, the wheels of carts, trucks and similar vehicles and in the movement of rice straw (Garcia de la Osa and Rivero 1999). Because the spikelets (grains) of many of the weedy rice phenotypes are pubescent and some have long, hispid awns, the seeds can be spread by adhering to the fur of domestic and wild animals and even the clothing of field workers.

In the United States of America, weedy rice (also known as red rice) infestations were reported as early as 1846 (Allston 1846). It is generally believed that red rice was introduced into the United States of America at a much earlier date as contaminants in imported seed rice in the states of North and South Carolina in 1698 from the India subcontinent (Cragmiles 1978). As rice cultivation expanded, seeds were imported from several other countries including Japan in a search for better varieties. Indeed, weedy rice strains from Brazil, China (upper Yangtze River area), Japan and the United States of America belong to the same group called crop "mimics" with *indica* characteristics (Tang and Morishima 1996). The majority of present-day red rice accessions in the United States of America fall into the mimics' category (Vaughan *et al.* 2001). While in Latin America and the Caribbean region, the original sources of weedy rice are believed to be rice seeds imported from the United States of America (Dominguez 1999, Garcia de la Osa and Rivero 1999), Spain or through The Netherlands, France and Portugal from Asian suppliers for cultivation in their "New World" colonies. It was apparently introduced into Venezuela from the United States of America in the mid-1940s in imported rice seed stocks (Dominguez 1999).

In Cuba, it was probably introduced in rice seeds from the United States of America during the intensification of rice cultivation beginning in 1927, or perhaps even earlier from Spain during the colonial period (Garcia de la Osa and Rivero 1999). Southern European and other Mediterranean countries have not escaped the weedy rice problem. According to Vidotto and Ferrero (2005), shattering types of weedy rices were reported in Italian paddy fields early in the nineteenth century. Since the beginning of the twentieth century, weedy rices in Europe have been classified as *O. sativa* var. *sylvatica*. According to Ferrero and Vidotto (1999), red grain weedy rices began to be considered a significant problem when direct seeding replaced transplanting about 30 years ago. In Asia and West Africa, the origin of weedy rices were different from that in the Americas or Europe because they are the sites of the evolution and domestication of the two cultivated rice species, *O. sativa* in Asia and *O. glaberrima* in Africa, where there are other wild rice species, many of which are troublesome weeds, and where rice has been cultivated for thousands of years. In Egypt, the types of weedy rice (including red rices) appear to be more similar to those in the Americas and Asia than to those in West Africa and south of the Sahel.

Important traits of weedy rice

Weedy rice plants show a wide variability of anatomical, biological and physiological features (Tang and Morishima 1997, Vaughan *et al.* 2001). One group includes plants with a black hull, purple apex and long awns, showing evidence of wild traits while the other group has straw hull and apex, and no awn, mimicking cultivated varieties (Federici *et al.* 2001). The important traits of weedy rice that distinguish it from cultivated rice are rapid early growth; taller canopy; high tillering capacity; spreading growth habit with long, drooping leaves; tendency to lodge because of weak culm; voracious consumption of fertilizer; tolerance to shade, asynchronous maturation of grains; seed dehiscence; seed dormancy and a red pericarp (Burgos *et al.* 2006, Delouche *et al.* 2007). Identification of weedy rice is possible only after tillering when several morphological differences such as numerous, longer and more slender tillers, leaves often hispid on both surfaces, tall plants, pigmentation of several plant parts, easy seed dispersal after their formation in the panicle, are visible with respect to cultivated rice.

Weedy rice seems to have inherited the high reproductive capacity from modern rice varieties, and seed shattering and dormancy from wild rice, which contribute towards build up and persistence of its seed bank in the soil. The seeds of most weedy biotypes of *O. sativa* and *O. glaberrima* have pigmented pericarps due to the presence of varying levels of anthocyanin, cathekin, and catheolic tannins. Because of this reason, the term 'red rice' is commonly adopted in international literature to identify these wild plants. This term, however, does not seem very appropriate as red-coat grains are also present in some cultivated varieties, but also absent in various weedy forms. Milled japonica red rice showed greater variations in physicochemical properties than white kernel cultivars: their protein, amylose, and cooked rice hardness trended higher, while their paste and breakdown viscosities, and cooked rice stickiness were lower (Goto *et al.* 1996, Matsue *et al.* 1997). Total carbohydrates and starch contents of milled red rice from India, however, were lower than those of un-pigmented rice (Srinivas 1976).

During flowering, the florets opening of weedy rice begin between 08: 00 and 09: 00 am and continue at least one hour longer than that of the cultivated varieties. For this reason, cross-pollination is higher in weedy rice than in cultivated varieties. The flowering period in weedy rice (8-93 days) is usually longer than that of cultivated rice (7-22 days) biotypes (Longevin *et al.* 1990, Mongkolbunjong *et al.* 1999). Due to heterosis, hybrids were generally taller and more vigorous and began flowering 20-30 days later than the parent weedy plants. The seeds of weedy rice show a variable degree of dormancy (Gu *et al.* 2005). Viable weedy rice seeds with red pericarp may remain dormant up to two years or more. The longevity of the weedy rice seeds can last up to 12 years; however, it is largely influenced by burial depth (Thanh *et al.* 1999). Early seed shattering is another specific characteristic of weedy rice (Azmi and Karim 2008). It starts 9 days after flowering and increases gradually up to 30 days until complete development of the panicle. In general, the shattered grains show a lower germinability up to 24 days after flowering, in comparison to that of non-shattered seeds of cultivated rice. The seeds that shattered after 15 days from flowering contained nearly filled and physiologically mature grains (Do Lago 1982). The shattered seeds required at least 70 days in favourable temperature and moisture conditions before germination starts.

Recent threats to rice cultivation in India

In India, *O. sativa f. spontanea* is considered a weedy species in cultivated rice fields. The country has been identified as the centre of origin of rice (Vavilov 1926), and many wild and weedy relatives are present in major rice-growing areas of the country. The Western Ghats region of South India is rich in biodiversity of wild *Oryza* species including *O. rufipogon, O. nivara, O. granulata, O. malampuzhaensis* and *O. officinalis* (Thomas *et al.* 2001). Similarly in Eastern India (e.g. eastern Uttar Pradesh, Madhya Pradesh, Bihar, Odisha, Manipur, Assam and West Bengal) where wild and weedy relatives are common, two wild species, *viz.O. nivara* and *O. rufipogon* are found abundantly in lowlands, swamps and marshes, in open ditches as well as in swampy grasslands. The world weedy rice types are classified into two distinct groups corresponding to *indica* and *japonica* cultivars (Suh *et al.* 1997) and the Indian weedy rice belongs to the *indica* group similar to the wild type which indicates that these weedy rice strains may have originated from hybridization between wild and cultivated rice.

Among the different wild species present in India, *O. nivara* and *O. rufipogon* share the same genome AA as cultivated rice and can easily be crossed with cultivated *O sativa*. (Olofsdotter *et al*. 2000). Due to this reason, weedy rice is now spreading rapidly in all the traditional rice growing regions of the country including South, West and western India, either through natural hybridization or through seed stocks admixing with weedy rice seeds. However, in North-western states of India (*e.g.* Haryana and Punjab), wild and weedy relatives are not present, thus, there are very low risks of development of weedy rice naturally. However, it may spread in this region through seed stocks from other contaminated regions as it happened earlier in many countries of the United States. Thomas (2009) reported that the rice production in India might fall drastically (by over 40%) in the next few years if the weedy rice infestation was not contained. About 24–32% infestation of weedy rice was reported from Ranchi, Khunti and East Singhbhum areas of Jharkhand with an estimated yield loss of 10–45% (Sharma and Upasani 2012). Recently, it was reported that weedy rice is prevalent in the areas where direct-sown rice has been practiced for a long time in the rainfed uplands as well as lowland rice ecosystems of eastern Uttar Pradesh, Bihar, Odisha, West Bengal, Assam, Manipur, and other hilly tracts of the North East. But, the threat will be much greater in irrigated rice systems, where direct-sown rice is being adopted by farmers on a large scale in view of the current challenges (Singh *et al.* 2013). Therefore, effective management strategies are needed to counter the weedy rice threat in the direct-sown rainfed lowlands as well as irrigated ecosystems of India.

Problems caused by weedy rice

Weedy rice disperses in rice fields, and grows alongside cultivated rice, making its identification and control very difficult because of its similarity with cultivated rice at early vegetative stage. Growth and competitive ability of weedy rice may vary considerably due to differences in plant height, tiller and leaf area producing capacity (Estorninos *et al.* 2002). Black-hull weedy rice biotypes in the United States, for example, tillered 27% more and produced 18% more straw than straw-hull biotypes (Diarra *et al.* 1985b). Short varieties are usually more susceptible to weedy rice competition than tall ones. Interference between cultivated varieties and weedy rice begins three weeks after rice emergence. Compared to cultivated rice, weedy rice has a greater response to higher N rates, takes up more N, and higher N use efficiency for biomass production than cultivated rice (Burgos *et al.* 2006, Chauhan and Johnson 2011).

Tall weedy rice plants, besides shading cultivated rice, may lodge over the crop; (Caton *et al.* 1997) make crop harvesting more difficult and reduce rice yields. With heavy infestations, complete lodging of weedy rice may result in total yield loss of the rice crop (Azmi *et al.* 2000). In addition, weedy rice responded more strongly than cultivated rice to rising CO_2 level, with greater competitive ability, and subsequent negative effects on cultivated rice (Ziska *et al.* 2010). This suggests that with rising CO_2 level in future due to climate change, weedy rice may become a more serious problem than now. Another important characteristic of weedy rice is early shattering of the grain and ability to remain dormant in the soil for several years, thus assuring future infestations (Azmi and Karim 2008, Chauhan 2013). The early and heavy shattering of seeds as they mature in the inflorescence, is an important mechanism for its quick dispersal and distribution. These seeds can be transferred from heavily infested field to neighboring fields by the combined harvester or other machines used in rice cultivation. It may also transmit by the commercial seeds contaminated with weedy rice.

Management of weedy rice

Control of weedy rice is much more difficult because of its greater morphological variability, similar growth behavior, and high biological affinity with cultivated varieties. Due to this reason, control of weedy rice is expensive, time-consuming and usually does not lead to total eradication of the infestation. Incomplete control of the weed for a given year could lead to eliminating the results of several years of good control. An appropriate combination of different methods including preventative, cultural, mechanical, chemical and/or genetic practices can reduce the chances of weedy rice infestation.

Preventive management

The first and most important step in reducing weedy rice infestation is the use of certified seeds or clean seeds from a known source that is free from weedy rice grains (Chauhan 2013). Farmers should inspect their fields regularly and must rogue weedy rice plants whenever these appear. Removal of weedy rice panicles by hand at heading/flowering stage helps to reduce weedy rice seed bank in soil. There is a need to increase awareness of weedy rice among farmers so that they are able to distinguish off type and weedy rice accessions from cultivated rice (Delouche *et al.* 2007). Closer watch on the species in new areas is needed to avoid its invasion, and such plants should be rogued out upon their initial appearance in the field. Use of clean machinery is another important aspect. The machine used for land preparation, sowing, harvesting and threshing should be cleaned if it is coming from infested fields. The canals, irrigation channels etc. should be cleared from infestations of wild/ weedy rice.

Cultural management

Emergence of weedy rice could be suppressed by deep tillage that buries seed below 8.0 cm (Chauhan 2012b). However, shallow tillage operations should be done subsequently in the next few seasons to avoid bringing back the buried seeds on the soil surface. Adoption of 'Stale seed bed' technique has been reported to reduce weedy rice infestations (Delouche *et al.* 2007). In heavily infested areas, it should be repeated to incrementally deplete the soil seed bank of weedy rice. In the Mekong Delta, farmers broadcast pre-germinated rice seeds in 10-15 cm deep water (Luat 2000). This practice of 'water seeding' or 'wet seeding' buries weedy rice seeds in the soil and is not able to emerge. In heavily infested areas, puddling the field combined with the presence of a thin layer of water over the well-leveled soil maintains the anaerobic conditions in the top soil and prevents weedy plants from becoming established (Diarra *et al.* 1985a, Vidotto and Ferrero 2000). Thus, 'manual or mechanical transplanting' could be a suitable alternative method of crop establishment to prevent weedy rice infestation. Transplanted seedlings will be more competitive against newly emerged weeds and weedy rice seedlings and it will be easy to distinguish cultivated rice seedlings from weedy rice seedlings. In addition, standing water/flooding in well-leveled soils at the time of transplanting limits weedy rice germination (Chin 2001, Azmi and Karim 2008, Chauhan 2012a, b). In a study in Italy, winter flooding between rice crops resulted in greater reduction of weedy rice seeds on the soil surface as compared to fields left dry between rice crops (Fogliatto *et al.* 2010).

Use of high seeding rates not only suppress weedy rice in highly infested fields but also ensure against uncertainty in crop establishment (Chauhan 2013). Seeding rate greater than 150 kg/ha was adopted in some weedy rice infested areas in Malaysia to reduce the problem of weedy rice (Azmi and Karim 2008). Again, row crops will have an advantage over broadcast crops as weedy rice emerging between the rows can easily be distinguished and pulled out (Chauhan, 2012a). Sowing of rice in rows also helps to remove the weedy rice seedlings grown between the rows by using mechanical tools like finger weeder or cono weeder. There is a strong-felt need by the farmers in eastern India for growing purple base rice cultivars in weedy rice infested areas (Tewari 2008). High yielding purple stemmed (base) cultivars with green foliage can also be used to get rid of weedy rice infestations. Green manuring by *Sesbania* sp. in rainfed lowlands helps in successfully smothering weedy rice (Labrada 1997). Proper crop rotation by growing soybean, groundnut, maize, wheat, sunflower, sorghum, mungbean etc. would help to suppress weedy rice as cultivation practices of these crops act like an alternative herbicide treatment (Watanabe *et al.* 1998).

Chemical control

The close anatomical and physiological similarity to cultivated varieties makes the control of weedy rice plants with selective post-emergence herbicides very difficult. The most successful management technique is based on application of pre-emergence herbicides before crop sowing/planting. In continued flooded monocultures, an effective management of weedy rice can achieve by adoption of stale seed bed technique followed by spraying of the graminicides, *viz.* dalapon (12 kg/ha), clethodim (0.2 kg/ha) and cycloxydim (0.6-0.8 kg/ha) or non-selective herbicides, *viz.* glyphosate (1-1.5 kg/ha), glufosinate ammonium (0.5-0.7 kg/ha), paraquat (0.8 kg/ha) and oxyfluorfen (0.8 kg/ha) once the weeds have reached 2-3-leaf stage (Vidotto *et al.* 1998). In rice field, it was observed that pre-sowing application of anti-germinative herbicides, *viz.* molinate at 7.2 kg/ha or butylate at 4.2 kg/ha are found effective to prevent germination of weedy rice seeds (Vidotto *et al.* 1998). However, these herbicides need to immediately be incorporated into the soil to avoid volatilization. In Malaysia, it was found that application of pretilachlor (1.5-2.0 kg/ha) just before or after tillage in standing water reduced weedy rice seed bank (Azmi *et al.* 2004). In Thailand too, application of pretilachlor by dripping the concentrate or slightly diluted product directly into the water during last leveling offered an effective control of weedy rice (Allard *et al.* 2005). Herbicides like oxadiazon and metolachlor may also provide effective control of weedy rice, but to avoid any phytotoxic effect on rice, these herbicides should be applied at least 15 days before rice sowing (Eleftherohorinos and Dhima 2002). Spraying of Maleic hydrazide on weedy rice plants at the heading stage helps in reducing seed viability. However, it should be done before milky-stage of cultivated rice to avoid its negative effects on the yield and seed viability (Noldin and Cobucci 1999).

Genetic and biotechnological approach

Dilday *et al.* 1995 suggested that the problem of weedy rice can be tackled by the introduction of herbicide-resistant varieties which allow the selective post-emergence control of weedy rice infestation. The introduction of herbicide-resistant Clearfield rice (IMI rice), a mutant developed by radioactive bombardment of a conventional rice plant, made selective control of weedy rice possible with the use of imazethapyr and imazamox (Webster and Masson 2001). This herbicide has proved to be effective against weedy rice and other rice weeds when applied twice at 70 kg/habefore flooding and oneapplication of imazamox (45 g/ha) during mid season to control weedy rice and other weeds(Avila *et al.* 2005, Levy *et al.* 2006, Ottis *et al.* 2004, Steele 2002). But there is great concern about its sustainability because of the potential evolution of herbicide-resistant weedy rice populations either via gene flow from IMI rice to weedy rice (Shivrain *et al.* 2007, 2008) or increased herbicide selection pressure on the weed. An out-crossing between IMI herbicide-resistant rice and weedy rice has been discovered in Arkansas (Schultz 2004). Therefore, IMI rice should not be planted in two growing seasons in a row to ensure the longevity of this technology. Additional reduction of the weed can be achieved using herbicides with different action mechanisms or with cultural and mechanical weed control means. Crop or rice cultivar rotation has an important role in preserving the usefulness of IMI.

Herbicide tolerance has been the predominant trait of genetically modified (GM) crops since their commercialization. The genetically modified herbicide tolerant (GMHT) rice could be an effective means for weed control, especially for the management of rapid emergence of weedy rice. Many have concerns that GMHT rice would bring reduction of biodiversity, and then affect the balance of agro-ecosystem; that exogenous gene of GMHT rice would escape to cultivated rice, weedy rice and its wild relatives through gene flow; and also that GHMT rice would become a weed or invasive natural habitats. To meet people's demand of food and ensure safety to people and environment, the research about the possible effects of GHMT rice on biodiversity is urgent and important (Jiang *et al.* 2010).

With current crop management practices, including direct seeding of rice, weedy rice infestations are likely to increase and will threaten sustainability of production systems in the country. Due to their high competitive ability, these weeds can remarkably affect rice yields. No selective herbicide is available to manage weedy rice in rice fields (Chauhan 2012). Multiple approaches need to be integrated to reduce weedy rice infestations in fields as farmers usually fail to reduce weedy rice populations using a single method of control (Saha *et al.* 2013). Further research is, therefore, urgently needed to determine the impact of different tillage systems, appropriate time and duration of flooding, the use of rice cultivars capable of emerging in anaerobic conditions, and herbicide practices on weedy rice growth and control. Integrated crop management practices with varietal aspects, such as crop plant density (seeding rate), narrow row spacing, weed competitive cultivars with good initial vigour and purple base rice varieties for easy identification of weedy rice in crop fields need to be evaluated for effective weedy rice management (Chauhan 2012).

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Integrated weed management in conservation agriculture systems

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ABSTRACT

Conservation agriculture (CA) technologies involve minimum soil disturbance, soil cover through crop residues or other cover crops, and crop rotations. Weeds are a major constraint in adoption of CA-based technologies. Conservation tillage influences weed infestation, and thus interactions between tillage and weed control practices are commonly observed in crop production. There are reports available that zero tillage increases as well as reduces infestation of certain weed species in different crops. In rainy season when the weed problem is generally more, growing crops with zero tillage requires additional measures for effective weed control, including use of non-selective herbicides like paraquat and glyphosate. Zero-till sowing in standing crop residues along with application of herbicides in proper combination, sequence or in rotation leads to lower weed population and higher yield than conventional planting. However, changing from tillage-based farming to no-till farming is not easy. No-till incurs a greater risk of crop failure or lower net returns than conventional agriculture, and this perception has seriously hindered its adoption in countries outside north and south America. Yields of no-till crops may be lower by 5-10% in the initial years, especially on fine-textured and poorly-drained soils. No-till farming demands use of extra N fertilizer and heavy reliance on herbicides. The continued practice of no-till is, therefore, highly dependent on development of new herbicide formulations and integrated weed management options.

Key words: Conservation agriculture, Crop residues, No-till farming, Non-selective herbicides, Rice-wheat system, Weed management

Transformation of 'traditional animal-based subsistence farming' to 'intensive chemical and tractor based conventional agriculture' has led to multiplicity of issues associated with sustainability of these production practices. Conventional crop production technologies have inculcated: (i) intensive tillage to prepare fine seed- and root-bed for sowing to ensure proper germination and initial vigour, improve moisture conservation, control weeds and other pests, mixing of fertilizers and organic manures, (ii) monocropping systems, (iii) clean cultivation involving removal or burning of all residues after harvesting leading to continuous mining of nutrient and moisture from the soil profile; and bare soil with no cover, (iv) indiscriminate use of pesticides, and excessive and imbalanced use of chemical fertilizers leading to declining input-use efficiency, factor productivity, and environmental, ground water, streams, rivers and oceans pollution, and (v) energy-intensive farming systems.

Emerging concerns

Green Revolution contributed to food security through increased food production and reduced volatility of foodgrain prices, and also demonstrated that agricultural development provides an effective means for accelerating economic growth and reducing poverty. But, post-Green Revolution input-intensive conventional agriculture production systems have led to several global concerns, such as: (i) declining factor productivity, (ii) declining ground water table, (iii) development of salinity hazards, (iv) deterioration in soil fertility, (v) deterioration in soil physical environment, (vi) biotic interferences and declining biodiversity, (vii) reduced availability of protective foods, (viii) air and ground water pollution, and (ix) stagnating farm incomes.

The current state of production systems management is posing a threat to food security and livelihood of farmers, especially to poor and under-privileged smallholders in vulnerable ecologies. Hence, the agronomic management in conventional crop production systems need to be looked into critically and understood with an overall strategy of: (i) producing more food with reduced risks and costs, (ii) increasing input use-efficiency, *viz.* land, labour, water, nutrients, and pesticides, (iii) improving and sustaining quality of natural resource base, and (iv) mitigating emissions and greater resilience to changing climates.

Change in conventional agricultural systems

Widespread resource degradation problems under conventional system, and the need of reducing pro-

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duction costs, increasing profitability and making agriculture more competitive, have made the conservation issues more imperative. Globally innovations of conservation agriculture-based crop management technologies are said to be more efficient, use less inputs, improve production and income, and address the emerging problems (Gupta and Seth 2007). Additionally, secondary drivers, such as: (i) availability of new farm machinery, (ii) availability of new biocide molecules for efficient weed, insect-pest and disease control, (iii) ever-decreasing labour force and ever-increasing labour cost, (iv) increasing production costs, energy shortages, erosion losses, pollution hazards and escalating fuel cost, and (v) residue burning, have accelerated change in thinking of researchers, policy makers and farmers to adopt modified methods for cultivation of crops aimed at improving productivity and resource-use efficiency.

Conservation agriculture - a new paradigm in crop production

Adequate food production for ever-increasing global population can only be achieved through the implementation of sustainable growing practices that minimize environmental degradation and preserve resources while maintaining high-yielding profitable systems. Conservation agriculture practices are designed to achieve agricultural sustainability by implementation of sustainable management practices that minimize environmental degradation and conserve resources while maintaining high-yielding profitable systems, and also improve the biological functions of the agro-ecosystem with limited mechanical practices and judicious use of external inputs. It is characterized by three linked principles, *viz.* (i) continuous minimum mechanical soil disturbance, (ii) permanent organic soil cover, and (iii) diversification of crop species grown in sequences and/or associations. A host of benefits can be achieved through employing components of conservation agriculture or conservation tillage, including reduced soil erosion and water runoff, increased productivity through improved soil quality, increased water availability, increased biotic diversity, and reduced labour demands.

Conservation agriculture systems require a total paradigm shift from conventional agriculture with regard to management of crops, soil, water, nutrients, weeds, and farm machinery (Table 1).

Adoption of conservation agriculture systems

Conservation agriculture systems are being advocated since 1970s but it is only in the last 2 decades that the area has been increasing rapidly. This has been accelerated due to development of efficient farm machinery and availability of effective herbicides coupled with trained manpower, which have resulted in reduced production costs and higher profitability, besides several indirect benefits. Presently, about 154.8 M ha area is practiced following the concepts and technologies for conservation agriculture; the major countries being USA, Brazil, Argentina, Canada and Australia (Table 2).

Farmers of the developing countries have also initiated to practice some of the conservation agriculture technologies. Accoridng to available estimates, the resource conservation technologies are practiced in >3 M ha under the rice-wheat based system in the Indo-Gangetic plains. The major CA-based technology being adopted in this region is zero-till (ZT) wheat in the rice-wheat system; and it is now foreshadowing

Table 1. Some distinguishing features of conventional and conservation agriculture systems

Conventional agriculture	Conservation agriculture
• Cultivating land, using science and technology to dominate nature	• Least interference with natural processes
• Excessive mechanical tillage and soil erosion	• No-till or drastically reduced tillage (biological tillage)
• High wind and soil erosion	• Low wind and soil erosion
• Residue burning or removal (bare soil surface)	• Surface retention of residues (permanently covered soil surface)
• Water infiltration is low	• Infiltration rate of water is high
• Use of *ex-situ* FYM/composts	• Use of *in-situ* organics/composts
• Green manuring (incorporated)	• Brown manuring/cover crops (surface retention)
• Kills established weeds but also stimulates more weed seeds to germinate	• Weeds are a problem in the early stages of adoption but decrease with time
• Free-wheeling of farm machinery, increased soil compaction	• Controlled traffic, compaction in tramline, no compaction in cropped area
• Monocropping/culture, less efficient rotations	• Diversified and more efficient rotations
• Heavy reliance on manual labour, uncertainty of operations	• Mechanized operations, ensure timeliness of operations
• Poor adaptation to stresses, yield losses more under stress conditions	• More resilience to stresses, yield losses are less under stress conditions
• Productivity gains in long-run are in declining order	• Productivity gains in long-run are in incremental order

the age-old concept, popularly known as "more you till and more you harvest". Adoption and spread of ZT wheat has been a success story in north-western parts of India due to: (i) reduction in cost of production by ` 2000-3000 per ha, (ii) enhanced soil quality i.e. soil physical, chemical and biological conditions in the long-term, (iii) enhanced C sequestration and build-up in soil organic matter, (iv) reduced incidence of weeds, such as *Phalaris minor* in wheat, (v) enhanced water- and nutrient-use efficiency, (vi) enhanced production and productivity, (vii) advanced sowing date, (viii) reduced greenhouse gas emission and improved environmental sustainability, (ix) avoiding crop residue burning, loss of nutrient, environmental pollution, reduced serious health hazard, (x) providing opportunities for crop diversification and intensification, (xi) enhanced resource-use efficiency through residue decomposition, soil structural improvement, increased recycling and availability of plant nutrients, and (xii) surface residues as mulch control weeds, moderate soil temperature, reduce evaporation, and improve biological activity.

Table 2. Global adoption of conservation agriculture systems

Country	Area (M ha)	% of Global Area
USA	35.6	23.0
Brazil	31.8	20.5
Argentina	27.0	17.4
Canada	18.3	11.8
Australia	17.7	11.4
China	6.7	4.3
Russian Federation	4.5	2.9
Paraguay	3.0	1.9
Kazakhstan	2.0	1.3
Others	8.2	5.3
Total	154.8	100.0

Source: FAO (2014)

Weed problems in CA

Weeds are the major constraints in CA-based systems. 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. Any reduction in tillage intensity or frequency may, therefore, influence the weed infestation. The composition of weed species and their relative time of emergence differ between CA systems and soil-inverting conventional tillage systems. Some weed seeds require scarification and disturbance for germination and emergence. Their germination and emergence may be accelerated by the type of equipment used in soil-inverting tillage systems than by CT machinery.

Shifts in weed populations from annuals to perennials have been observed in CA systems. Perennial weeds are known to thrive in reduced or no-tillage systems. Most perennial weeds have the ability to reproduce from several structural organs other than seeds. For example, Bermuda grass (*Cynodon dactylon*), nutsedge (*Cyperus rotundus*) and Johnson grass (*Sorghum halepense*) generally reproduce from underground plant storage structures: stolons, tubers or nuts and rhizomes, respectively. Conservation tillage may encourage these perennial reproductive structures by not burying them to depths that are unfavorable to emergence or by failing to uproot and kill them. 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. Crop yield losses in CA due to weeds may vary depending on weed dynamics and weed intensity. However, the recent development of post-emergence broad-spectrum herbicides provides an opportunity to control weeds in CA. Crop yields can be similar for conventional and conservation tillage systems if weeds are controlled and crop stands are uniform (Mahajan *et al.* 2002). Results of on-farm trials at several locations in Haryana revealed that population density of *Phalaris minor* was considerably lower and grain yield of wheat was comparatively higher under zero tillage than conventional tillage (Fig. 1).

In the Vertisols of Jabalpur, zero-tillage significantly increased the population of *Vicia sativa* but reduced the population of *Chenopodium album* compared with conventional tillage. Higher yields of pea and linseed were recorded under ZT with herbicide application, which also proved to be more profitable than conventional tillage (Table 3).

In CA systems the presence of residue on the soil surface may influence soil temperature and moisture regimes that affect weed seed germination and emergence patterns over the growing season. This shows that under CA system, farmers have to change the timing of weed control measures in order to ensure their effectiveness. Soil surface residues can interfere with the application of herbicides, so there is a greater likelihood of weed escapes if residue is not managed properly or herbicide application timings or rates are not adjusted.

Weed seed bank dynamics

The success of CA system depends largely on a good understanding of the dynamics of the weed seed bank in soil. A soil weed seed bank is the reserve of viable weed seeds present in the soil. The seed bank consists of new seeds recently shed by weed plants as well as older seeds that have persisted in the soil for

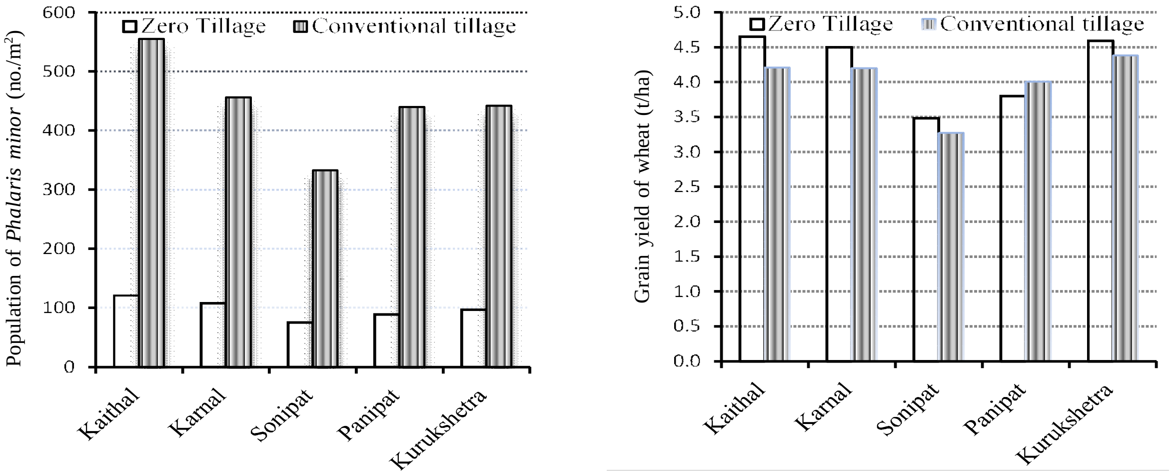

Fig. 1. Effect of tillage on wheat yield and population of *Phalaris minor* at different locations in Haryana

Source: Gupta and Seth (2007)

Table 3. Effect of tillage and weed control on weed growth and yield of winter crops after rice at Jabalpur

Winter crops	Pendimethalin 1.0 kg/ha		Weedy check	
	Zero tillage	Conventional tillage	Zero tillage	Conventional tillage
Chickpea				
Seed yield (t/ha)	1.59	2.03	1.45	1.68
Net returns (x10^3 `/ha)	16.43	21.04	15.53	16.39
Pea				
Seed yield (t/ha)	2.23	2.01	1.51	1.26
Net returns (x10^3 `/ha)	23.20	16.08	13.09	5.74
Linseed				
Seed yield (t/ha)	1.09	0.98	0.65	0.79
Net returns (x10^3 `/ha)	8.23	3.04	2.35	1.29

Source: Mishra and Singh (2011)

several years. The seed bank in the soil builds-up through seed production and dispersal, while it depletes through germination, predation and decay. Different tillage systems disturb the vertical distribution of weed seeds in the soil in different ways (Fig. 2). Moldboard ploughing buries most weed seeds in the tillage layer, whereas chisel ploughing leaves most of the weed seeds closer to the soil surface. Similarly, depending on the soil type, 60-90% of the weed seeds are located in the top 5 cm of the soil in reduced or no-till systems (Swanton *et al.* 2000). As these seeds are at a relatively shallow emergence depth, they are likely to germinate and emerge more readily due to suitable moisture and temperature than those seeds which are buried deeper in conventional systems.

There is a need to gain understanding on weed management as it is the major hindrance in CA-based crop production systems. Weed control in CA is a greater challenge than in conventional agriculture. The behaviour of weeds and their interaction with crops

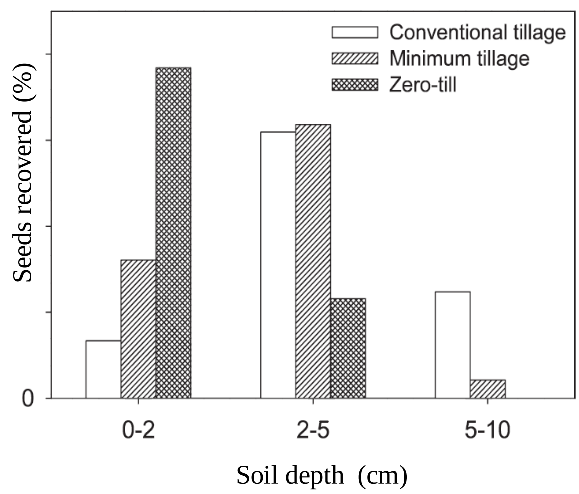

Fig. 2. Effect of tillage systems on vertical distribution of weed seeds

Source: Chauhan and Johnson (2009)

under CA tend to be complex and not fully understood. CA often causes weed shift resulting in increase in the density of certain weeds. The 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. Hence, effective weed control techniques are required to manage weeds successfully. 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. Various approaches being employed to successfully manage weeds in CA systems include: preventive measures, cultural practices (tillage, crop residue as mulches, intercropping, cover cropping, competitive crop cultivars, planting geometry, sowing time, nutrient management *etc*.), use of herbicide-tolerant cultivars, and herbicides.

Preventive measures

Weed seeds resembling the shape and size of crop seeds are often the major source of contamination in crop seeds. Contamination usually happens during the time of crop harvesting if the life cycle of crops and weeds are of similar duration. Preventive measures are first and the most important steps to be taken to manage weeds in general and especially under CA as the presence of even a small quantity of weed seeds may cause a serious infestation in the forthcoming seasons. The various preventive measures include: (i) using weed-free crop seed, (ii) preventing the dissemination of weed seeds/ propagules from one area to another, (iii) using well-decomposed manure/ compost so that it does not contain any viable weed seeds, (iv) inspecting nursery stock/ transplants to prevent transplanting of weed seedlings from nursery to main field, (v) removing weeds near irrigation ditches and fence rows prior to flowering, (vi) mechanically cutting the reproductive part of weeds prior to seed setting, and (vii) implementing stringent Weed Quarantine Laws to prevent the entry of alien invasive and obnoxious weed seeds/propagules in the region.

Cultural practices

A long term goal of sustainable and successful weed management is not to merely control weeds in a crop field, rather to create a system that reduces weed establishment and minimizes weed competition with crops. Further, since environmental protection is a global concern, the age-old weed management practices, *viz.* tillage, intercultivation, intercropping, mulching, cover crops, crop rotation/diversification and other agro-techniques, which were once labeled as uneconomical or impractical should be relooked and be given due emphasis in managing weeds under CA. 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. 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. Shrestha *et al.* (2002) concluded that long-term changes in weed ûora are driven by an interaction of several factors, including tillage, environment, crop rotation, crop type, and the timing, and type of weed management practice.

Laser land leveling is an integral component of CA as it provides uniform moisture distribution to the entire field and allows uniform crop stand and growth, leading to lesser weed infestation. On the other hand, unleveled fields frequently exhibit patchy growth of crops. The areas with sparse plant populations are zones of higher weed infestation. Weed management in laser leveled field is relatively easier and requires less labour and time for manual weeding operation due to lesser weed infestation than unleveled one. A reduction of 75% in labour requirement for weeding operation is possible due to precision land leveling. Reduction in weed population in wheat after 30 DAS was recorded under precisely leveled fields in comparison to traditional leveled fields (Jat *et al.* 2009).

Chemical weed control

Herbicides are an integral part of weed management in CA. Use of herbicides for managing weeds is becoming popular as it is cheaper than traditional weeding methods, requires less labour even to tackle difficult-to-control weeds, and allows flexibility in weed management. However, for the sustenance of CA systems, herbicide rotation and/or integration of weed management practices is preferable as continuous use of a single herbicide over a long period of time may result in the development of resistant biotypes, shifts in weed ûora, and negative effects on the succeeding crop and environment. In CA, the diverse weed flora that came up in the field after harvesting of preceding crop must be killed by using non-selective herbicides like glyphosate, paraquat, or ammonium-glufosinate. Non-selective burn-down herbicides can be applied before or after crop planting but prior to crop emergence in order to minimize further weed emergence.

Unlike in conventional system, crop residues present at the time of herbicide application in CA systems may decrease the herbicide's effectiveness as the residues intercept the herbicide and reduce the amount of herbicide that can reach the soil surface and kill germinating seeds. Proper selection of herbicide formulations for application under CA may be necessary to increase its efficacy. For example, pre-emergence herbicides applied as granules may provide better weed control than liquid-formations in no-till systems. Some herbicides intercepted by crop residues in CA systems are prone to volatilization, photo-degradation, and other losses. The extent of loss, however, may vary depending upon their chemical properties and formulations. Herbicides with high vapour pressure, e.g. dinitroaniline herbicides are susceptible to volatilization loss from the soil surface. Climatic conditions and herbicide application methods may also have significant effect on herbicide persistence under CA systems. Crop residues can intercept 15-80% of the applied herbicides and this may result in reduced efficacy of herbicides in CA systems (Chauhan *et al.* 2012). Choosing an appropriate herbicide and appropriate timing is very critical in CA systems as the weed control under no-till systems varies with weed species and herbicides used.

Several low-dose, high-potency, selective, post-emergence herbicides and mixtures are presently available in India for effectively managing weeds in crops like rice and wheat grown in sequence under CA (Table 4).

Herbicide-tolerant crops

Weeds of different types emerge in the field and therefore, the farmers have to use several types of narrow-spectrum herbicides to control them. This weed control method can be very costly and can harm the environment. Weed management, however, could be simplified by spraying a single broad-spectrum herbicide over the field anytime during the growing season. The important contribution of biotechnology has been the development of herbicide-tolerant crops for effective weed management. Several crops have been genetically modified to be resistant to non-selective herbicides. These transgenic crops contain genes that enable them to degrade the active ingredient in an herbicide, rendering it harmless. Herbicide-tolerant crops (HTCs) offer farmers a vital tool in fighting weeds and are compatible with no-till methods, which help preserve top soil. They give farmers the flexibility to apply herbicides only when needed, to control total input of herbicides and to use herbicides with preferred environmental characteristics. Farmers can thereby easily control weeds during the entire growing season and have more flexibility in choosing times for spraying. The HTCs of several common crops, *viz*. soybean, maize, canola and cotton are being used by the growers, and the area under HTCs is rapidly increasing across the globe (Fig. 3). Herbicide resistant crops also facilitate low or no tillage cultural practices, which are considered to be more sustainable.

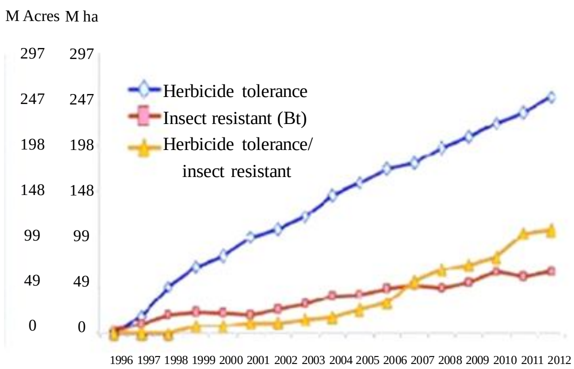

Fig. 3. Global area of biotech crops by trait

Source: James (2012)

Table 4. Promising post-emergence herbicides for weed control in rice-wheat cropping system under CA

Herbicide	Dose (g/ha)	Time of application	Control of weed flora
Rice			
Azimsulfuron	35	20 DAS/ DAT	Annual grasses and some broad leaved weeds
Bispyribac-sodium	25	15-25 DAS/ DAT	Annual grasses and broad-leaved weeds
Chlorimuron+ metsulfuron	4	15-20 DAS/ DAT	Annual broad-leaved weeds and sedges
Pyrazosulfuron	25-30	20-25 DAS/ DAT	Annual grasses and some broad-leaved weeds
Fenoxaprop-p-ethyl	60-70	30-35 DAS/ DAT	Annual grasses, especially *Echinochloa* spp.
Fenoxaprop-p-ethyl + 2,4-D	60 + 500	20-25 DAS/ DAT	Annual grasses and broad-leaved weeds
Fenoxaprop-p-ethyl + almix	60 + 20	20-25 DAS/ DAT	Annual grasses, broad-leaved weeds and sedges
Bensulfuron + pretilachlor	10000	0-3 DAS/ DAT	Annual grasses and broad-leaved weeds
Wheat			
Clodinafop-propargyl	60	25-30 DAS	Annual grasses, especially *Avena* spp.
Metribuzin	175-200	30-35 DAS	Annual grasses and broad-leaved weeds
Sulfosulfuron	25	25-30 DAS	Annual broad-leaved weeds and grasses
Sulfosulfuron + metsulfuron	32	25-30 DAS	Annual grasses, broad-leaved weeds and sedges
Mesosulfuron + idosulfuron	12 + 2.4	20-25 DAS	Annual grasses, broad-leaved weeds and sedges
Isoproturon + metsulfuron	1000 + 4	20-25 DAS	Annual grasses and broad-leaved weeds
Metsulfuron + clodinafop	4 + 60	20-25 DAS	Annual grasses, especially *Avena* spp. and broad-leaved weeds

Adoption of HTCs is the fastest growing agro-technology in several countries of the world, as the area is expanding by 15-20% annually. This is also leading to conservation agriculture-based farming systems, resulting in reduced costs and improved soil health. It is unfortunate that the farmers in some countries, including India are being deprived of such innovations in modern science due to some unfounded apprehensions. Introduction of such approaches will definitely contribute to the livelihood security of farmers and help in bringing about second green revolution in the country. However, 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.

Integrated weed management

Considering the diversity of weed problems, no single method of weed control, *viz.* cultural, mechanical or chemical could provide the desired level of weed control efficiency under CA. Therefore, a combination of different weed management strategies should be evaluated for widening the weed control spectrum and efficacy for sustainable crop production. Integrated weed management system is basically an integration of effective, dependable and workable weed management practices that can be used economically by the producers as a part of sound farm management system. This approach takes into account the need to increase agricultural production, reduce economic losses, risk to human health and potential damage to flora and fauna, besides improving the safety and quality of the environment. Integrated weed management system is not meant for replacing selective, safe and efficient herbicides but is a sound strategy to encourage judicious use of herbicides along with other safe, effective, economical and eco-friendly control measures. The use of clean crop seeds and seeders and field sanitation (weed-free irrigation canals and bunds) 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. 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 competitiveness with a combination of pre- and post-emergence herbicides should be integrated to develop sustainable and effective weed management strategies under CA systems.

Payoff-trade off equilibrium in adopting CA systems

Conservation agriculture is not a panacea to solve all the agricultural production constraints, but offers potential solutions to scientists and farmers to break productivity barriers and sustain natural resources and environmental health. But, for wider adoption of CA, there is an urgent need for researchers and farmers to change the past mindset and explore these opportunities in a site- and situation-specific manner for local adaptation. The current major barriers in spread of CA systems can be summarized as: (i) lack of trained human resources at ground, (ii) non-availability of suitable machinery other than north-western India and no quality control mechanism in place for CA machinery, (iii) competing use of crop residues in rainfed areas, (iv) weed management strategies, particularly of perennial species, (v) localized insect and disease infestation, and (v) likelihood of lower crop productivity if the site-specific component technologies are not adopted. Several factors including biophysical, socio-economic and cultural limits the adoption of this promising innovation by the resource-poor small land farmers of south and south-east Asia. Despite several payoffs, there are also many trade-offs to adoption of CA systems (Table 5).

Conclusions

It is possible to achieve the same or even higher yield with CA as with conventional tillage. Retention of crop residues on soil surface is essential for success of CA in the long-run. Zero-tillage along with residue has beneficial effects on soil moisture, temperature moderation and weed control. However, continued adoption of such systems cause shift in weed flora, and may result in emergence of perennial weeds like *Cyperus rotundus, Cynodon dactylon and Sorgum halepense* in most crops; and others like *Malava parviflora* and *Rumex dentatus* in wheat. Restricting tillage also reduces weed control options and increases reliance on herbicides. Altering tillage practices change weed seed depth in the soil, which play a role in weed species shifts and affect the efficacy of control practices. The CA is a machine-, herbicide– and management-driven agriculture for its successful adoption. Integrated weed management involving chemical and non-chemical methods (residue, cover crops, varieties *etc.*) is essential for success of CA systems in the long-run.

Research needs

Weed management research is lacking under conditions of CA. Major efforts should be made to get profound understanding of weed, disease and insect responses to no-till soil and microclimate conditions

Table 5. Two sides of conservation agriculture

Payoffs	Trade-offs
• Timeliness of operations • Reduces soil erosion • Conserves water • Improves soil health • Reduces fuel and labour costs • Reduces sediment and fertilizer pollution of lakes and streams • Sequesters carbon • Climate smart production practices	• Mindset: transition from conventional farming to no-till farming is difficult • Relatively knowledge intensive • CA equipments are not available locally and adds on cost for transport • Reliance on herbicides and their efficacy • Prevalence of weeds, disease and other pests may shift in unexpected ways • Need to refine nutrient and water management practices

Source: Adapted from Huggins and Reganold (2008); Sharma *et al.* (2012)

on long-term basis. Research should be conducted on soil biological aspects and on rhizosphere environment under contrasting soils and crops, and with a special emphasis on optimizing fertilizer management under CA. Because herbicides cannot be eliminated from no-tillage, crop management, degradation pathways, adsorption–desorption and transport processes of herbicides remain important research areas. There is a need to carry out an analysis of factors affecting adoption and acceptance of no-tillage agriculture among farmers. Development of integrated weed, disease or pest control strategies is of paramount importance under conservation agriculture systems.

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Conservation agriculture and weed management in south Asia: perspective and development

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ABSTRACT

It was 20 years ago which marked the beginning of conservation agriculture (CA) with introduction of zero-tillage (ZT) in wheat to (1) reduce cultivation cost so that farmers can afford to purchase new but expensive alternate herbicides for the control of herbicide-resistant population of *Phalaris minor* Retz., the most troublesome weed of wheat, and (2) reduce land preparation period for timely wheat planting. Worldwide, CA has spread mostly in the rain-fed agriculture but India witnessed its success more in irrigated rice-wheat cropping systems (RWCS) of the Indo-Gangetic Plains (IGP). High input based crop culture in the North West IGP has enabled weeds such as *P. minor* in wheat and *Echinochloa crusgalli* (L.) Beauv. in rice to dominate the weed flora. In wheat, zero tillage (ZT) is widely adopted by farmers in North West India and recently it is widely accepted by farmers in the eastern IGP also. In North West India, under ZT wheat, emergence and biomass of *P. minor* was reduced, but weed flora shifted toward more broad-leaf weeds such as *Rumex dentatus* (L.). In the Eastern IGP, perennial weeds such as *Cynodon dactylon* L. Pers. and *Cyperus rotundus* L. are also problematic weeds in some cases under ZT. In rice, the focus now is on dry direct-seeded rice (DSR) and machine transplanting of non-puddled rice (MTNPR) as an alternate option to puddled transplanted rice (PTR). Shifting from PTR to DSR results in changes in tillage, crop establishment method, water and weed management which often results in changes in weed composition and diversity. Weedy rice has emerged as a major threat for DSR in countries where DSR is widely adopted. In the eastern IGP, *Physallis minima* and *Cyperus rotundus* are also becoming major problematic weeds in DSR. Increased net profit for farmers by using this new technology was the main reason for rapid adoption of ZT. Since 2009, the Cereal Systems Initiatives for South Asia (CSISA), project funded by Gates Foundation and USAID and implemented by four consultative group on International Agricultural Research (CGIAR) (CG) Centers (CIMMYT, IRRI, IFPRI and ILRI) in collaboration with national partners, has explored options for sustainable intensification across the IGP, including CA-based crop management. This paper highlights the weed management scenario in conservation agriculture in India.

Key words: Conservation agriculture, Herbicide resistance, South Asia, Weed management, Zero tillage

Farmers in India adopt conservation tillage (CA) because, in the short-term, the technology can reduce operating costs, increase profitability and make better use of resources especially labor, water, and land. In the long run, farmers adopt these technologies because of benefits associated with sustainable intensification of cropping systems. In the present era, the climate change and sustainability of cropping systems have emerged as an area of importance. These are sound reasons for introduction of CA in South Asia. It was 20 years ago which marked the beginning of CA with introduction of zero-tillage (ZT) in wheat to (1) reduce cultivation cost so that farmers can afford to purchase new but expensive alternate herbicides for the control of herbicide-resistant population of *Phalaris minor* Retz., the most troublesome weed of wheat and (2) reduce land preparation period for timely wheat planting (Harrington *et al.* 1992, Malik and Singh 1995, Malik *et al.* 2002). Simplification of weed flora have had its effect on the adoption of herbicides in both rice and wheat and in the same way CA will have its impact on shift in weed flora and adoption of improved weed management in India. Worldwide, CA has spread mostly in the rain-fed agriculture but India witnessed its success more in irrigated rice-wheat cropping systems (RWCS) of the Indo-Gangetic Plains (IGP). How radical shift in weed flora may or may not happen with the shift in tillage and crop establishment methods in South Asia has been explained in the recent publications (Kumar and Ladha 2011, Kumar *et al.* 2013)

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Weed problems in rice-wheat cropping systems

High input based crop culture in the North West Indo-Gangetic Plains IGP has enabled weeds such as *P. minor* in wheat and *Echinochloa crusgalli* (L.)

Beauv. in rice to dominate the weed flora. In the Eastern IGP, where input use is less and productivity levels are low, weed flora is dominated by both annual grasses and broad-leaved weeds and some perennial grasses and sedges. However, the increasing use of more inputs has meant a shift in flora in favor of *P. minor* and *E. crusgalli* in the Eastern IGP also. The high input based crop management is mainly responsible for fostering the dominance of a simplified weed flora. Simple weed flora leads to the adoption of herbicides. After long periods of continuous use of a single herbicide, isoproturon, accompanied by poor spray techniques resulted in evolution of resistance in *P. minor* against isoproturon in 1990s. Resistance was so severe that it led to large reductions in wheat productivity in North West IGP in 1993-94. The major challenge facing the RWCS in India now is to sustain its long-term productivity. There are signs that the productivity and economic gains of this cropping system are consistently becoming smaller.

In wheat, zero tillage is widely adopted by farmers in North West India and recently it is widely accepted by farmers in the Eastern IGP also. In North-west India, under ZT wheat, emergence and biomass of *P. minor* was reduced, but weed flora shifted toward more broad-leaf weeds such as *Rumex dentatus* (L.). The higher population of *R. dentatus* under ZT wheat after puddled transplanted rice (PTR) may be because the seeds of this species concentrate on the soil surface under ZT than under conventional tillage (Chhokar *et al.* 2007, 2009). After puddling operations in rice, it has been seen that seeds of *R. dentatus* float (because seeds are light and have a perianth) and accumulate on the soil surface and remain on soil surface in a ZT wheat system; in contrast, under CT wheat, seeds are buried during tillage operations and hence emergence is reduced. Since seeds of *R. dentatus* are sensitive to burial depth, it has been found that seeds buried at a depth of 4 cm could not emerge (Dhawan 2005). In the Eastern IGP, perennial weeds such as *Cynodon dactylon* L. Pers. and *Cyperus rotundus* L. are also problematic weeds in some cases under ZT.

In rice, the focus now is on dry direct-seeded rice (DSR) and machine transplanting of non-puddled rice (MTNPR) as an alternate option to puddled transplanted rice (PTR). The weed growth medium in rice is different in different ecological zones based on the rice crop establishment method. In DSR, weeds are more diverse and severe compared to PTR because of (1) lack of flooding at early stage to control initial flush of weeds and (2) weeds in DSR emerge early or simultaneously with the emergence of crop, hence more competitive to emerging seedlings than transplants (Kumar and Ladha 2011). The imbalance between crop and weed growth makes this system vulnerable to losses caused by weeds. Shifting from PTR to DSR results in changes in tillage, crop establishment method, water and weed management which often results in changes in weed composition and diversity. Our inability to predict and manage weeds for those species which will dominate with this shift poses major threat for the sustainability of DSR production systems. Adoption of DSR may result in shifts in weed flora towards more difficult-to control and competitive grasses and sedges. Weedy rice has emerged as a major threat for DSR in countries where DSR is widely adopted (Kumar and Ladha 2011). In the IGP, in addition to *Echinochloa* species, other difficult-to-control grasses such as weedy or volunteer rice, *Leptochloa chinensis*, *Dactyloctenium aegyptium* and *Eragrostis japonica* have started dominating in DSR. In the eastern IGP, *Physallis minima* and *Cyperus rotundus* are also becoming major problematic weeds in DSR.

Typically in the Eastern zone, rice is grown as upland rice fully grown in rainfed dry land and lowland rainfed rice in which soil is puddled for transplanting or wet seeding. Much of the rainfed rice in lowland plains is dominated by *Echinochloa crusgalli* and *Paspalum scrobiculatum* among annual grasses, *Cyperus iria* L., *Cyperus difformis* L. and *Fimbristylis miliacea* (L.) vahl among sedges and *Sphenoclea zeylanica* Gaertn and *Monochoria vaginalis* (Burn f) Presi among broad-leaf weeds. Two farmer friendly booklets on weed flora of wheat and rice and their management have been published recently (Malik *et al.* 2012, 2013)

Participatory approach

Farmers' participatory approach is the process of collaboration that optimizes greater technology extension and then adding value to it. It gives an extra-ordinary access to modify technologies. It relies on farmers' experimentation and farmers' interaction with important market opinion, backstopping and follow up research. Even longterm trials may be monitored to anticipate and deal with any kind of undesirable consequences that may arise out of recommendations. Scaling out strategies have been discussed by Coventry *et al.* (2003). Increased net profit for farmers by using this new technology was the main reason for rapid adoption of ZT. Zero tillage has been accepted; it has to some extent, delayed resistance, but could not prevent the development of cross resistance against the alternate herbicides recommended in 1997-98.

Among scientist, there is increased interest to extend CA to the RWCS as a whole extending it further in maize based cropping systems. They are now experimenting with DSR, establishing rice without soil puddling and using ZT and permanent bed planting systems. In the rice phase, weed control is more difficult and use of residue mulch, development of equipment to seed into loose residues, efficient use of herbicides, crop diversification through rotations, stale seedbed techniques and competitive varieties will all be included in an integrated approach to resolve new and emerging problems as we go along. An expanded stakeholder partnership including innovative farmers will allow faster success in this endeavor. Use of herbicide resistant rice and other crops would also help resolve the weed problem in future.

Cropping system optimization

During last five decades, productivity growth of cereal in Bihar and Eastern Uttar Pradesh which constitutes the Eastern Indo-Gangetic Plains (EIGP) has been markedly slower than the Western IGP (WIGP). During green revolution phase, introduction of high yielding varieties helped farmers to improve their yields across the IGP. To meet contemporary challenges to improving crop performance among the dominantly small holder agriculture in the EIGP, it is essential that elite varieties are combined with improved crop management practices that will help farmers cope with water limitations, high energy costs, and a contracting market for agricultural labour. In rice wheat cropping system (RWCS) of these ecologies, late transplanting of rice followed by late seeding of wheat leads to a cascading sequence of abiotic stresses that reduce the yield of both crops and hence system productivity. Since 2009, the Cereal Systems Initiatives for South Asia (CSISA), project funded by Gates Foundation and USAID and implemented by four CG Centers (CIMMYT, IRRI, IFPRI and ILRI) in collaboration with national partners, has explored options for sustainable intensification across the IGP, including CA based crop management.

In the present study (3 years for rice and 4 years for wheat), on-farm participatory research in Bihar and Eastern UP has identified several critical entry points for improving cereal systems productivity. Major gains in the cropping system productivity are possible with DSR, MTNPR and early wheat sowing under ZT. The study area included five districts of Eastern UP and 4 districts of Bihar. For example, in 2012 the average paddy yields of 202 DSR, 95 MTNPR and 14 PTR trials in Eastern UP was 5.6, 6.0 and 5.3 t/ha, respectively for DSR, MTNPR and PTR with attendant gains in net returns and timeliness of harvest for both DSR and MTNPR. During the last 4 years, grain yield of wheat declined by approximately 50% with delays in wheat sowing from November to December due to the influence of terminal heat stress. Sowing in the first 20 days of November resulted in grain yield of wheat in the range of 5.4-5-6 t/ha under zero tillage (ZT) compared to a range of 4.2-4.7/ha under conventional tillage (CT). When the sowings were done after December 10, the grain yield of wheat was in the range of 3.4-3.7 t/ha under ZT and 2.7 -3.2 t/ha under CT. Results demonstrate that it is possible to increase both rice and wheat yields by introducing DSR and MTNPR technologies and to further advance the timing of wheat sowing by using ZT technology. These management approaches hold the promise of providing a stable foundation for sustainable intensification in the EIGP under contemporary climates and projected climate changes.

Herbicide use

New herbicides promised to control *P. minor* in wheat are now showing the signs of cross resistance (Walia *et al.* 1997). Development of effective weed management strategies for DSR has played an important role in the expansion of area under DSR. Diverse and complex weed flora and prolonged weed emergence pattern contribute to the complexity of weed management in DSR. In North West IGP, integrated weed management strategies based on herbicides and manual weeding has been successful in DSR. Based on on-farm and on-station trials, bispyribac-sodium 25 g/ha sprayed at 15-25 days after sowing (DAS) was extremely effective against *Echinochloa* species and some broad-leaf weed (BLW) and sedges in DSR and transplanted rice. Tank-mix of azimsulfuron 20 g/ha or pyrazosulfuron 25 g/ha with bispyribac-sodium 25 g/ha has also provided excellent control of complex weed flora including BLW and sedges including purple nutsedge. Azimsulfuron alone also provided effective control of most BLW and sedges. Halosulfuron alone at 60 g/ha was found excellent on sedges including *C. rotundus*. Many researchers have reported that pendimethalin (pre-emergence) followed by post-emergence application of bispyribac or azimsulfuron or bispyribac-sodium + azimsulfuron 15-20 DAS yielded similar to weed-free conditions (Walia *et al.* 2008, Kumar and Ladha 2011, Yadav *et al.* 2013).

In the EIGP, most herbicides available in the market are used in transplanted rice. This has put DSR farmers under pressure to use alternate methods like hand weeding which is becoming costly and scarce. Bispyribac-sodium + pyrazosulfuron or halosulfuron or azimsulfuron ares potential mixture which can control complex weed flora dominated by sedges including *C. rotundus* in these ecologies. The DSR based herbicides and/or their mixtures are being accepted in transplanted rice as well. Some weeds like *L. chinensis, D. aegyptium* and *Eragrostis* spp. are not controlled by bispyribac-sodium. For these weeds, fenoxaprop-ethyl with safner (Ricestar) at 60-90 g/ha or cyhalofop–butyl or propanil have been found effective. Pre-emeregnce herbicides such as pendimethalin at 1000 g/ha or oxadirgyl at 90 g/ha are also found very effective against these weeds.

Herbicide resistance management

Herbicide resistance in *P. minor* against isoproturon was the most serious problem in wheat in RWCS during early 1990s. Efforts on herbicide resistance management before 1996-97 were concentrated around alternate crops (Malik *et al.* 2002). The problem of resistance was so serious that farmers in Haryana started sowing sunflower to exhaust the seed bank of *P. minor*. Crop rotation was possible only in small area and farmers needed a viable technology for herbicide resistance management. Zero-tillage made it possible to achieve three major objectives leading to create competition in favour of crop. These are optimum plant population, seeding at a time which is not conducive to *P. minor* emergence and accurate fertilizer placement. Zero-tillage in wheat reduces the emergence rate of *P. minor* compared to CT (Franke *et al.* 2007). In a study conducted by Franke *et al.* (2007) at farmer's field in Haryana, correlating the number of germinable *P. minor* seeds in soil with the number of *P. minor* seedling emerged; it was found that ZT reduced the emergence rate of first flush of *P. minor* by 50% (Fig. 1). Rate of emergence of second and third flush was also lower in ZT plots compared to CT plots (Fig. 1). The first flush of *P. minor* is more damaging to the crops compared to later flushes and ZT is found relatively more effective in reducing first flush than other flushes.

Reduced population of this weed does not mean that *Phalaris* problem will be solved by ZT alone. It also does not mean that farmers will stop using herbicides. Long term trials at different sites in different villages indicate that farmers can skip herbicide once in 3-4 years. Emergence of very heavy population during early phases of crop cycles can be prevented with ZT. There is a constant danger that this weed will constantly evolve resistance to new herbicides. Using herbicides alone is not a long term solution for managing resistance. Details of resistance development and its management using integrated approach with focused attention on ZT have been published (Malik *et al.* 2002, Franke *et al.* 2007, Kumar *et al.* 2013).

Zero-tillage when combined with residue mulch improve weed control in CA based systems (Kumar *et al.* 2012). When rice residues are kept on soil surface as mulch, reduced weed emergence of key weeds of wheat in the range of 45-99%, depending on species and mulch amount. Emergence of *P. minor*, *Chenopodium album*, and *R. dentatus* was inhibited by 45, 83 and 88%, respectively at 6 t/ha rice residue load compared to without residue mulch (Kumar *et al.* 2013). With 8-10 t/ha of rice residue mulch, *P. minor* emergence was inhibited by 65% and that of *C. album* and *R. dentatus* by >90%. ZT also facilitates timely wheat planting which further create ecological conditions in favor of crop than *P. minor*. When ZT in wheat is combined with residue mulch (6-8 t/ha) and early planting (25 October), the emergence of *P. minor* was reduced

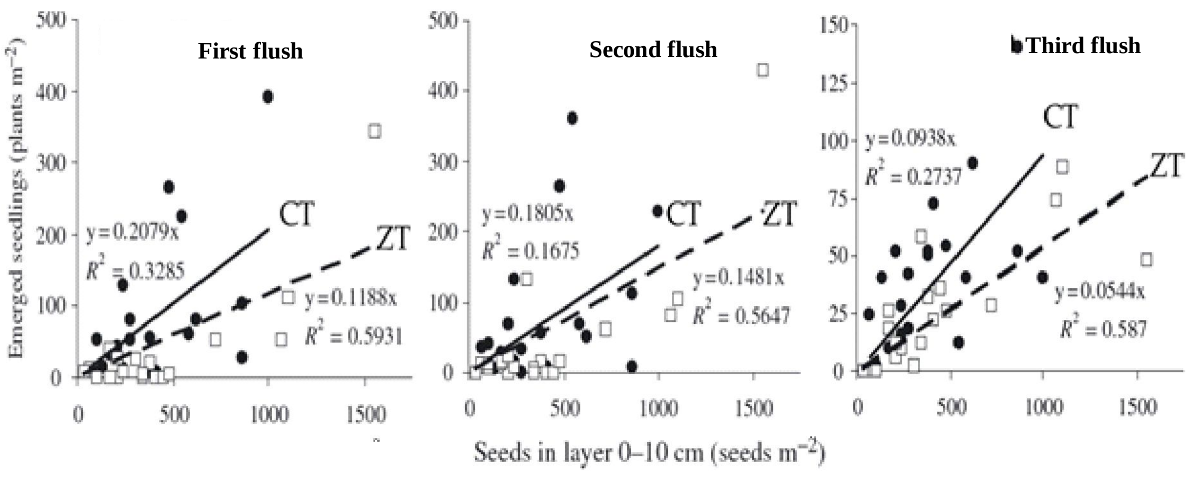

Fig. 1. Emergence rate of the first, second, and third flush of *Phalaris minor* under conventional (●), solid line) and zero-tillage (□), dashed line) in wheat

Source: Franke *et al.* (2007).

by 83-98% compared with normal (mid November) or delayed (25 November) planting without residue. In a long term experiment at CSSRI Karnal, where wheat is planted early (30 October) under ZT with full rice residue as mulch, weeds in wheat are managed without any herbicide applications from last two years after effective control in initial 2-3 years.

The majority of farmers in RWCS, especially in North Western IGP, burn residues of previous rice crop for its rapid disposal before wheat sowing because it can interfere with drilling. However, recent advances in planting technology have made it possible to sow wheat successfully into heavy residues and facilitated the use of residues as mulches for weed suppression. In particular, turbo happy seeder can seed wheat in heavy residue mulch of up to 8 to 10 t/ha without any adverse effect on crop establishment.

In addition to the suppressive effects on emergence of weeds, residues can contribute to weed seed bank depletion through seed predation. Preliminary studies conducted in India indicate that post dispersal seed predation of *P. minor* during a 1-week period between wheat harvest and rice planting was 50 to 60% under ZT with residue compared with 10% under CT (Kumar *et al.* 2013). This could be one of the many reason for lower population of *P. minor* under ZT.

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Biology and control measures of *Orobanche*

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ABSTRACT

Orobanche or broomrape obligate, troublesome root parasite which completely depends on the host plant to complete its life cycle. The host plants of *Orobanche* includes crucifers such as oilseed rape (*Brassica* spp.), broad bean (*Vicia faba*) and other crops belonging to Apiaceae, Asteraceae, and Solanaceae families. In India, *Orobanche* has emerged as a major threat to rapeseed mustard production. Many farmers have abandoned the cultivation of mustard under the threat of this parasitic weed. *Orobanche* infestation is mostly confined to major mustard growing states of northern Rajasthan, Haryana, Punjab, Western UP, and North East Madhya Pradesh. In Andhra Pardesh, 50% area under tabacco (40,000 ha) is infested with *Orobanche* and causing 50% crop losses. In Karnataka state, 90% area under tobacco is infested with this weed with 50-60% yield losses. Tomato crop is also infested with *Orobanche* spp. in Mewat and Bhiwani districts of Haryana. Depending upon the extent of infestation, environmental factors, soil fertility, and the crops' response damage from *Orobanche* can range from zero to complete crop failure. *Orobanche aegyptiaca* is the most dominating species in India; however, localized infestation of two other species namely *O. cernua* and *O. ramosa* has also been observed to some extent. In spite of continuous and extensive research by the scientists, no single method for effective and economical management of *Orobanche* is available. Integration of cultural, preventive and chemical methods is required in spite of its costly inputs. Following methods may be adopted in integration fashion: crop rotation with non-host crops like wheat, barley and chickpea depending on the irrigation facilities; delayed sowing (25 October - 10 November) of mustard supplemented with higher seed rate; use of organic manures in combination with increased fertilizer N dose for enhancing crop vigour; two sprays of glyphosate at 25 g/ha at 30 DAS and 50 g/ha at 55 days after sowing provided the crop does not experience any moisture stress at the time of spray; and hand removal/pulling of left-over emerging shoots before flowering to reduce weed seed bank in the soil

Key words: Biology, Cop rotation, Infestation, Mustard, Delayed sowing, Management, Tomato

Parasitic plants belong to 17 different families, but only eight of these contain plants that are considered weeds. Witch weed (*Striga* spp.) and broomrape (*Orobanche* spp.) are the most economically important notorious and destructive parasitic weeds in cultivated crops. In this paper, discussion is focused primarily on biology and management of broomrapes in various crops in context to their effectiveness, advantages, disadvantages, simplicity *etc.*

Orobanche or broomrape (*Orobanche* spp.) locally known as margoja, rukhri, khumbhi or gulli or bhuiphod is a phanerogamic, obligate, troublesome root parasite that lack chlorophyll (Baccarini and Melandri 1967, Saghir *et al.* 1973) and obtain carbon, nutrients, and water through haustoria which connect the parasites with the host vascular system. (Dorr and Kollmann, 1976, Press *et al.* 1986, Punia *et al.* 2012). The attached parasite functions as a strong metabolic sink, often named "super-sink", strongly competing with the host plant for water, mineral nutrition and assimilate absorption and translocation. Depending upon the extent of infestation, environmental factors, soil fertility, and the crops' response damage from *Orobanche* can range from zero to complete crop failure (Dhanapal *et al.* 1996). This parasitic weed has the tendency to proliferate well in coarse textured soils with high pH, low in nitrogen status having poor water holding capacity where the crop cultivation is either rain fed or dependent on sprinkler systems for irrigation.

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Geographical distribution

Broomrapes belong to the family Orobanchaceae. The genus *Orobanche* has more than 150 species (Musselman 1980) among which only a few parasitize agronomic crops. Broomrapes vary in host range, some parasitizing a broad range of crops, whereas others are more specific. The majority of broomrapes are found in the warm and temperate parts of the Northern Hemisphere, especially the Mediterranean region (Sauerborn 1991), but some species have spread to many other parts of the world. Globally, root parasitism of *Orobanche* to numerous important broad-leaf crops including common vetch (*Vicia sativa* L.), crucifers such as oilseed rape (*Brassica* spp.), broad bean (*Vicia faba* L.) and other crops belonging to Apiaceae, Asteraceae, and Solanaceae families have been reported (Goldwasser *et al.* 1997, Hodosy 1981, Ismael and Obeid 1976, Sauerborn 1991), especially in Mediterranean region Southern, Northern and Eastern Europe, Africa, New Zealand, Australia, North, Central and South America. *Orobanche aegyptiaca* occurs mainly in Southeastern Europe, Northeastern Africa, and the Middle East, whereas *O. ramosa*, which is closely related to *O. aegyptiaca*, is mostly found in the Middle East. *O. cernua* and *O. cumana* are primarily distributed in the Middle East, Southern and Eastern Europe, and Northern Africa.

Orobanche ramosa has the widest host range, parasitizing many solanaceous crops such as potato (*Solanum tuberosum* L.), tobacco (*Nicotiana tabacum* L.) and tomato (*Lycopersicon esculentum* Mill.), members of brassicaceae, leguminaceae, and several other families. *Orobanche aegyptiaca*. has a host range similar to that of *O. ramosa*, and is also parasitic on carrot (*Daucus carota*), legumes such as common vetch (*Vicia sativa*), and crucifers including oilseed rape (*Brassica napus*). In the Middle East, *O. crenata*. has a debilitating effect on broad bean (*Vicia faba*), and also attacks carrot. *O. cernua* and *O. cumana* Wallr. are extremely damaging to sunflower (*Helianthus annuus* L.).

In India, *Orobanche* spp. has emerged as a major threat to rapeseed-mustard production in northern Rajasthan, Haryana, Punjab, and north east Madhya Pradesh. In Andhra Pardesh, 50% area under tobacco (40,000 ha) is infested with broomrapes and causing 50% crop losses. In Karnataka, 90% area under tobacco is infested with this weed with 50-60% yield losses in some areas (Dhanapal *et al*. 1998). Yield losses due to *Orobanche* spp. in tobacco growing areas of Tamil Nadu, Gujarat and Maharastra is also reported to be very high. Tomato and brinjal crops are also infested with *Orobanche* spp. in Mewat and Bhiwani districts of Haryana state (Anonymous 2013). Even *Orobanche* infestation on cauliflower and cabbage was observed in Dadri areas of Bhiwani, Haryana.

Weed biology

Plant characteristics: Broomrapes are dicotyledonous annual plants (10-60 cms tall, depending upon the species) and recognized by its yellow to straw coloured stems, bearing yellow, white,or blue, snap dragon like flowers. The leaves are merely triangular scales and both stem and leaves show absence of chlorophylls. Flowers appear in the axils of leaf and are white and tubular. The fruits are capsular and contain numerous tiny black seeds. Broomrapes reproduce only by seeds which are usually dark brown, oval shaped, measure 0.35 x 0.25 mm (Kadry and Tewfic 1956), dust sized weighing 3 to 6 µg (Parker and Riches 1993) and very difficult to recognize without a magnifying microscope. Each capsule contains 600-800 seeds and a single plant may produce more than one lakh seeds depending upon species. Seeds have a pattern of raised ridges (rough surface) and hardened testa, surrounding a fatty endosperm that has an undifferentiated embryo at one end (Kadry and Tewfic 1956). Once ripe, some seed may remain in the capsule but majority of them fall to the ground. Seeds can emerge from as deep as 15 cm below the soil surface. Seed generally remains viable in soil for 10 to 13 years (Brenchley 1920) but the viability can be up to 20 years (Puzilli 1983).

Seed dispersal mechanism: Weed dispersal is mostly confined to contaminated crop seeds owing to poor quarantine services, however, animal grazing, unfermented contaminated manures, wool, fur and farm machinery could be the other sources of seed dissemination. The seeds can easily pass unharmed through animal's alimentary tract and infest the host plants (King 1966). Wind and flowing water contributes negligible to seed dispersal as the seeds are heavy enough to be dispersed away. The seeds do not float in water because of their high specific gravity and once surface tension is broken they sink in water. Thus, wind and floodwater is a low risk vector.

Seed dormancy and germination: Seeds of *Orobanche* generally remain dormant and require a post-harvest ripening period for their germination in response to chemical stimulation (alectrol/orobanchol) from the host plant roots. The stability of the chemical stimulant is very short-lived in the soil. Before germination, seeds must undergo conditioning period under suitable temperature and moisture conditions (Van Hezewijk *et al.* 1993). These conditions ensure that only seeds with in the rhizosphere of an appropriate host root will germinate to contact a host root before exhausting its limited energy resources. Suitable temperatures of conditioning of *Orobanche* seeds are between 15-20 °C for at least 18 days for maximum germination. However, prolonged storage in these conditions causes the seeds to enter secondary dormancy (Van Hezewijk *et al*. 1994a). Increasing storage temperatures increases the percentage of seeds going dormant, there is also some decrease in viability at higher temperatures, with viability reaching zero at 80 °C (Mauromicale *et al*. 2000). The decrease in viability conforms to a sigmoidal curve proportional to moisture and temperature levels (Kebreab and Murdoch, 1999b). For *O. ramosa*, the conditioning period appears to be shorter, with 7 days at 21 °C being sufficient in one trial (Zehar *et al*. 2002).

Optimum temperatures for conditioning and germination are different among broomrape species. Studies on the effect of temperature on germination of *O. aegyptiaca*, *O. crenata*, and *O. cumana* indicated that every species had a specific optimum temperature range for germination and development which generally reflected its geographical distribution (Sauerborn 1991). Kasasian (1973a) showed that optimum tempera-tures for both conditioning and germination were about 18 °C for *O. crenata* and about 23 °C for *O. ramosa*. Similarly, Weldeghiorghis and Murdoch (1996) reported an optimal temperature of 18 °C for *O. crenata* germination. Van Hezewijk *et al*. (1991b) reported an optimum conditioning temperature of 15 to 20 °C for *O. crenata*. Although temperature is known to influence germination in broomrape, its effect on subsequent development of the parasitic seedling has not been studied. Soil pH (within the normal range of arable soils) has little influence on germination. Germination of *O. crenata* was not reduced at any pH between 5 and 8.5, although subsequent growth of the radicle was favoured by higher pH within this range (Van Hezewijk *et al*. 1994c).

Formation of haustorium and host-parasite attachment : Following the conditioning phase, germinated seed produces a germ tube or radicle in close proximity to the host plant roots that elongates chemotropically and develops an organ of attachment 'the haustorium', which serves as a bridge between the parasitic weed and host plant to drive water, mineral nutrients and carbohydrates from the host plant. The radicle elongates by cell division and attaches itself to the host plant roots mainly in the region of root elongation and absorption (Foy *et al*. 1989, Parker and Riches 1993). The tip of the radicle enlarges, subsequently the haustorial tissue penetrates the epidermis and cortex tissues, and ultimately fuses in to the root vascular system and establishes connections with the host root vascular system by enzymatic degradation, rather than mechanical destruction (Kujit1977, Joel *et al*. 1988, Dorr 1996)

The development of a functional attachment can depend on favourable conditions, such as temperature. *Orobanche* spp. that normally parasitize carrots may fail to get past the initial stage if soil temperatures are too high (Eizenberg *et al*. 2001). *Orobanche* draws its nutrition from the host phloem by direct cell contact. By draining carbohydrates, it can force the host to increase its rate of photosynthesis (Hibberd and Jeschke 2001).

Reproductive phase: The part of the broomrape seedling swells outside the root of host plant to form a tubercle. Within 1-2 weeks, a shoot bud develops on the tubercle producing a flowering spike which elongates, and emerges outside the surface soil. Within a period of 15-20 days, the parasitic weed completes its life cycle and shed thousands of seeds per plant (Pieterse 1979, Foy *et al*. 1989, Holm *et al*. 1997). Findings of Dinesh and Dhanpal (2012) on biology of *O. cernua* revealed that broom rape spikes started emerging above ground from 43-58 days after transplanting, flowering was completed in 7-13 days after emergence while stem drying was completed by 26-38 days after emergence of spike and it completed its life cycle by 37-50 days after emergence.

Management of *Orobanche*

Why *orobanche* is difficult to control?: Compared with non-parasitic weeds, the control of *Orobanche* has been proved to be exceptionally difficult in agricultural crops due to its underground location, close association with host plant roots, complex mechanisms of seed dispersal, germination, and longevity (Cubero and Moreno 1979, Puzzilli 1983, Foy *et al*. 1989, Linke and Saxena 1991a). Because the parasite germinates only in response to host root exudates and then attaches and develops underground on the host plant for the major part of its life, it is inaccessible to conventional control methods such as tillage and herbicide treatments. Furthermore, when the plant becomes visible above ground, much of the damage has already been done and control would be futile. The late appearance of parasite shoots above the soil and the lack of a photosynthetic system as a potential herbicide target does not seems to be practically feasible. The characteristics of *Orobanche* seeds account for much of the difficulty in controlling this parasitic weed. The extremely small seeds produced in vast numbers and seed longevity in fields for 13 years (Parker and Riches 1993) and in Israel up to 35 years (Kleifeld, unpublished), easily dispersal of tiny seeds to near and far by wind, water and livestock are the major factors causing hindrance in developing control measures. Human practices are significantly responsible for distributing *Orobanche* seeds by transporting and using contaminated agricultural vehicles, farm implements and produce containers (by direct seed contamination or through clinging of contaminated soil). Further parasite seed distribution is caused by transportation of contaminated plant material (such as crop seeds and hay) and contaminated soil and manure movement. The use of organic manure from livestock fed with contaminated hay is a cause of further seed dispersal, since the parasite seeds do not lose their viability while passing through animal's digestive systems (Jacobsohn *et al.* 1987).

Several means for managing broomrape have been tried over the years, albeit with somewhat limited effectiveness. Neverthless, following management options may be employed in an integrated manner to manage the orobanche.

Preventive method

The strength of broomrape lies in its ability to form a bank of seeds in the soil. A management or eradication program must aim at reducing this seed bank, while minimising the production of new seeds and their dispersal to new sites. Quarantine is therefore an essential element in control or eradication programs. The best option for winning against broomrapes is avoiding the fight. It is not possible when the fields are already infested with the seeds, but preventive measures must be taken into consideration to avoid spreading the infestation into neighbouring fields.Since massive amounts of tiny seeds are produced continuously for many weeks and are easily dispersed away by air, water and soil, it is almost impossible to prevent seed transfer from a heavily infested field to its close surroundings. In such cases the only preventive method is the discontinuation of growing *Orobanche* host crops, but this does not seems to be practically feasible because of compulsion of farmers to cultivate crops being more suitable and remunerative than other competitive crops under the existing agro-climatic conditions.

Preventive measures could be more effective if the initial specific infestation is sparse and timely precautionary measures are being adopted to counter long distance seed dispersal. The individual farmer could be held responsible, but in most cases the cooperation with neighbours and intervention by local, regional or national agencies is required.

Jacobson (1986) listed some phyto-sanitary measures for avoiding the seed dispersal of *Orobanche* from infested fields to new areas are as under:

- Use healthy and certified planting material of improved varieties free from weed seed contamination.
- Clean farm machinery and equipments to prevent the movement of infested soil to newer areas.
- Use well-rotten decomposed farm yard manure, if needed. Prevent weed seed dispersal by wind or water erosion and farm animals. Since *Orobanche* seeds may pass easily through digestive system of the animals without losing viability, so grazing or feeding hay from infested fields should be prohibited/restricted.
- Do not use irrigation water from *Orobanche* contaminated ponds or reservoirs.
- Practice deep tillage during hot summer months. Placement of weed seeds below 20 cm soil depth was observed to reduce the emergence; however, buried seeds could be brought back by subsequent tillage operations.
- Collect parasite weeds prior to flowering, and do not throw them at random, rather collect at a place and burn.

Cultural method

Crop rotation: A crop rotation system includes *Orobanche* host crops, trap crops and catch crops and non-host crops. Most publications and reviews dealing with *Orobanche* control and management describe crop rotation as a strategy for reducing parasite infestation, but only few suggest concrete guidelines. One exception is the proposal of rice cropping in which flooding throughout the growing season destroys *Orobanche* seeds (Sauerborn and Saxena 1987, Parker and Riches 1993). Theoretically, repeated planting with non-host crops for many seasons should deplete the parasite seed bank in the field. However, we have evidence of very heavy O. *aegyptiaca* infestations of fields after 30-35 years of repeated non-host cultivation and cases of O. *crenata* infestations following more than 20 years of fanning various non-hosts. There is an agreement that monoculture with the same *Orobanche* host crop, or with other hosts of the same *Orobanche* species, rapidly increases *Orobanche* infestation. We have documented evidence that a small spot of infestation could develop into a large-scale heavily infested field as a result of 2-3 years of mono cropping (Kleifeld unpublished).

Crop rotation of mustard with non-host crops like wheat, barley, chickpea *etc*. is the most effective and commonly used management strategy for reducing the weed seed bank in heavily infested areas. The major restriction in adopting crop rotation in long-run is the longer viability of its seeds. Thus, heavy infestations may remain in a field despite absence of host crops for several years. Weed seeds buried in the soil beneath the crop root zone can be brought up to surface soil as a result of subsequent ploughings, germinate and provide competition to the host crop in later years. Frequent planting of susceptible crops on the same field should be avoided and as far as possible grow mustard in alternate years with diverse growing habit genotypes (Braun *et al.* 1984).

Trap and catch crops: Kleifeld *et al.* (1994) justified the importance of using ‘trap crops yielding suicidal parasite germination’ as a management option for reducing *Orobanche* seed bank in the infested fields. These crops exude stimulants that induce *Orobanche* seed germination but no viable attachment to the host plant roots is established and the weed seedlings withers away and die up and ultimately their seed bank in the soil gets reduced. Resistant varieties that induce parasite seed germination, but do not support the young parasite after attachment, may serve an excellent trap crops as well (Goldwasser *et al.* 1997, Eizenberg 2002). In Indian conditions, at Agricultural Research Station, Nepani (Karnataka), sun hemp and green gram proved to be promising trap crops for *Orobanche cernua* control where tobacco is grown in long growing (Kharif and Rabi) seasons (Dhanapal and Struik 1996). Maize and snap bean has also been found to stimulate germination of *Orobanche* seed bank by 74 and 71%, respectively and helped to increase seed yield of tomato in the 3rd season (Abede *et al.* 2005). Acharya *et al.* (2002) noticed that a local cultivar of *Brassica campestris* has been used as a catch crop in Nepal, reducing the *O. aegyptiaca* seed bank by around 33.35 per cent. Experimental results in Tehran indicated that using trap crops namely sesame, brown indian-hemp, and common flax and black-eyed pea decreased broomrape biomass by 86, 85.3, 75.2, and 74.4 per cent, respectively. Reducing broomrape biomass caused increases in the tomato yield. Meanwhile, sesame, brown Indian hemp, Egyptian clover and mungbean increased total biomass of tomato by 71.4, 67.5, 65.5, and 62.5 per cent, respectively. It was observed that these plants have a great potential to reduce broomrape damage and they can be used in rotation in broomrape infested fields (Sirwan *et al.* 2010).

Krisnamurthy and Rao (1976), Krishnamurthy *et al.* (1977), Abu-lnnaileh (1984), Sauerborn and Saxena (1986) AI-Menoufy (1991), Saxena *et al.* (1994) and Kleifeld *et al.* (1994a) listed some trap crops found effective and may help to reduce seed bank of *Orobanche* spp . Trap crops for *O. crenata* were sorghum *(Sorghum vulgare*), barley *(Hordeum vulgare*), vetch *(Vicia vilosa* var. *dasycarpa)* and purple vetch. *(V. atropurpurea),* clover *(Trifolium alexandrinum),* flax *(Linum usitatissimum),* and coriander *(Coriandrum sativum).*

Trap crops for *O. cernua,* O. *aegyptiaca* and O. *ramosa* were pepper (*Capsicum annuum),* sorghum (*Sorghum bicolor*), cowpea (*Vigna unguiculata*), hemp (*Hibiscus subdariffa*), mungbeans, (*Phaseolus aureus*), flax, alfalfa (lucerne) *(Medicago sativa*), soybean (*Glycine max*), vetches (*Vicia* spp.) and chickpea (*Cicer arietinum*). An additional cultural means for reducing *Orobanche* seed bank in the soil is the use of catch crops *i.e.*, planting an *Orobanche* host crop for inducing parasite seed germination and attachment and that will be destroyed later on by means of light tillage practices or residual soil herbicides. But the use of trap and catch crops to manage this weed is somewhat limited due to (a) enormous amount of *Orobanche* seeds dispersed in the soil and only a small proportion may be exposed to germination stimulants in the rhizosphere (b) feasibility and economics of growing these crops in the existing situations is also a big question mark.

Sowing dates and cropping density: Germination of *Orobanche crenata* tends to be very much reduced below 8 °C and further development is greatly reduced at low temperatures. Delaying the planting date affects *Orobanche* more than its hosts; the delay should be two weeks only from the date optimal for sowing in an uninfested field. However, this method must be adapted for different regions and for different hosts. Early planting dates are beneficial in certain instances. Late planting of mustard (last week of October-first fortnight of November) is observed to be helpful in reducing the parasitism of *Orobanche* a result of specific weed and host plant differential response to low temperatures (Yadav *et al.* 2005) in Indian conditions. Moreover, farmers' perception for late sowing is pessimistic owing to limitation of mustard cultivation to conserved moisture conditions and competition for water utilization for pre-sowing irrigation in wheat; therefore, alternation in sowing time seems to be uncommon and unrealistic approach under Indian context.

Resutls in faba bean showed that shifting sowing from October to November, December or January reduced numbers and dry weight of attached and emerged broomrapes, both *O. crenata* and *O. foetida* (Grenz *et al.* 2005a). Since faba bean development is less susceptible to low temperatures and can be accelerated by increasing day length, pods enter the critical phase of rapid biomass accumulation relatively earlier than parasites. As a result, more parasites and lesser pods are aborted (Grenz *et al.* 2005a) observed a more pronounced effect of late sowing in dry years, which also may indicate the existence of soil moisture-driven effects.

Increased seed rate may reduce competition and number of attachments to some extent but additional cost of seed and other inputs besides providing congenial crop growth environment should also be taken care of while deciding the fate of such interventions.

Host plant resistance/tolerance

Based on inheritance of resistance and variability in pathogenicity, breeding for herbicide resistant crops can be an option towards managing this weed by the mechanism of herbicide translocation through the host plant to suppress and/or kill the obligate parasite. Globally, specific research has been carried out on the development of herbicide tolerant varieties having significant resistance to *Orobanche* infestation in different crops but no such concerted efforts have been put forward to breed such varieties till date in India.

A mustard variety, '*RRN 593*' (Durgamani) earlier reported to be tolerant/resistant to *Orobanche* but it has shown varying degree of limited effectiveness under actual field conditions in the later concluded experiments (Yadav *et al.* 2005), During *Rabi* 2011-12, nine most popular mustard varieties/hybrids, *viz.* *'Korel-432', 'Pro Agro 5444', 'Pioneer 45J21', 'Pioneer 45J42', 'AK 47', 'RH 30', 'RB 50', 'RH 0749'* and *'RH 0406'* were screened for their tolerance against *Orobanche* at village Bidhwan (Bhiwani), Haryana but none of them was found tolerant, however, the differences in seed yield were observed due to differences in their genetic make up and yield potential (Anonymous 2012).

Water management

Less infestation of the parasitic weed has been observed in raya/mustard grown under flooded irrigation compared to sprinkler irrigation or on conserved moisture as the seeds of *Orobanche* do not survive an extended period of inundation. Availability of water and undulating topography are again the limiting factors to practice flooding.

Nutrient management

Higher *Orobanche* infestation and its parasitism on host plants is generally more localized in inherently poor fertility soils dominated by major mustard growing areas of the India. Reports on inhibitory action of increased nitrogen fertilization and manures and compost application on the growth of *Orobanche* are available, however, adequate amount of phosphorus and potash fertilization are also required to raise/ maintain the crop productivity. Application of urea or ammonical form of nitrogen during conditioning and germinating phases has been reported to reduce the germination, radicle length and weed proliferation (Pieterse 1991, Jain and Foy 1992). Low or absence of glutamine synthase (GS) activity in this weed may contribute to sensitivity to N-fertilization and the knowledge about the N-inhibitory mechanism of this weed in relation to their host continues to be elusive, which is central to practical utilization of this strategy.

Urea at 276 and 207 kg/ha, ammonium nitrate, and ammonium sulfate at 207 kg/ha and the goat manure at 20 and 30 t/ha were found most effective in reducing parasitism of *Orobanche* and enhancing growth of tomato plants. Even though drastic reduction of broomrape infestation was obtained, ammonium nitrate and ammonium sulfate at 276 kg/ha seemed to be injurious to tomato plants. As nitrogen rates increased, the numbers and dry weights of shoot of branched broomrape decreased and the yields of tomato increased linearly except the yields obtained from the highest rate of ammonium nitrate and ammonium sulfate. This result indicated that broomrape infestation of tomato decreased with increases of soil nitrogen (Mariam and Rungsit, 2004). The mixtures of chicken manure (20 t/ha) and sulphur (0, 1, 4, 8, and 12 t/ha) at all tested rates significantly reduced the dry weight of *Orobanche* and increased eggplant and potato yield compared with the control (Haidar and Sidahmed 2006).

To confirm the effect of nitrogen fertilization through different sources on *Orobanche* inhibition in mustard, localized field studies were carried out through farmers' participatory approach in Haryana state of India during 2004-2010. Erratic response over the years was observed with respect to weed infestation and population dynamics when nitrogen sources *viz.*, ammonium sulphate, calcium nitrate and urea were evaluated alone or in combination with FYM, poultry manure, castor cake, press mud or vermicompost. Use of neem cake/vermi-compost/castor cake and increased N fertilization (120 kg/ha) increased/maintained the crop productivity with parasitism of *Orobanche* by sustaining the host plant growth even with depleted fertility status.

Mechanical and physical methods

Hand weeding/hand pulling: Hand weeding or hand pulling before flowering followed by burning can be an effective and practicable method of checking seed production. Profuse emergence of new inflorescence from below ground plant parts has also been observed within a short span of 7-10 days of hand weeding or hoeing therefore, this warrant for frequent repetitive measures. It only limits the seed production but does not compensate the damage in terms of yield losses. It was reported that three years of hand weeding could control *O. cernua* in tobacco in India (Krishnamurthy and Rao 1976), but the problem remained persistent. Knowing more about the reproduction of *Orobanche* will lead to a better acceptance of hand pulling, especially in areas with recent infestation. However, in combination with other methods, it can reduce the seed bank very efficiently (FAO 2008).

Tillage/ intercultivation: Deep tillage during summer months causes seed desiccation and places them below the root zone preventing seed germination to some extent, but again the longer viability (up to 20 years) of weed seeds raises a question mark in long run.

Deep inversion plowing and fire: Placement of seeds at 20-cm depth was observed to cause little emergence of *O. cernua* (Krishnamurthy *et al.* 1987). However, the buried seeds could be brought up by subsequent tillage. Parker and Riches (1993) propose burning of residue from infested crops to reduce carry over of broomrape seeds back to the soil.

Soil solarization: Covering moist soil (with or without minimum disturbances at planting) with white or black polyethylene sheet for a month or so can increase the soil temperature by almost 10 °C (48-57 °C) compared to uncovered soil resulting in killing of *Orobanche* seeds that are in the imbibed state; therefore, soil must be wet at the time of treatment (Jacobsohn *et al.* 1980, Braun *et al.* 1987, Sauerborn and Saxena 1987). Seeds of *O. ramosa* can survive 35 days at 50 °C in dry air, but are quickly killed by temperatures of 40 °C when wet. This technique has been used successfully on cropping land in many countries around the world like Middle East with an endemic *Orobanche* problem, as a pre-planting treatment for tomato, carrot, eggplant, faba beans and lentils. Soil solarization has been proven to be the most effective methods in controlling broomrape in open crops fields (Haidar and Sidahmad 2000). But high cost of polyethylene, appropriate machinery and cloud-free sunny days may restrict its use on larger scale (Foy *et al.* 1989). Soil solarization coupled with no-till was found better in controlling *Orobanche c*ompared to solarization under conventional tillage. This approach has attracted the interest in many warm-climate countries because of its effectiveness, simplicity and safety for humans, plants, and the environment.

Biological methods

There are some reports on managing *Orobanche* through biological perpetuation of a fly, *Phytomyza orobanchia* (Girling *et al.* 1979, Trenchev 1981, Klyueva and Pamuchki 1982, Mihajlovic 1986). Tillage may bury broomrape stalks, containing *Phytomyza* pupae, deeper in the soil, thus preventing emergence of adults. Crop-specific insecticides and parasites of *Phytomyza* may reduce the fly population considerably. Crop rotations may also have negative impact on the survival mechanism of *Phytomyza*. With deep ploughing hibernating pupae can be destroyed and/or buried and thus prevent insect emergence. Managing weed infestations to some extent through mycoherbicides have been reported by Hodosy (1981) and Bedi and Donchev (1991).

Fungi such as *Trichoderma viridae* and *Psuedomonas inflorescence* were tested at farmers' fields in village Hasan (Bhiwani) and CCS HAU Hisar during 2010-11, but these were found ineffective against *Orobanche* in mustard (Anonymous 2011). Inoculation of fungus *Fusarium oxysporum* sp. *orthoceras* in the field resulted 90% control of *Orobanche* in sunflower (Bedi and Donchav 1991, Bedi 1994, Sauerborn *et al.* 1994) or tomato (Hodosy 1981). Relative high soil humidity and soil temperatures are required for the development of soil fungi. More research is needed to develop a reliable biological method under Indian conditions.

Chemical methods

During the last decades, some potential useful chemical interventions have become available for the control of parasitic weeds (Garcia-Torres 1998). However, this form of control is complicated by a number of factors including: (i) it is effective only as a prophylactic treatment, since in most cases we do not know the infestation level; (ii) the parasite is directly connected to the host; (iii) if the herbicide is to be applied to the parasite through the conductive tissues of its host, the host must be selective to the herbicide without reducing its phytotoxicity; (iv) herbicides have low persistence and the parasite can often continuously germinate throughout the season, developing new infections (Perez-de-Luque *et al.* 2010).

These are Soil fumigants, residual soil applied herbicides and post-emergence applied herbicides have been reported to possess potential to control *Orobanche*.

Soil fumigants: Earlier, soil fumigation with methyl bromide (MB) prior to planting was used (Wilhelm, 1958) but World Health Organization (WHO) and Agricultural authorities ultimately banned the use of methyl bromide for fumigation purpose because of its negative environmental effects (United Nations Environmental Protection Service 1992). Fumigation by compounds that release methyl isothiocyanate was suggested for *Orobanche* eradication. Metham sodium, applied directly by injection or by chemigation via irrigation systems into the soil, or dazomet incorporated mechanically into the soil, followed by irrigation that releases the toxic ingredient, were found to be very effective for *Orobanche* control. Methylisothiocyanate was effective in deeper soil layers, but very ineffective on the surface, because of its rapid evaporation (Goldwasser *et al.* 1995). The difficulties in application of 1,3-dichloropropen and the narrow pest control range limit its utilization to small-scale intensive farming only.

Residual soil applied herbicides: Several reports are being published on the beneficial effect of mechanically incorporated herbicides belonging to dinitroanilines, sulfonyl areas, substituted ureas group showing host crop selectivity and significant soil residuality for better control of *Orobanche* (Parker and Riches 1993).

Seed treatment: Seed treatments with imidazolinones have proven to be effective for controlling *O. crenata* in faba bean. Coating sunflower seed with 2 kg/ha and soaking the seeds in 50% of pronamide has lowered broomrape shoot dry weight and increased the yield of sunflower from 2.14 (control) to 2.85 t/ha in coated seed and from 1.24 (control) to 1.79 t/ha in soaked seeds (Sanchez *et al.* 2003). The sulfonylureas also have the advantage of selectivity for preventing emergence of broomrape growing on broad-leaved weeds in a non-host cereal crop: 3 g/ha metsulfuron-methyl, 15 g/ha chlorsulfuron or 22.5 g/ha triasulfuron gave 100% control of *O. ramosa* without damage to wheat or barley crops (Matthews 2002). This may be due to their direct effect on *Orobanche* and to their reduction of broad leaved weed hosts.

Soil and foilar applied herbicides: Chlorsulfuron applied at 3.75 g/ha directly to the soil completely controlled O. *aegyptiaca* (Hershenhom *et al.* 1998b). This herbicide, which has a longer soil activity than most other sulfonylureas, was applied directly into the soil by "chemigation" (delivering of the herbicide through irrigation water) to tomato transplants after establishment in the field. The phytotoxic contact of the herbicides with the host foliage was avoided by using very dilute solutions, and by washing of the herbicide into the soil by additional sprinkler irrigation. Three split applications of 2.5 g/ha chlorsulfuron through sprinkler irrigation, starting at 14 days after tomato planting and at intervals of 10-14 days followed at each application by 300 m^3/ha irrigation, controlled 80-90% *Orobanche* without phytotoxicity to the tomato crop. Single or double split application, application through a drip system or at high volume spray did not sufficiently control *Orobanche* throughout the growing season (Hershenhom *et al.* 1998c). Aplication of of chlorsulfuron, through drip-irrigation systems to control late season *Orobanche* emergence around drip emitters in tomato effectively controlled *Orobanche* emergence (Kleifeld *et al.* 1999), but its efficacy was inconsistent in other trials.

Sulfonylurea herbicide is registered worldwide for pre- and post-emergence of grass and broad-leaf weeds in wheat. Though sulfosulfuron was initially developed and registered for controlling an array of grass and broad leaf weeds in wheat, its selectiveness to some broadleaf crop species has recently led to its registration for weed control in potato in Poland (Anonymous 1995, Hatzios 1998). In extensive research conducted in Israel, sulfosulfuron has proven to be highly efficient and selective for O. *aegyptiaca* control (Eizenberg *et al.* 2001b). While chlorsulfuron and triasulfuron were most effective when applied by chemigation, sulfosulfuron can be sprayed on tomato foliage followed by sprinkler irrigation to wash the herbicide into the soil where it is absorbed directly by the young parasites or via the tomato host roots. Greenhouse experiments with activated charcoal suggested that the herbicide acts mainly through the soil and not by translocation through the host tomato plant. To achieve good parasite control, high herbicide rates at early developmental stages of the parasite were needed, that is two or three applications of 37.5 g/ha starting two weeks after tomato planting and repeated at two week intervals. Study conducted in Chickballapura district of Karnataka state (India) revealed effectiveness of pre-emergence sulfosulfuron at 75 g/ha in controlling *Orobanche* in tomato grown under irrigated conditions (Dinesha *et al.* 2012)

The imidazolinones are ALS-inhibiting herbicides with the same mode of action and similar characteristics as the sulfonylurea herbicides. These herbicides are used pre-emergence and post-emergence for control of annual and perennial grass and broadleaf weeds.

Various legumes are resistant to some of the imidazolinone herbicides and this resistance has led to selective use of these herbicides in certain legume crops. Legumes are tolerant to imazapyr because they can metabolize it to an inactive form (Shaner 1989). Garcia Torres *et al.* (1998) reported selective *O. crenata* control in faba bean by pre-emergence and post-emergence applications of imazethapyr, imazapyr and imazaquin. In our studies we have found that crops belonging to other botanical families are imidazolinone- tolerant: split application with various imidazolinone herbicides on potato, sunflower and parsley foliage selectively controlled *O. ramosa, O. cumana,* and *O. crenata,* respectively. In these cases the herbicides were extensively translocated to the attached root parasite directly through the host plant, in contrast to the mode of control with sulfonylurea herbicides that act on the parasite directly through the soil. This method eliminates the need for irrigation following application.

Three doses of imazapic at 4.5 g/ha, sprayed at 2 weeks after crop emergence and reapplied at 2 weeks intervals, followed by its deliverance in potato root zone by sprinkler irrigation prevented *Orobanche* infestation. Although these treatments increased crop vigour and potato yield but potato tuber quality was severely damaged in light sandy soil (Goldwasser *et al.* 2001). Split application of imazapic at 2.5-5.0 g/ha applied on 5-7 leaf parsely before first cutting and on young new growth after each cutting provided effective and selective control of *O. crenata* and *O. aegyptiaca* (Gold Wasser 2003)

Imazethapyr herbicide was developed for the control of many broadleaf and grass weeds by pre-plant, pre-plant incorporated and post-emergence applications in soybean, peanuts and edible legumes (Ahrens 1994) and parsely. This herbicide was the first of the imidazolinone group to be registered for *Orobanche* control. A post emergence application of 20 g/ha on garden and field pea *(Pisum sativum* and *Pisum arvense,* respectively) one month after planting and an additional treatment of 20-40 g/ha two weeks later, was selective to pea and efficient in *Orobanche* control (Jacobsohn *et al.* 1998). Imazethapyr has been registered at these rates for post-emergence *O. crenata* control in peas in Israel and at 75-100 g/ha pre-emergence applications for *O. crenata* control in faba bean in Spain (Garcia-Torres *et a*l. 1998). There are reports of some promising results of *O. crenata* control by faba bean and pea seed treatments with imazethapyr (Jurado-Exposito *et al.* 1996, 1997, 1999).

Rimsulfuron, a sulfonylurea herbicide, was developed originally for early post-emergence control of broad-leaved and grass weeds in com (Hatzios 1998). The selectivity of this herbicide to the Solanaceae family led to its registration for weed control in tomato and potato (Reinke *et al.* 1991). A new sulfonylurea herbicide selective to tomato when applied through drip irrigation in tomato root zone controlled *O. aegyptiaca*. Since rimsulfuron's residual soil activity is short, so repeated applications were necessary for season long weed control (Kleifield *et al.* 1994). Three repeated doses of rimsulfuron at 12.5 g/ha each followed by irrigation, sprayed on potato foliage two weeks after crop emergence and re-applied at two week intervals effectively and selectively controlled *O. aegyptiaca* with no damage to potato yield or tuber quality (Goldwasser *et al.* 2001). Rimsulfuron achieved efficient *Orobanche* control in potato fields but not in tomato fields because potato fields were sprinkler irrigated while tomato fields were drip-irrigated and the herbicide was rapidly leached around the drip emitters.

Some of the locally available common herbicides at different concentrations, *viz.* pendimethalin (PE) 1000 g/ha, linuron (PE) l000g ha, trifluralin (PPI) 1000 g/ha, fluchloralin (PPI) 1000 g/ha, metribuzin (PE/PPI) 175-200 g/ha, sulfosulfuron (PE) 5-10 g/ha, oxyfluorfen (PE) 125-175 g/ha, thiazopyr (PE) 240 g/ha, isoproturon (PE/PPI) 500-1000 g/ha, chlorsulfuron (PE/PPI) 2-6 g/ha and triasulfuron (PE/PPI) 5-10 g/ha were tested in field trials conducted at farmers' fields in Bhiwani district and KVK, Mahendergarh (Haryana) by scientists of CCS HAU Hisar from 2000-2008. These herbicdes were found inconsistent in their efficacy against the parasitic weed over the years and sometimes even showed phyto-toxicity to the mustard crop or both (Yadav *et al.* 2005).

In pot culture (2004-05), seed immersed with chlorsulfuron (0.05-0.1% solution) or triasulfuron (0.15-0.30% solution) for 5-10 minutes resulted in severe crop phyto-toxicity just after emergence. However, seed coating with chlorsulfuron, triasulfuron or sulfosulfuron at 0.05-0.1 mg/kg seed proved safe for crop. Since there was no germination of *Orobanche* in pots filled with infested soil (may be due to consistently high moisture and poor aeration), these results were further exploited under field conditions. Results of experiments conducted from 2005-08 under farmers' management practices revealed that seed treatment of mustard with triasulfuron, sulfosulfuron and chlorsulfuron have been found to delay the emergence and attachment of *Orobanche* but the results were inconsistent over the years. Over-dosing of the herbicide seed treatment some times caused poor germination and suppression in crop growth (Punia *et al.* 2012).

***Orobanche* control with glyphosate:** Foy *et al.* (1989) and Kleifeld *et al.* (1999) reported selectivity to various herbicides against broomrape in a variety of crops. Parker and Riches (1993) earlier reported the glyphosate use on limited areas for *Orobanche* control in broad bean, carrot and celery. Kukula and Masri (1984), Van Hezewijk *et al.* (1991) and Jain and Foy (1992) have also demonstrated the effectiveness of systemic herbicides and fertilizer application in increasing the broomrape control efficacy. Host crops which are tolerant to glyphosate are fababean, carrot, cabbage and Celery. Tomato and pea are extremely sensitive to glyphosate (Jacobson and levy 1986). All these reports favour the use of glyphosate as a potential herbicide for *Orobanche* management, but there is dire need to conduct research particularly under real time farm situations to determine the optimum period and dose of herbicide application during which the parasite is most sensitive and the mustard crop is most tolerant. Since glyphosate is a broad spectrum non-selective foliar applied herbicide, its efficacy in managing *Orobanche* could be quite useful but at the same time the selectivity of this herbicide is limited and needs critical precautionary measures to have effective results.

A study undertaken at Hisar (Haryana) to evaluate the efficacy and to standardize the dose and time of glyphosate application against the parasitic weed *Orobanche* in mustard (*Brassica juncea*) from 2006-

2010, indicated that higher dose of glyphosate at early crop stages sometimes caused localized phytotoxicity on mustard plant viewing marginal leaf chlorosis, slow leaf growth, interveinal leaf bleaching, and/or slight elongation of apical leaves but the crop recovered within 7-10 days after spray with no yield penalty. Single application of herbicide though provided effective control of the weed; however, late emergence of new shoots were observed in the later half of crop growth, ultimately causing reduction in seed yield and adding weed seeds to the soil. Glyphosate applied twice at 25 g/ha at 30 DAS followed by 50 g/ha at 55 DAS provided 65-85% control of *Orobanche* even up to harvest (without any crop injury) with yield improvement from 12 to 41% over the traditional farmers' practice (Table 1) in different years of the study (Punia *et al.* 2010, Punia and Singh 2012). Similar findings on the control of *Orobanche* in mustard through herbicide application were also reported by the scientists at Gwalior and Bikaner (DWSR 2009).

The tolerance of plants to glyphosate was mainly attributed to readily degradation of this herbicide to non-toxic metabolites. It is readily absorbed by the mustard plant foliage and translocated to the young parasites attached to the roots, leaves and meristems, thereby inhibiting the synthesis of enzyme 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase that leads to the production of aromatic amino acids (phenylalanine, tyrosine and tryptophan) and thus protein synthesis and growth (Amerhein *et al.* 1980). These results were further validated in large scale multi-locational trials conducted at different locations through farmers' participatory approach in Haryana during the *Rabi* seasons of 2010-11 to 2013-14. A total of 157 demonstrations were conducted in mustard growing areas of Haryana covering 267 ha area and it was observed that overall 74.4% (range 40-95%) reduction in *Orobanche* weed infestation with 15.1 per cent (range 13.9-16.3%) yield superiority was noticed with glyphosate treated plots (25 g/ha at 30DAS followed by 50 g/ha at 55-60 DAS) when compared with the farmers' practice of one hoeing at 25-30 DAS (Table 2).

There were reports on the effectiveness of glyphosate in tomato, tobacco, faba beans, and other crops under greenhouse conditions elsewhere, but have not been yet reported from India, particularly under field conditions. Foliar spray of glyphosate twice, 25 g/ha at 30 DAS followed by 50 g/ha at 55 DAS may be helpful in reducing the *Orobanche* infestation by checking the further increase in weed seed bank without any crop suppression, but at the same time requires certain precautionary measures in its use. Since most of the mustard cultivation in India is limited to light textured soil having inherent poor fertility status and water holding capacity, care should be taken that the crop should not suffer from any moisture stress at the time of foliar spray, therefore, the fields should be ir-

Table 1. Effect of glyphosate application on *Orobanche* management and seed yield of mustard

Treatment	Dose (g/ha)	Time of application (DAS)	Reduction in *Orobanche* (%)			Crop phyto-toxicity (%)	Seed yield (t/ha)
			70 DAS	120 DAS	Harvest		
Glyphosate	25	30 and 55	98 (96-100)	94 (84-96)	82 (72-92)	-	1.67
Glyphosate	50	30 and 55	98 (93-100)	90 (85-95)	86 (70-88)	10-20	1.63
Glyphosate	25	30 and 55	59 (52-70)	41 (30-48)	30 (56-52)	-	1.53
Glyphosate	25	30 and 55	92 (86-98)	71 (64-82)	42 (38-50)	10-20	1.50
Farmer's practice (one hoeing)	-	30	-	-	-	-	1.40

Figures in parentheses indicate range of the treatment effect (mean of 4 years)

Table 2. Comparative performance of glyphosate application *vis-à-vis* farmers' practice for *Orobanche* management in mustard

Year	No. of trials	Area covered (ha)	*Orobanche* control (%)	Seed yield (t/ha)		Percent increase in yield over farmers practice
				Treated*	Farmer's practice*	
2010-11	12	5	82 (70-95)	1.72 (1.40-2.10)	1.49 (1.20-1.95)	15.5
2011-12	24	20	79 (65-90)	1.59 (1.20-2.20)	1.37 (0.90-1.80)	16.3
2012-13	86	156	72 (55-90)	1.75 (1.25-2.25)	1.54 (1.00-1.95)	13.9
2013-14	35	82	63 (40-90)	1.65 (1.25-2.40)	1.44 (1.10-2.10)	14.6

*25 g/ha at 30 DAS and 50 g/ha at 55-60 DAS, **one hoeing at 25-30 DAS

Figures in parentheses indicate range of the treatment effect on *Orobanche* control and mustard seed yield rigated 2-3 days prior to herbicide application. The proper time and dose of herbicide should also be taken care of to have better efficacy of herbicide application as repetitive/higher/lower than the recommended dose may lead to adverse impact on mustard crop or may result in development of herbicide-resistant weeds (Shoeran *et al*. 2014). The present study has shown that glyphosate, if used at desired concentrations can be very helpful in reducing the parasitic weed infestation while affording tolerance to the mustard crop. This would definitely obviate the *Orobanche* seed bank to further increase as well as improve the overall productivity and economic well being of the mustard growing farmers' fraternity.

Other approaches

Putting 1-2 drops of diesel oil, boiling water and kerosene oil on each shoot have also been suggested for the control of this weed (Krishnamurthy *et al*. 1976, Linke and Saxena 1991b). Similarly, oils of gingelly, groundnut, palm, sunflower, safflower, niger, castor, linseed, coconut, tobacco, eucalyptus, pongamia, soybean, rice bran *etc*. applied 2-3 drops on the top of heads have been reported to kill broomrape shoots within 2-4 days, but with less effect on flowering shoots (Krishnamurthy and Chari 1991, Krishnamurthy and Nagarajan 1991b, Krishnamurthy 1992). Not all oils were quite effective, but they have the advantage of not being phytotoxic to the host plant. However, these techniques have practical problems and 3-4 repeated applications on emerging shoots at an interval of 4-5 days is required for its effective control. All these aforesaid oils causes only localized desiccation and prevent seed setting but later on emergence of other shoots was observed.

Based on two years (2003-05) field trials conducted in Haryana, the author is also of the view that application of kerosene, diesel and soybean oil, caused only localized desiccation and blackening of inflorescence (3-4 cm from the top), however, profuse emergence and regeneration of new shoots were observed after 10 days of chemical treatment. Moreover, application of these oils is tedious if not impossible, besides being ineffective and uneconomic (Yadav *et al.* 2005). Spraying under the influence of dense crop canopy restrict the movement of applicator. Desired liquid flow abilty through spray nozzles due to high viscosity of spraying oils is another area of concern to get the desired results. Use of plant hole application of neem cake at 200 kg/ha at 30 DAT or post-emergence application of imazethapyr at 30 g/ha at 55 DAT has been suggested to control *Orobanche* in tobacco under Western zone of Tamil Nadu in India (AICRPWC 2013).

Genetically engineered herbicide-resistant crops

The recent development of transgenic herbicide-resistant crops, and especially those resistant to amino-acid inhibiting herbicides, has opened up new opportunities (Joel *et al.* 1995). The use of these transgenic crops for parasitic plant control will intensify in future with the identification and utilization of additional herbicide resistant genes. Concern may also arise regarding the possible gene transfer from transgenic crop plants to wild plants, although different ways to overcome these concerns have been proposed (Gressel 2004). Complete control of *0. aegyptiaca* was achieved when modified acetolactate synthase enzyme induced transgenic tobacco was treated with chlorsulfuron. Excellent control of broomrape with glyphosate application in oilseed rape having modified enolphosphate-shikimate phosphate synthase (EPSP) and with asulam resistant tobacco plants having modified dihydropteroate synthase (methyl carbamate) has also been well documented. However, a variety of tomato engineered for resistance to glufosinate, an inhibitor of GS, was infested with broomrape in spite of application of glufosinate. Similar cases have been reported in sunflower also

Aviv *et al.* (2002) engineered a mutant AALS gene into carrot, allowing the control of broomrape by imazapyr (an imidazolinone ALS inhibitor). Several tobacco cultivars transformed with a mutant acetohydroxy acid synthase (AHAS) 3R gene (isolated from a sulfonylurea resistant *Brassica napus* cell line) were resistant to the herbicide chlorsulfuron (Slavov *et al.* 2005). A very low percentage of chlorsulfuron (from 0.1 to 4 %) of its active ingredient that reached the plant roots was sufficient to kill the parasite at an early developmental stage after two treatments (Slavov *et al.* 2005).

Parasitic weeds will rapidly evolve resistance to herbicides because of their prolific seed production. Therefore, resistance to glyphosate, asulam, chlorosulfuron, or imazapyr will eventually appear. Therefore, herbicide resistance crops should be wisely used or combined with other control methods, and new resistant crops continually developed (Radi 2007)

Dissemination and evaluation of technology

A training programme on the use of glyphosate for effective control of *Orobanche* in faba bean was propagated in Morocco for more than 15 years, but only 15 per cent of the interviewed extension workers were able to demonstrate the correct description of its application technology. Therefore, training of extension staff is as an important component in facilitating effective advisory work and in assisting farmers' knowledge, attitude and beliefs towards assessing and adopting a new technology intervention in right and effective manner. Apart from technical knowledge, extension workers may also require trainings on the appropriate use of extension material and on how to improve their communication skills.

Conclusions

In spite of continuous and extensive research by the plant breeders, weed scientists and plant protectionists, *Orobanche* spp. are still causing serious problems in large number of crops worldwide and are aggravating in many areas. The nature of *Orobanche* makes its control extremely difficult, costly, or environmentally hazardous. Several methods for managing broomrapes include hand weeding, deep ploughing, crop rotation, alteration in seeding windows and fertilizer N scheduling, the application of organic manures and biofertilizers, chemical seed treatment, and kerosene/soybean oil droplets spray; however, they are inconsistent and have limited effectiveness. No single technique provides complete control of *Orobanche*. Physical methods are very useful to prevent the *Orobanche* but are tedious, time-consuming and costly and prevent only seed setting not yield losses. Chemical, agronomic control methods and host resistance appear to be the most appropriate measures when available and affordable. Moreover, some biological and crop resistance approaches are promising but they are too expensive and control may not be complete and still need more research. Integration of cultural, preventive and biological and chemical methods is required even though it is very costly to deplete weed seed bank and to avoid further dispersal. However, these integrated programmes are practiced only on a small scale in a few countries because of cost and technical problems. Therefore, it is reasonable to hypothesize that GMO approaches will be adopted for parasitic weed control in the near future.

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Management of perennial weeds under non-cropland hill ecosystems

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ABSTRACT

Lantana camara L.var. *aculeata, Parthenium hysterophorus* (L.), *Chromolaena adenophorum* Spreng., *Imperata cylindrica* (L.) Beauv,*Urtica dioca* (L.) and *Ageratum houstonianum* (Mill.) are the major obnoxious perennial weeds of non-cropland hill ecosystems. These weeds are difficult to control and have spread like a wild fire in almost all the state because of the favourable climatic conditions, ability to propagate by seeds, stems and roots, faster dissemination by wind, water, birds, animals, machinery *etc.* and ability to adapt adverse conditions of hills. These weeds have become more problematic in hilly regions due to availability of more uncultivated land. These weeds are responsible to suppress useful vegetation in pasture and grasslands, orchards, forests, tea gardens, field bunds and other cropped and non-cropped lands by their competitive and allelopathic effects. These are responsible to threat plant biodiversity, shrinkage of grazing land, economic losses to the forest wealth, reduction in productivity of grasslands up to 90%. The toxins present in these weeds are proving hazardous to the health of animals and human beings. Preventive, mechanical, chemical, biological, utilization and integrated methods to manage these obnoxious perennial weeds have been discussed in this paper. These weeds should be cut at frequent intervals before flowering to exhaust food reserves in their vegetative propagules, check production of seeds and their dissemination. The cut biomass should be utilized to prepare compost, as mulch, biogas production, making furniture, as fuel wood and other industrial uses as per the property of weed species. A three phased integrated technology to manage *Lantana camara* under different hill ecosystems has been developed and demonstrated in large areas. In waste lands and forestland ecosystems, biological agents like *Zygogramma bicolorata*, *Cassia tora* or *Cassia sericea* are effective to manage Parthenium, hence should be introduced to check the rampant growth of this weed. In pasture and grasslands, herbicides should only be used in integration with plantation of fast growing forage species, recommended fertilizer, and harvesting or grazing schedules. These integrated technologies to manage *Parthenium*, *Lantana* and *Ageratum* have been demonstrated on large scale in hilly regions. However, for effective results, these technologies need to be adopted on campaign basis with the active participation of public, Government, scientists and policy makers.

Key words: *Ageratum,* Management, Hilly regions, *Lantana,* Non-cropped weeds, *Parthenium,* Perennial weeds

Hilly regions are gifted with plenty of land that can not be put under frequent cultivation. Such lands are under orchards, pastures, grasslands, forests and wasteland ecosystems. Since most of these lands do not receive frequent cultivation and intensive care of the owners, the obnoxious perennial weeds like *Lantana camara, Ageratum houstonianum, Parthenium hysterophorus, Chromolaena adenophorum* and *Urtica dioica* have invaded most of these areas. They are regarded as the worst weeds because of their invasiveness, potential for spread and economic and environmental impacts. Most of these weeds forms dense, impenetrable thickets and take over the native bush land and pastures. They reduce the productivity of pastures, orchards and forestry plantations by their competition for resources and allelopathic effects. The low productivity of these non-cropped ecosystems lead to scarcity of food, fuel wood, fodder, fruits, monkey menace and migration of men to towns and cities in search of jobs after leaving the land fallow. However, the majority of people depend upon their subsistence needs on such uncultivated yet degraded lands. Productivity of such lands can be restored by managing these obnoxious perennial weeds with the available technologies. In this paper, efforts have been made to discuss the biology of important obnoxious perennial weeds of hills, their ecological impacts and management techniques. Some of the major obnoxious weeds of hilly regions are given (Table 1).

These obnoxious weeds have immense capacity of propagation by seeds, stems and roots, high rate of dispersal and adaptation to adverse conditions. These weeds compete with the associated vegetation for nu-

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Table 1. Major obnoxious perennial weeds of non -cropland hill ecosystems

Scientific name	English / local / vernacular names
Lantana camara L.	Wild sage, Panchfuli, Phulbehri, Chudel buti, Lal phulnu
Ageratum houstonianum (Mill.)	Bill goat weed, Neela Phulnu, Pudini, Ujaru, Ukhal buti, Shadian
Parthenium hysterophorus L.	Congress grass, Gajar ghass, Chatak chandni
Imperata cylindrica (L.) Beauv.	Thatch grass, Chiz, Seerua, spear grass, alang alang, cogongrass
Urtica dioica (L.)	Stinging nettle, Bitchu booti, Ahn, Common nettle
Chromolaena adenophorum Spreng.	Crofton weed, Kali basuti, Siam weed, Bitter bush, Charismas weed

trients, moisture, and light and also suppress the native vegetation by allelopathic effects. They have invaded all such land masses that are not under cultivation or are poorly managed. Hilly regions have more such lands which are under forests, pastures and grasslands, orchards, tea gardens and uncultivable waste lands. Consequently these weeds have led to shrinkage of grazing area for animals, reduction in productivity of grasslands by 90 per cent, threat to plant biodiversity, reduced growth of newly planted trees in man made forests and interference in succession of natural forests, act as hiding place for wild animals and threat to ecology of the region. These weeds also cause toxic effects on animals and are threat to human health and environment.

Ecological implications of obnoxious perennial weeds in hill ecosystem are:

- The pasture and grazing lands in the hills are most affected due to infestation of these weeds. For example, in Himachal Pradesh, pasture and grasslands which constitute about 40% (94.2 million hectares) of the total geographical area provide fodder and grazing ground for the entire livestock population of the state. Taking an average figure of 25% invasion, the invaded area with these weeds comes around 23.55 million hectares. Although, these weeds cause about 90% reduction in productivity of grasses but even if an average of 50% is taken, the total loss of production is estimated to be more than 17.62 million tones, valued at approximately more than ` 90 billion per annum. Besides this ,the robbing of nutrients by these weeds make the land less fertile and further regeneration of grasses is also checked by their allelopathic and interference.
- Though these weeds are not palatable to the livestock due to their aroma, disagreeable taste and presence of trichomes, yet the accidental or willful intake for want of green fodder cause severe syndrome leading to death of cattle grazing in infested areas due to presence of toxic alkaloids.
- These weeds cause allergies like giddiness, loss of hairs, dermatitis, asthma, aczema, vomiting, headache, eruptions on the exposed body parts like eye lids *etc.* and even death due to contact with them or even with their presence in the nearby environment. Consequently, farmers hesitate to uproot these weeds by manual methods and are leaving the land fallow which is further create favorable conditions for their growth and spread.
- Due to fodder scarcity caused due to invasion by these weeds, farmers are leaving their cattle loose for stray grazing which cause damage to the cultivated crops.
- The monkey menace, one of the major problem in the hilly areas is also attributed to impenetrable thickets formed by these weeds and their allelopathic effects has extincted most of the wild fruit plants in the natural forests. In the absence of wild fruit plants, monkeys have shifted to domesticated areas causing lot of damage to the cultivated crops and human dwellings, compelling the farmers to leave their land fallow.
- The fast growth and spread of these weeds prevent establishment of native trees and shrubs thus posing serious threat to the plant biodiversity in natural and manmade forests.
- Most of these weeds like *Lantana* and *Imperata* increase the risk of fires in plantations and forests as they readily burn, even when still green, destroying other vegetation and microfauna while they regenerate very rapidly, thereby displace other plant species
- Increased danger of wild animals to the inhabitants and their livestock.
- Environmental pollution due to pollen grains and volatile compounds released into the environment.
- Make the land barren by exploiting nutrients and moisture from the soil.
- Disrupt insect-plant associations necessary for seed dispersal of native plants.
- Disrupt native plant-pollinator relationships.
- Reduce and eliminate host plants for native insects and other wildlife.

- Hybridize with native plant species, altering their genetic makeup.
- Serve as host reservoirs for plant pathogens and other organisms that can infect and damage desirable native and ornamental plants.
- Replace nutritious native plant foods with lower quality sources.

Biology of problematic weeds of hill regions

Lantana camara (Linn.) belonging to family Verbanaceae is a woody scrub plant having 150 varieties with different flower colours and heights. Out of these, three varieties namely *aculeata*, *mista bailey* and *nivea bailey* have been reported from India (Gujral and Vasudeva 1983). Among these, *Lantana camara* var. *aculeata* is the most common having yellow or pink flowers changing to orange or scarlet, average plant height 30-120cm, thick pubescent leaves and having good seed production potential. It propagates by seeds, stem and roots and is disseminated by birds through their droppings and feces of moving flocks of sheep and goats who feed on its seeds. The compound lantadene 'A' lantadene 'B' and lancamarone have been reported to be the major toxic compounds present in this plant which cause phytotoxic effect to the animals (Sharma *et al.* 1981). It is also known to directly affect humans (Morton 1962). Its fruits are toxic to the children (Wolf and Solomons 1964). It is one of the ten most toxic weeds in the world (Holm and Herberger 1969). *Lantana camara* is reported to be a native of tropical America (Guana, cuba) and West indies. It has been found to be present in 50 countries but is the principal weed in twelve countries (Holm *et al.*1977) spreading over Oceania, Asia, Africa, South America and North America. It was introduced in India during 1809 as an ornamental plant (Gupta and Pawar 1984) but has now spread to almost all the states but its spread has been fast and abundance more in regions where unculturable wastelands are relatively more. The low and mid hills of Himachal Pradesh, Uttarakhand, Jammu & Kashmir and Eastern regions have been found to be very favorable for its luxuriant growth. It is spreading like a wild fire each year and is causing damage to the ecology thus increasing economic losses in term of forest wealth, livestock and reduced productivity of pastures and grasslands.

Ageratum, a herbaceous plant belonging to the family Asteraceae has two species namely *Ageratum conyzoides* L. and *Ageratum houstonianum* (Mill). Former is an annual weed infesting mainly cultivated upland *Kharif* crops like pulses, oilseeds and vegetable crops. It emerges in July and completes its life-cycle by October. Flowers are white to blue in colour and propagation is mainly by seed. The latter species is perennial invading uncultivated lands like pastures and grassland, orchards, tea gardens, forests, field bunds, wastelands and water channels. *Ageratum houstonianum* has violet- blue flowers and propagate through seeds, stem and roots. It has potential to produce up to 94,772 seed per plant having pappus structure at one end of the seed which help it to disseminate by wind, water, animals and machinery. Optimum and minimum temperature for germination of its seeds is 30-35 ^oC and 20 ^oC, respectively. The seeds remain dormant for 3 months (Angiras and Kumar 1995). Emergence occurs during June and October. The period of maximum growth is March-April. Alkaloids precocene-I & II, present in this weed cause giddiness, headache, skin and eye irritation to human beings and hazardous to animals when consumed with fodder. *Ageratum* is a native of tropical America and was introduced as an ornamental plant in India. Still, it is being grown as an ornamental plant in Gujarat. Because of favorable conditions for its germination, growth, development and seed production in hills and its faster rate of dissemination by wind, this weed has spread like a wild fire first in hilly regions and gradually to the plains. Although, it has spread to almost all the states of India but at present it is a serious problem in Himachal Pradesh (all districts except Lahaul and Spiti and Kinnaur), Punjab, Haryana, Assam, Uttarakhand and Uttar Pradesh.

Parthenium hysterophorus, a native of West indies and tropical North and South America, is an herbaceous plant belonging to family Asteraceae. It was introduced in India accidentally along with imported wheat from USA under PL-480 programme in 1955. Since then, it has invaded 35 million hactare land in India (Sushilkumar and Varshney 2010). It is a photo-thermo insensitive plant growing throughout the year and has invaded non cultivated and cultivated areas. The genus *Parthenium* has 20 species growing to a height of 1.0 -1.5 m. But *P. hysterphorus* is the most dominant as a weed. Morphologically characterized by angular longitudinally grooved, profusely branched hairy stem, irregularly dissected carrot like or *Chrysanthemum* like leaves with white flower heads. It propagates by seeds and crown buds. It gets disseminated by wind, water, machinery and animals especially sheep and goat. It may produces up to 25000 seeds from a single plant which are non-dormant and germinate at 25-30 ^oC. The plant normally completes its life-cycle within four months. Periodicity, however depends upon frequency and distribution of rains during the year. Accordingly, the plant completes 2-3 generations in a year. Under adverse conditions, plants remain dormant in vegetative phase and propagate through roots and stem. This characteristic helps it to persist over longer periods and makes difficult to control. Phyto-sociologically, it is rapid colonizer and outgrows other vegetation in its vicinity within two growing seasons. The average height of plants of *Parthenium* in hilly areas was recorded upto 2.09 m and its root system deep upto 17.32 cm below the ground level. It produced enormous number of seeds which help in its invasion in to various habitats. It was estimated that single plant of *Parthenium* produce more than 7397 seeds during one season. The seeds were lighter in weight and were 2.31 mm in length and 1.03 mm in width. In the Nort-West Himalaya, *P. hysterophorus* completed its two life cycles in one year, that is, from March to June and from July to November (Dogra *et al.* 2009)

Imperata cylidrica, a native of tropical America are rhizomatous, C_4 perennial grass weed belonging to the family *Poaceae*. It propagates by rhizomes and seeds but disseminate by wind and machinery. It flowers in April-May and September-October months. It colonizes rapidly in abandoned farm lands, orchards, tea gardens, field bunds, roadsides, pasture and grasslands suppressing the growth of other vegetation. Weed develops a thick mat of slender branched yellow-brown rhizomes just below the soil surface which produce slender leaves of 25-30 cm long. It produces feathery inflorescence among the leaves. It is fast disseminated even by light wind and seeds require moist conditions for germination. One plant can produce uptp 3000 seeds, which have little, or no dormancy period and may remain viable for over a year (Santiago 1965). Soon after germination, the plant starts to produce rhizomes and form dense stand in few years. Its spread is favoured by regular burning or slashing which removes competitors and helps to grow rapidly from the protected rhizomes. Allelopathy also helps them to compete with other species and its dominace in large area. The aggressive and invasive nature of *I. cylindrica* is attributed to its rhizomes. These are normally concentrated in the upper 15-20 cm of soil where they can remain dormant but viable for a long time (Ivens 1980). Rhizomes have a high regenerative ability because of the numerous buds that readily sprout into new shoots after fragmentation by tillage or any other form of disturbance. Rhizomes are resistant to fire because of deep soil burial. Deep burial also makes *I. cylindrica* very resistant to most control strategies (Holm *et al.* 1977, Ivens 1980). The ability of rhizome fragments to regenerate decreases with a reduction in length of rhizome segment. Longer rhizomes have better chances of sprouting because they have more carbohydrate reserves than short fragments (Ivens 1975).

Imperata cylindrica can grow on soils with a wide range of nutrients, moisture and pH (Santoso *et al.* 1997). Although, sometimes reported to be a weed of poor soils, *I. cylindrica* probably dominates these areas because of lack of competition from other plant species that cannot survive on marginal land (Santoso *et al.* 1997). It is a poor competitor and is easily suppressed by other species on fertile soils (Eussen and Wirjahardja 1973). It does not tolerate shaded environments because it assimilates carbon via the C_4 photosynthetic pathway (Paul and Elmore 1984). It is a strong competitor for growth factors such as water, nutrients, and light and sprouts and grows more rapidly than crops (C_3 plants).

Chromolaena, synonymus to *Eupatorium* and *Ageratina*, considered to be the native of Mexico and Jamaica belongs to the family Compositae have around 500 species all over the world. But in India *Chromolaena adenophorum, Chromolaena odora* and *Chromolaena riparium* are the most dominating species in hilly regions of North-East, North-West and Southern regions of India. Among these, *C. adenophorum* dominates in Himachal Pradesh. In India, it was introduced as an ornamental plant in 1924 and thereafter it naturalized Nagaland and other hilly states of the country. It flourishes in the areas located between 550 to 2000 m above mean sea level having year round rainfall and has overcome the native vegetation. There are reports that its faster growth and allelopathic effects even suppress the *Lantana camara* during rainy season. In hilly areas, it grows luxuriantly about 0.8-1.5 m tall on road sides, abandoned fields, sides of irrigation channels, pasture and grasslands, water channels, thin pine forests and tea gardens. It produces more than 3000 seeds per plant having more than 75 per cent viability. In Himachal Pradesh, this weed germinates in April–May and the plant grows vegetatively up to November-December with fast growth during June–September. Flowering starts in the last week of January and full blooming is observed in first week of April. The flowers are small and white in colour. The weed propagates through seeds as well as vegetative parts and is disseminated fast by wind, water and animals (Singh *et al.* 1996).

Urtica dioica (stinging nettle), a native of Europe and North America is a herbaceous perennial weed belonging to the family Urticaceae, 1 to 2 m tall in the summer and dying down to the ground in winter. It has widely spreading rhizomes and stolons, which are bright yellow as are the roots. The soft green leaves are 3 to 15 cm long and are borne oppositely on an erect wiry green stem. The leaves have a strongly serrated margin, a cordate base and an acuminate tip with a terminal leaf tooth longer than adjacent laterals. It bears small greenish or brownish numerous flowers in dense axillary inflorescences. American stinging nettle and hoary nettle are predominantly monoecious whereas European stinging nettle is typically dioecious. The fruit is an achene.

Stinging nettle may reproduces vegetatively and by seeds. It produces abundant seeds. Plants growing in the shade produce approximately 500 to 5,000 seeds per shoot and plants growing in full sunlight produce 10,000 to 20,000 seeds per shoot. Seeds are not dormant and can germinate 5 to 10 days after maturity (Basset *et al.* 1977). It is found mostly in soils rich in phosphate and Nitrogen. The leaves and stems are very hairy and also bear many stinging hairs (trichomes), whose tips when touched, transforming the hair into a needle that will inject painful chemicals. As a perennial weed, common nettle is troublesome around the margins of arable fields, pasture and grasslands, gardens and often encroaching into the fields under mid and high hills.

Management strategies

Perennial weeds are usually more difficult to manage than annuals because of their capacity to reproduce by vegetative means as well as seeds. In pastures and grasslands, proper management to establish and maintain desirable forage species is critical to prevent or retard the successful establishment of perennial weeds. The effective management of perennial weeds require integration of prevention, mechanical, utilization of cut biomass, chemical methods and utilization of the land as per its capability with improved practices. In addition, the control of shoot growth must be continued throughout the year. Different techniques which can help in managing these weeds are discussed hereunder.

Preventive approaches

The spread of these weeds can be checked by many ways described by (Angiras 2000). This can be achieved by:

- Creating awareness among public through press and media, field days and mass rallies in schools, colleges and universities about the harmful effects of these weeds so that people may remove the new plants entering in their areas before flowering.
- Educating the farmers not to leave the land fallow and to avoid use of feed and fodder from areas invaded by these obnoxious weeds.
- Creating competitive environment by managing the pasture and grasslands by planting improved grass species and favouring their growth and development with recommended fertilizer application, rotational grazing and cutting management techniques *etc.*
- Avoid over grazing beyond carrying capacity of the pasture lands.
- Avoid grazing of sheep and goats in *areas* invaded by these weeds.
- Monitor tourist places for presence new weed plants and kill them before flowering.
- Adopt phytosanitary measures by cleaning machinery, vehicles and livestock coming from weeds invaded areas.
- Manage these weeds on road sides through road maintenance staff of the Public Works Department as the first entry of these weeds in new areas occur along the roadsides and thereafter invade adjoining non cropped lands.

Mechanical methods

It involves physical methods of removing the weeds by manual or through machinery before flowering by:

- Slashing, burning and uprooting of obnoxious weeds immediately after rains.
- Frequent cutting before flowering to check seed formation and to exhaust, the food material of vegetative organ.

Lantana camara can be managed by following principal of destroying its food reserves, stoppage of food supply for their survival and and creating competition by growing useful vegetation. It involves cutting, pulling of the stumps during rainy season, planting of competitive plants or grasses and frequent uprooting of re-growth (Katoch 1988). This method is highly labour intensive and can not be applied in rocky areas and on steep slopes due to danger of soil erosion.

Six cuttings per year at 45 days interval from March or four cuttings at an interval of 45 days from July was also found to be effective to completely exhaust the food material in the roots to kill the plant completely without any regeneration (Singh and Angiras 2011). *Ageratum* and *Parthenium* plants should be cut or uprooted before flowering at frequent intervals. Put the cut biomass in compost pits with alternate layers of dung or prepare compost or vermicompost. Since the roots of *Chromolaena* are shallow, it can easily be uprooted during the rainy season before flowering. The uprooted biomass can be used for composting (Singh and Angiras 2008) or as mulch in the field. Three cuttings at 45 days interval from May or two cuttings at 45 days interval from

August exhausted the food material of the roots completely and did not allow it to regenerate thereafter (Singh and Angiras 2010). Frequent ploughing of land during hot weather expose the rhizomes of *Imperata cylindrical* and *Urtica dioca*to the drying action of the sun rays.

Biological methods

Both the classical biological control and use of allelopathic and competitive plants have been found effective to manage these weeds in areas where seasonal fluctuations in temperature and humidity are less. The effective bioagents and botanicals are given (Table 2)

Table 2. Bioagents for biological control

Weed	Biological agents
Lantana camara	Lace bug - *Teleonemia scruplosa* (Sushilkumar 1993, 2001) Flower feeder - *Asphondylia lantanae* Fruit borer - *Homona micaceana* Stem and root borer - *Plagiohamus spinipennis, Epinotia lantanae*
Ageratum houstonianum	*Cassia tora* (Angiras 1998)
Parthenium hysterophorus	Mexican beetle - *Zygogramma bicolorata* (Sushilkumar 2006, 2009) Allelopathic and Competitive plant *Cassia sericea* (Joshi 1989), *Cassia tora (*Angiras and Saini 1997, Sushilkumar and Bhan 1997, Sushilkumar and Varsheny 2007, Sushilkumar 2009) Gall midge - *Orsioliella javanica*
Chromolaena adenophorum	Gall fly (*Procecidochares utilis*), Fungus - *Cercospora eupatrii* (Singh 1989, Sushilkumar 1993)

Integrated methods

These obnoxious weeds can effectively be managed by integrated approach of chemical, mechanical and biological methods.

Lantana camara: Three phased integrated technology has been developed at CSKHPKV by Angiras *et al*. (1988) and demonstrated in large areas (Table 3) in farmers field as follows:

- Cut the *Lantana* bushes in August-September at 5-7 cm above ground and utilize the cut biomass for making furniture, vermicompost, charcoal brickets, agarbaties, mulch and fuel wood *etc*.
- Apply glyphosate 0.41% or 0.31% + surfactant 0.1% in September-October on 30-45 cm regenerated foliage.
- Utilize the land as per its capability to avoid emergence of other weeds by planting fast growing grasses (*Setaria*, *NB-37, Guinea*), fodder trees and other useful vegetation.
- Uproot or give spot treatment on plants (1-2%) emerging from already fallen seeds.

This technology has also been tested by other scientists in other states like Jammu & Kashmir (Sharma *et al.* 2012).

Table 3. Rehabilitation of *Lantana camara* invaded lands

Sites/District	Land use system	Approximate area (ha)
Saliana, Kangra	Pasture and grassland	10
Bandla, Kangra	Pasture and grassland	15
Ghaneta, Kangra	Forest and pasture land	1
Haroli, Una	Pasture and grassland	4

Ageratum houstonianum: This may be controlled as follows:

- Apply atrazine 1.5 kg/ha on emerging plants at their 2-3 leaf stage in May-June and or September -October by spray or broadcast application after mixing with 150 kg sand in grassland or pastures (Angiras 1998) or
- Apply glyphosate 1.5 kg/ha in 800 L water in May-June and September- October on old *Ageratum* plants before flowering (Angiras and Kumar 1995).
- Plant the improved grasses like *NB-37*, *Setaria*, Guinea grass *etc*. as per agroclimatic conditions.
- Apply atrazine 1.5 kg/ha or 2,4-D (Na) 1.5 kg/ha, if new plants emerge from seed already fallen in the soil (Angiras and Kumar 1995).
- Broadcast seeds of *Cassia tora* so that 35-40 plants/m^2 are maintained in wastelands (Angiras 1998).
- Cut or slash or spray paraquat 0.6 kg/ha at frequent interval before flowering on campaign basis so that further spread is checked.

In Hamirpur and Kangra district of Himachal Pradesh, at five large sites, *Ageratum* invaded area was rehabiliated (Table 4)

Table 4. Rehabilitation of *Ageratum* invaded lands

Site	District	Land use system	Area (ha)
Dhadamb	Kangra	Wasteland, pasture and grassland, orchard & cultivated land	3
Garh	Kangra	-do-	3
Bharmoti	Hamirpur	Wasteland, pastureland & orchard	3
Jajoli	Hamirpur	-do-	3
Bara	Hamirpur	Whole village	

***Parthenium hysterophorus*:** The following integrated technologies for different ecosystems have been developed and demonstrated on large scale (Sushilkumar and Varsheny 2007, Angiras and Kumar 2010):

- Wasteland ecosystem: Spray of glyphosate 0.5% before flowering + release of 350 adults of *Zygogramma bicolorata* during June-July + broadcast of seeds of *Cassia tora* by mixing with dung and soil.
- Grassland ecosystems: Spray of 2,4-D ethyl ester 0.2% / metribuzin 0.25%/ atrzine at 2-3 leaf stage + manual removal of old plants .
- Fertilize with 30 kg N/ha to stimulate and restore the growth of indigenous grasses to suppress the growth of *Parthenium.*
- Introduction of improved grasses like *NB-37, Setaria*.
- Forest land ecosystem: Introduction of *Zygogramma bicolorata* and broadcast of *Cassia tora*
- Roadsides: Mechanical removal by Public Works Department; spray of glyphosate 0.5 % + broadcast of *Cassia tora* seeds by mixing with dung and soil before the onset of monsoons + release of *Zygogramma bicolorata*.

In Kangra district, this technology was successfully demonstrated at Bairghatta area in abut 50 hactare land.

Imperata cylindrica: This weed may be managed by following approach:

- Hot weather cultivation during May-June by deep ploughing
- Spray glyphosate 1.0 kg/ha or glyphosate 0.75 kg/ha + surfactant 0.5% in June or dalapon 4.5 kg/ha in February or paraquat 0.6 kg/ha or cheeling (scrapping of existing weeds with spade) followed by spray of oxyfluorfen 0.25 kg/ha (Angiras *et al.* 1990).

Urtica dioca: This may be managed by following method:

- Cut the well grown stinging nettle plants close to the ground during dry periods and burn or compost the cut biomass. This will help to dry the surface roots in the sun and dry wind.
- Cut the overgrown plants and leave them to dry in the grazing areas for drying. The livestock eat the wilted plants and also damage the rootstocks by their trampling action
- After cutting, uproot the rootstocks as thoroughly as possible or give frequent surface cultivation or hoeing to exhaust the rootstocks eventually
- Spray glyphosate 1.5 kg /ha in waste lands or 2,4-D ethyl ester 0.75 kg/ha in pasture and grasslands on the newly generated seedlings
- Grow competitive grasses.

Utilization

Some studies have also been conducted on their utilization to check their further spread. Except some, most of the uses have not been exploited on commercial scale.

- Use as a fuel wood, biogas production, mulch and raw material for paper pulps, agarvatis, dhoop, baskets and furniture making, *etc*.
- These are rich source of plant nutrients after composting (Singh and Angiras 2011) and can add 30-40 kg N/ha.
- *Ageratum* has been used to protect the potato from attack of potato tuber moth.
- *Chromolaena adenophorum* has been reported to contain essential oils like 1-phellandrene, torreyol, anthemol and borryl (Katoch *et al.*2013). Therefore can be exploited as a valuable source for pharmaceutical industry.
- Extracts of these weeds have insecticidal, bactericidal, herbicidal and amoebicidal properties.
- These weeds may be utilized to checks soil erosion.
- Stinging nettle has been used as a food plant when young and tender. Plant is a rich source of protein, iron, calcium and magnesium and is considered to have the medicinal value. Fibres from the stem were used to make linen and ropes

Future research and management strategies

- Assessment of land area invaded by these weeds and losses by these weeds on environment, animal and human health and bio diversity required to be made with sophisticated techniques at national level.
- Antidotes against *Lantana*, *Parthenium* and *Ageratum* poisoning in animals and human beings are required to be investigated.
- Identification of allelochemicals and insecticidal factors are required to be investigated for development of bio herbicides and bio insecticides of the future.
- Biological agents to control these weeds are required to be investigated.
- Integrated technology to manage these weeds in respective areas on campaign basis with the involvement of Government agencies, scientists and people participation required to be developed.
- Need to screen competitive useful plant species to replace the obnoxious weeds in natural ecosystem.

- Mass education through extension activities regarding their hazardous effects need to be imparted.
- Need to adopt strict quarantine measures and mechanisms to monitor the introduction of new weed species at regular intervals and their management
- These weeds can be managed successfully by giving priority to manage them in Hills as they continue to act as a source of seed for the plains
- Need to create national level obnoxious weed management body to monitor and plan strategies to use the developed technologies on campaign basis at national level.

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Crop-weed interactions under climate change

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ABSTRACT

Weeds are major threat to agriculture and biodiversity as they out-compete crops and native species and contribute to land degradation. Changes in geographic distributions, abundances and life-cycles of weeds are the likely outcome of the effect of climate change. Natural evolution and certain specific characteristics such as short life cycles, dispersal mechanisms, may give the weeds a competitive advantage over less aggressive species under changing climate. Climate change may favour certain native plants to such an extent that they then become weeds. The dynamics of competition between weed and crop plants are affected by environmental conditions, and have been shown to change with atmospheric CO_2 concentration, temperature, precipitation and adaphic factors. Invasive weeds like *Lantana* and *Parthenium* may become more aggressive under climate change especially due to increases in atmospheric CO_2. Growth at elevated CO_2 would result in anatomical, morphological and physiological changes that could influence herbicidal uptake rates, besides translocation and overall effectiveness. The physiological plasticity of weeds and their greater intraspecific genetic variation compared with most crops could provide weeds with a competitive advantage in a changing environment. There is a possibility that agricultural weed populations will evolve new traits in response to emerging climate and non-climate selection pressures.

Key words: Climate change, CO_2 effect, Crop-weed interaction

Climate change projections suggest 2.4 to 6.4 ^{O}C increase of global average temperature by the end of 21st century (IPCC 2007). Studies indicate that significant warming is inevitable regardless of future emission reductions. If these forecasts are realized, crops and cropping systems are likely to experience significant changes and it is so for the associated weeds too. Weeds are major threat to agriculture and biodiversity as they out-compete crops and native species and contribute to land degradation. They reduce farm productivity through yield reduction and contaminate the crop produce. Research data strongly suggest that geographic range transformations for agricultural weeds are highly probable outcomes from global climate change (Patterson 1995, Fuhrer 2003). Climate change poses several challenges for managing weeds. Globally, there is a growing list of recent changes in species' distributions, abundances and life-cycles that are highly likely to be due to climate change.

Climate change means more extreme weather events, greater stress on native species, climate driven activities such as introduction of new species/crops. The increased extremes expected with the climate change, such as long drought periods and occasional very wet years, may worsen weed invasion because established vegetation (both native and crop) will be vulnerable, leaving areas for invasion. Weeds with high reproduction and efficient seed dispersal mechanisms may be better able to take advantage of the expected calamities like cyclones and floods. The characteristic of weeds to be able to respond rapidly to disturbances such as climate change, may give them a competitive advantage over less aggressive species. Agricultural adaptations to climate change, including new products and shifts into new areas, will also create more opportunities for weeds.

Extreme events create conditions congenial for weeds to extend their range and invade new areas or out-compete native species in their existing range. Drought and dry soil conditions prolong the weed seed bank longevity. Under drought the competitiveness of native vegetations get reduced and new weeds get the opportunity to invade. Floods assist in spreading weeds to weed free areas; provide characteristics for new weed invasion by washing away the vegetation and exposing the areas of disturbed soil. Warmer temperatures will force some species to relocate, adapt or perish. Species that are active in summer will develop faster. Warmer climate restrict temperature sensitive species to high altitudes. In plain areas, this effect on distribution range is magnified because species without the ability to move to higher elevations must relocate further in the same altitude. Weeds with efficient dispersal mechanisms are better equipped to shift their

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range, while species with short life-cycles are better equipped to evolve, and increase their tolerance of warmer temperatures.

Weeds respond to climate change by changes in geographic distribution, changes in the timing/duration of life cycles, changes in the population dynamics, shift in natural habitats and changes in the ecosystem structure and composition (decline or extinction of some species and invasion by other species)

Weed invasion and climte change

Climate change is expected to increase the risk of invasion by weeds from neighboring territories. With the competitive ability, weeds often find an opportunity to establish new populations when natural or desirable plant species decline. Climate change may also favour expansion of range of weeds that have already established but are currently restricted in range. The range expansion can be attributed to evolutionary adaptation (Clements and Di Tommaso 2011 and 2012). Weeds which have higher spread and establishment potential have the potential to invade new areas and increase their range. Weeds that are well-suited to adapt to the impacts of climate change may not only fill gaps left by more vulnerable native plants, they may have an even greater effect by altering the composition of ecosystems and their integrity. In fact, climate change may favour certain native plants to such an extent that they then become weeds. Land management practices such as land clearing, habitat fragmentation and over grazing that clear native vegetation and degrade its condition adversely affect the biodiversity and favour weed invasion by providing opportunities for them to colonise new areas and by reducing the ability of native vegetation to compete with and suppress invading species.

Growth and development of weeds

Weeds have a greater genetic diversity than crops. Consequently if the availability of a resource changes within the environment, it is more likely that weeds will show a greater growth and reproductive response (Trumble 2013). Number of studies showed that the rise in CO_2 induces growth stimulation without any discrimination between desirable (crops) and undesirable (weeds) plants. C_3 weeds (using one of two types of photosynthetic pathway, which responds to higher levels of CO_2 such as *Parthenium hysterophorus* may grow more rapidly under higher carbon dioxide levels and become more competitive (Poorter and Navas 2003 2008 McFadyen, Naidu and Paroha 2008,). CO_2 can affect plant and leaf size, seed size and production, the nutritive value of leaves to herbivores, plant toxicity and pollen production. Due to changing climate, changes in timing of life-cycles are expected that will affect flowering, fruiting and reproduction as the flowering is the most thermal sensitive stage of plant growth (Boote *et al.* 2005). Flowering can be faster, slower or unchanged at elevated CO_2, depending on species. From the studies conducted in OTCs at Directorate of Weed Science Research, Jabalpur, India, it was observed that under elevated $CO_{2,}$ wild oat (*Avena fatua*), seeds matured two weeks in advance compared to the plants grown under ambient CO_2 conditions (Naidu 2011).

Crop-weed competition: effect of CO_2, temperature and moisture stress

Changes in temperature, precipitation and increasing CO_2, all have potentially important consequences for crop/weed interactions, which is evident from a consideration of the basic biology of weeds and crops. Effects of climate change on crop-weed interactions are likely to vary by region and crop. These affects can be assessed by understanding the response of the physiological mechanisms to such factors. The dynamics of competition between weed and crop plants are affected by environmental conditions, and have been shown to change with CO_2 enrichment (Patterson and Flint 1980).

If the high CO_2 fixation rates are coupled with characters such as stoloniferous or rhizomatous spreading roots or the production of many easily disseminated seeds, the result is likely to be a very competitive plant. It was reported that the efficient species become relatively more competitive as light intensity increases. In addition, these species have high optimum temperature for photosynthesis and thus would become more competitive as temperature increases from 20 ^{0}C to 30 ^{0}C or 40 ^{0}C. At mid-day when light intensity and temperature both reach peak values weeds such as *Amaranthus* spp (C_4) and Johnson grass (*Sorghum halepense*, C_4) are expected to fix CO_2 at higher rate than the crops like soybean (C_3) and cotton (C_3). As high temperatures would also create increased evaporative demand, with its high water use efficiency and CO_2 compensation point C_4 photosynthesis is better adapted to high evaporative demand (Bunce 1983).

Some studies have shown that low or high temperatures reduce or eliminate the high CO_2 growth enhancement (Hofstra and Hesketh 1975, Idso 1990, Coleman and Bazzaz 1992), whereas others have shown that CO_2 enrichment may increase the plant tolerance to temperature extremes (Sionit *et al.* 1981, Potvin 1985, Baker *et al.* 1989). Based on the differences in temperature optima for physiological processes it is predicted that C_4 spp. will be able to tolerate high temperatures than C_3 spp. Therefore, C_4 weeds may benefit more than the C_3 crops from any temperature increases that accompany elevated CO_2 levels. Data from the results of the experiments by Alberto *et al.* (1996) suggest that competitiveness could be enhanced in C_3 crop (rice) relative to a C_4 weed (*Echinochloa glabrescens*) with elevated CO_2 alone but simultaneous increases in CO_2 and temperature still favor C_4 spp. An increase in temperature with accompanying soil moisture stress will offset the positive effect of the CO_2 fertilization; the net effect depends on the level of moisture stress. Increased temperatures have the potential to result in more invasive species introductions through expanded habitat range and greater potential for destructive outbreaks (Butler and Trumble 2012, Trumble 2013).

The interaction between CO_2 enrichment and other environmental factors such as water and nutrient availability and temperature may also result in differential response to CO_2 enrichment among weeds and crops (Patterson and Flint 1982, Bazzaz and Carlson 1984). The CO_2 enrichment tends to reduce the deleterious effects of drought (Sionit and Patterson 1985, Trumble 2013). Even under water limited conditions, growth enhancement by CO_2 appears to be greater in C_3 crops than C_4 weeds if the temperature increase is not as dramatic as predicted (Patterson 1986). Deep-rooted, woody plants and legumes are likely to have an advantage over grasses at higher CO_2 levels due to their ability to tap deep water reserves while still competing with grasses for moisture in the shallow soil layers.

Spread of invasive weeds and wake up of sleeper weeds

Invasive weeds are usually non-native, whose introduction results in wide-spread economic or environmental consequences (e.g. *Lantana camara* in India). Many of these weeds have strong reproductive capability. In many cases the impacts of invasive species beneûting from climate change are likely to exceed the direct impacts of climate change.

Invasive species generally benefit from habitat disturbances because they have characteristics that are likely to make them benefit from climate change. Recent evidence indicates that invasive weeds may show a strong response to recent increases in atmospheric CO_2 (Ziska and George 2004). Spread of invasive weed *Parthenium hysterophorus* was reported to be due to its response to climate change especially elevated CO_2 (Naidu 2013). Many invasive weeds are opportunistic breeders with wide climatic tolerance, whereas native communities may be more susceptible to climatic stress, making them vulnerable to invasion. Also, some native species may become invasive where other anthropogenic influences also favour them. Responses to climate change will be specific to individual species and will depend on a range of interacting factors. For example,the potential distribution of *Lantana* under historical climate exceeded the current distribution in some areas of the world, notably Africa and Asia. Under future scenarios, the climatically suitable areas for *L. camara* globally were projected to contract (Taylor *et al.* 2012).

Climate change, as well as the interactions between climate change and other processes (such as land management and new crop/cultivar introductions), may also turn some currently benign species (both native and non-native) into invasive species and may lead to sleeper weeds becoming more actively weedy. Increasing temperature might also allow some sleeper weeds to become invasive. Huge environmental damage and control cost can be prevented if these weeds are eradicated before they become widespread.

Indirect effects of climate change on weed menace

Higher temperatures and other factors are likely to increase pollinators, (insects) breeding cycles and provide more weed pollination there by increase the weed population. As animals, including invasive species, move into new areas in response to climate change, they are likely to spread weeds or create disturbance advantageous for weeds. Climate change will render native species more vulnerable to weeds either directly or indirectly, for example by facilitating the spread of the serious plant diseases. Importing of fodder and grain into drought prone areas can bring new weed problems to the region.

Climate change: challenge to weed management

Tillage is regarded as a global method of weed control in agronomic systems. Elevated CO_2 commonly stimulate the growth of roots and rhizomes more than that of shoots. Increased below ground growth in such species may make manual removal a difficult task as CO_2 rises. Growth at elevated CO_2 would result in anatomical, morphological and physiological changes that could influence herbicidal uptake rates, besides translocation and overall effectiveness. Climate change especially elevated CO_2 reduce the efficacy of foliar applied herbicides. The reasons for the reduced efficacy of the herbicides might be that increasing CO_2 can increase leaf thickness and reduce stomatal number and conductance possibly limiting the uptake of foliar applied herbicides. Greater increases in biomass could result in dilution of applied herbicide and thereby reducing its efficacy (Patterson 1995). If the growth of the weeds is stimulated by the future levels of atmospheric CO_2, the efficacy of the post-emergence herbicides would be reduced because the time spent by the weeds in seedling stage *i.e.* the stage of greatest herbicide sensitivity would be shortened (Ziska *et al.* 1999). At this situation, further applications or additional concentrations of the herbicides may be needed to control such weeds but add to the cost of control. Drought-stressed weeds are more difficult to control with post-emergent herbicides than plants that are actively benefitting. For example, systemic herbicides that are translocated within the weed need active plant growth to be effective. Pre-emergence herbicides or herbicides absorbed by plant roots need soil moisture and actively growing roots to reach their target species.

Natural and manipulated biological control of weeds and other potential pests could be affected by increasing atmospheric CO_2 and climate change. Climate changes could alter the efficacy of the biocontrol agent by changing the growth, development and reproduction of the selected weedy target. Elevated CO_2 and temperature directly alter morphology and reproduction of weeds. Change in C: N ratio may alter the feeding habits and growth rate of herbivores. Direct effects of CO_2 on increasing starch concentration in leaves and lowering nitrogen contents could also affect the biocontrol by altering the behavior and growth rate of herbivores.

Conclusions

Ecological systems are complex, with many factors being influenced by changing climate and land management practices. Weeds are both impacting on and being impacted on by factors such as land clearing, drought, fire and climate change. Many factors other than climate substantially influence actual species distributions including competitive exclusion, dispersal limitations, and patterns of disturbance. The physiological plasticity of weeds and their greater intraspecific genetic variation compared with most crops could provide weeds with a competitive advantage in a changing environment. Agronomic practices for particular crops are not static in time and space; new classes of herbicides, cultivars, tillage innovations, use of irrigation, and seed cleaning practices can all influence the geographic distribution and crop damage caused by agricultural weeds. For example recent introduction of glyphosate resistant crops can significantly change weed community composition (Harker *et al.* 2005). There is a possibility that agricultural weed populations will evolve new traits in response to emerging climate and non-climate selection pressures. (Clements *et al.* 2004). Reducing the impacts of weeds and preventing new weeds are essential to increasing the resilience of ecosystems and giving native species the best chance to deal with the adverse impacts of climate change. If weed species can be identified as favored due to emergent climate conditions in a given region, expanding or newly introduced populations can be targeted for control before they become well established.

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Herbicides residues in soil, water, plants and non-targeted organisms and human health implications: an Indian perspective

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ABSTRACT

Herbicides use is increasing throughout the globe due to increasing labour cost, choice of application of herbicides, quick weed control in crop and non-crop areas. In India, herbicide use has increased up to 30% during the last 10 years in the country. Herbicides are chemical in nature, therefore, excessive and repeated use may pose residue problems, phytotoxicity to crop plants, residual effects on susceptible intercrops or succeeding crops, adverse effects on non-target organisms and ultimately health hazards to human and animals. Many herbicides are found as bound residues which make them not only unavailable to the targets but also polluting the soil ecosystem in a number of ways. Thus monitoring of these residues in soil, water, plants, fishes and other matrixes is very much important. The fate of herbicide in soil depends on adsorption, absorption, volatilization, leaching, runoff, photodecomposition, degradation by microbial and chemical processes etc. In Indian tropical conditions, the half-life of imadazoline, phynylureas, sulfonylureas, triazines, chloroacetinalides, dinitroanilines, diethyl ethers, thiocarbamates, and fop group of herbicides in soil are found to varied 57-71, 13-60, 13-147, 12-58, 5-60, 12-77, 19-29, 19-24, and 8-24 days. At harvest, herbicides in various commodities were found either below the maximum residue limit or below detectable limits. Indirect effects of herbicides are not common in India. However increasing incidences of intentionally acute pisioning by some of the herbicide such as butachlor, fluchloralin, paraquat, 2,4-D, pendimethalin, glyphosate *etc.* are emerging problem in India. Paraquat poisoning is an uncommon entity in India, and is associated with a high mortality rate. It can be concluded that in India herbicide contamination of soil, plants and natural waters occurs infrequently and at low levels.

Key words: Health hazard, Herbicides residues, Implication, Monitoring of residue, Non-targeted organisms

Over the years herbicides have emerged as an important tool in management of weeds. Herbicides use is increasing throughout the globe due to increasing labour cost, choice of application of herbicides, quick weed control in crop and non-crop areas etc. After the discovery and use of 2,4-D as a herbicide following 2nd World War, there has been a phenomenal growth in development of new molecules as herbicides. Due to intensive research in herbicide discovery and mode of action of herbicides, many new molecules are available to cater the farmers need. Globally consumption of herbicides is 44% followed by the insecticides (22%), fungicides (27%) and others (7%). In India, herbicide use has increased to 30% during the last 10 years in managing weeds in the country. As herbicides are chemical in nature and thus excessive and repeated use may pose residue problems, phytotoxicity to crop plants, residual effect on susceptible inter-crops or succeeding crops or non-targets organisms and ultimately health hazards due to accumulation of herbicide residues in the soil, crop produce and ground water. Many herbicides are found as bound residues which make them not only unavailable to the targets but also polluting the soil ecosystem in a number of ways. There is a need to monitor herbicide residues in various commodities to assess buildup, bioma-gnifications and bioaccumulation of residues and adverse effects if any. Thus an exhaustive study on fate, degradation and monitoring of herbicide residues in soil, water, crop plants, fishes *etc.* have been conducted by Sondhia between 1999-2014 at Directorate of Weed Science Research, Jabalpur. Residue data was further strengthen by incorporating data from other studies conducted across the country.

Herbicide use pattern

In India, currently 51 herbicides are registered for use in various crops. Out of these, one belongs to category I of pesticide class (extremely hazardous), four belongs to highly hazardous, 26 belongs to moderately hazardous and 24 belongs to fourth category that is unlikely to cause any harmful effects with LD_{50} value > 5000 mg/kg (Table 1)

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Table 1. Herbicides registered in india under/section 9 (3) of the insecticide Act 1968 as on January 2014

Herbicide	Oral LD_{50} (mg/kg)	Toxicity rating *	Herbicide	Oral LD_{50} (mg/kg)	Toxicity rating
2,4-Dichlorophenoxy acetic acid	375-1200	II-III	Linuron	1254	III
Alachlor	930-1350	III	Mepiquate chloride	500-2000	II-III
Anilophos	>2000	III	Mesosulfuron-methyl +	5000	IV
Atrazine	3090	III	Iodosulfuron-methyl sodium	5000	IV
Azimsulfuron	5000	IV	Methabenzthiazuron	1000	III
Bensulfuron -methyl	>5000	IV	Metolachlor	2877	III
Bispyribac Sodium	4111	IV	Metribuzin	1090	III
Butachlor	3300	III	Metsulfuron- methyl	>5000	IV
Carfentazone ethyl	5143	IV	MCPA	700	III
Chlorimuron- ethyl	>5000	IV	Orthosulfamuron	>5000	IV
Clodinafop-propargyl	2276	III	Oxadiargyl	>5000	IV
Clomazone	1326	III	Oxadiazon	>5000	IV
Copper sulphate	30	I	Oxyfluorfen	>2000	III
Cyhalofop-butyl	>5000	IV	Paraquat dichloride	40-150	I-II
Dazomet	>2000	III	Pendimethalin	4050	IV
Diuron	3400	III	Penoxsulam	>5000	IV
Diclofop-methyl	563-693	III	Pinoxaden	>5000	IV
Ethoxysulfuron	3270	IV	Pretilachlor	6099	III
Fenoxaprop-p-ethyl	3110	III	Propanil	3269	III
Fluazifop-p-butyl	>5000	IV	Propaquizafop	>5000	IV
Fluchloralin	5580	IV	Pyrazosulfuron -ethyl	5000	III
Flufenacet	371-1365	II-III	Quizalofop ethyl	1210-1670	III
Glufosinate ammonium	2170	III	Quizalofop-p-tefuryl	1012	III
Glyphosate	>2000	III	sulfosulfuron	>5000	IV
Hexazinone	1690	III	Thiobencar (benthiocarb)	1033	III
Imazamox	>5000	IV	Triallate	1200	III
Imazethapyr	>5000	IV	Triasulfuron	>5000	IV
Isoproturon	>2000	III	Trifluralin	>5000	IV

Source: Central Insecticidal Board and Registration Committee

*I= Extremely hazardous, II= Highly hazardous, III= Moderately hazardous, IV= Unlikely to pose any hazards

Out of the total consumption of pesticides, 80% are in the form of insecticides, 15% are herbicides, 1.46% is fungicide and less than 3% are others. In comparison, the worldwide consumption of herbicides is 47.5%, insecticides are 29.5%, and fungicides 17.5% and others account for 5.5% only. Herbicide application is more common in wheat crop (44%), followed by rice (31%), plantation crop (10%), soybean (4%), and other crops (11%) (Fig. 1).

Herbicide residues

According to World healthorganization (WHO) "any substance or mixture of substances in food for man or animals resulting from the use of a pesticide and includes any specified derivatives, such as degradation and conversionproducts, metabolites, reaction products, and impurities that are considered to be of toxicological significance" are defined as herbicide/ pesticide residues.

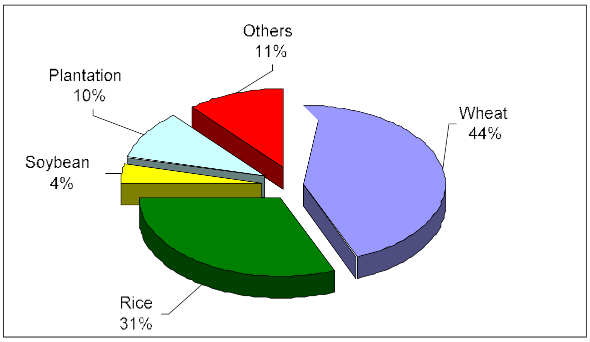

Fig. 1. Herbicide consumption in differet crops
Source: Shobha Sondhia

Fate and persistence of herbicide

As soon as a herbicide is applied, a number of processes immediately begin to remove the compound from the original site of application. For the herbicide which is intercepted by plants, the chemicals may be taken up by the plant itself, may be washed off by precipitation onto the soil, may undergo chemical/ microbial and /or photodegradation on plant surface or may volatile back into the air. Herbicides persistence in the soil is expressed as half-life or time required to degrade fifty percent of the original molecule (Table 2). However the half-life is not absolute because it depends on the soil type, temperature, and concentration of the herbicide applied. The persistence varies with the nature of a chemical, soil properties and climatic conditions. The herbicide should persist long enough to check weeds until the end of critical period of weed competition but should not persist beyond the crop harvest, as it would be injurious to the sensitive crops grown in rotation (Buchholtz 1965, Cornish 1992, Brandenboger 2007, Sondhia 2009, 2013). Beside herbicides structure, soil conditions prevailing during and after the application of a herbicide as well as herbicide application methods influence the fate of the herbicides in the soil (Elefttherohorines 1987, Webster and Show 1996, Latchana 1987, Sondhia 2005, Sondhia and Singh 2009). Heavy rainfall will cause greater leaching and runoff. Sandy soil would have a higher leaching potential than a clay soil due to larger pore spaces and lower CEC (Sondhia and Yaduraju 2005, Sondhia 2007, Sondhia 2008, 2009).

Higher humidity enhances the soil microflora proliferation. Similarly the persistence of herbicides in dry soil is greater as compared in wet soil. There are many chemical reactions which govern chemical degradation of herbicide in soil. Chemical degradation by redox reactions is common with anilines, phenols and dinitroanilines. Hydrolysis, ester formation, oligomerization/polymerization reactions catalyzed by clay surfaces and photolysis are common with fluchloralin, bentazon, and olefins. Some common pathways of biotic transformations such as oxidative process is common with phenoxy alkanoic acids, aromatic compounds, anilines phenylureas etc. However alkenes, alkines and nitro compounds undergo reductive transformation. Carboxylic esters, sulfates, 2, 6-dchloroben-zonitriles etc undergo hydrolytic process of transformation are common by biotic reactions (Table 2).

Degradation of herbicides by biotic reactions is generally followed by oxidative processes such as beta-oxidation, C-cleavage, C-hydroxylation, N-oxidation, N-demthylation, either cleavage, C-reduction, N-reduction, hydrolysis and mineralization. Whereas oxidation, reduction, mineralization, hydrolysis, ester formation, photolysis, polymerization etc. reactions are common by abiotic degradation.

Table 2. Half-lives of some herbicides in soil

Herbicide	Half lives (Days)	Herbicide	Half lives (Days)
Atrazine	13-58	Metribuzin	23-49
Butachlor	5-24	Metolachlor	8-27
Fluazifop-p-ethyl	8-24	Oxyfluorfen	12-29
Fluchloralin	12-46	Pendimethalin	15-77
Dithiopyr	11-25	Pretilachlor	10-11
Imazethapyr	57-71	Sulfosulfuron	3-27
Isoproturon	13-21	2,4-D	7-22
Chlorosulfuron	31-93	Metsulfuron-methyl	70-147
Chlorimuron	60	Thiobencarb	19-24
Flufenaccet	9-22	pyrazosulfuron	16-21

Source: Sondhia and Varsheny (2010)

Herbicide degradation and residues in the soil

A herbicide is said to be persistent when it may be found to exist in soil in its original or a closely related but phytotoxic form longer than one crop season after its original application (Sondhia 2005, 2011). Herbicide residues in crop produce above the safe level can cause health hazards to men and animals. Ultimate fate of herbicide in soil depends on number of processes such as volatilization, leaching, runoff and degradation by microbes, chemical processes and photodecomposition. Persistence of pyrazosulfuron-ethyl was studied in three different soils (Shimoga, Mandya and Chamrajanagar) of Karnataka under three moisture regimes (maximum water holding capacity, half maximum water holding capacity and submergence). The persistence of pyrazosulfuron-ethyl indicated a close correspondence to first order exponential degradation kinetics in soils and mainly influenced by soil organic matter and moisture. Faster disappearance was noticed under submergence followed by maximum water holding capacity and half maximum water holding capacity in all soils. Half lives for pyrazosulfuron-ethyl in soil under various water holding ranged from 42.9-85.5 days (Mukherjee *et al.*2010, Kumar *et al.* 2011, Singh *et al.* 2012, Sondhia *et al.* 2013). Chlorsulfuron degraded faster in low pH soil rather than in high pH soil and showed higher GR_{50} value in low pH soil as compare to high pH soil (Amarjeet *et al.* 2003). Half life of some herbicides under Indian tropical conditions in soil is presented in Table 2.

The addition of organic manure affects the biological, chemical and physical properties of soil that control the fate of herbicides. Three dinitroaniline, pendimethalin, trifluralin and fluchloralin herbicides were studied to assess their persistence, dissipation and residue management in sandy loam soil with and without addition of farmyard manure (FYM) under Middle Western Indian agro-climatic conditions in Indian mustard (*Brassica juncea* L.). FYM incorporation at a rate of 10 t/ha decreased herbicide persistence and relatively lower half-lives of 44.93 to 39.09 days were recorded with FYM incorporation, each at the rate of 0.5 and 1.0 kg/ha for pendimethalin, trifluralin and fluchloralin . On the other hand, the half-life in absence of FYM was higher for all three dinitroaniline herbicides. Triasulfuron residues dissipated from field soil with half-life of 5.8 -6 days at two rates of application following a first-order-rate kinetics through biphasic degradation with faster rate initially ($t_{1/2}$ = 3.7 days), followed by a slower dissipation rate at the end ($t_{1/2}$ = 9.4 days). Similar trend was observed with non-sterile soil in laboratory with a longer half-life. Acidic pH and microbial activity contributed toward the degradation of triasulfuron in soil (Singh and Kulsherestha 2006).

Metsulfuron-methyl dissipated more rapidly in acidic silty loam soil as compared to high pH soil and light did not play any role in altering the persistence (Yadav *et al.* 1997). A bioassay technique could detect the residue of metsulfuron-methyl up to 30 days in surface soil, while, with HPLC, residues detectable upto 15 day only. The half-lives of metsulfuron-methyl was found 6.3-17.5 days (Paul *et al.* 2009). However residues of metsulfuron-methyl rice soil at 30 days was found 0.008-0.016 µg/g at 2-8 g/ha application rates. Whereas residue in soil, rice grains and straw at harvest was found below 0.001 µg/g (Sondhia 2009b). Sushilkumar *et al.* (2008) reported that metsulfuron-methyl residues were not detected after 60 days at 16 g/ha application rate, but at higher application rates 20-24 g/ha, 0.002 and 0.011 mg/kg residues were found in back soils of Jabalpur. However Sondhia and Singhai (2006) and Sondhia (2008b, 2009b) found residues below the detection limit at 3–5 g/ha application rates and 0.002 µg/g residues were detedted at 8 g/ha, in wheat plants at harvest. The oxyfluorfen residue dissipated faster in wheat plants than in soil respectively, with a mean half-life of 6.1 and 11.2 days. Dissipation followed first-order kinetics. A sorption study revealed that the adsorption of oxyfluorfen to the soil was highly influenced by the soil organic carbon with the K_{oc} value of 5450 and dissipation of oxyfluorfen in soil and onion was dependent on the physico-chemical properties of the soil and environmental conditions (Janaki *et al.* 2013). Ethoxysulfuron residues were found below <0.001 µg/g in rice soil at harvest at 15 to 20 g/ha doses, respectively (Sondhia and Dixit 2012).

Atrazine in soil showed a gradual degradation with advancement in maize plants growth and residue were not found at harvest whereas 0.056 mg/kg of residue in the post-harvest soil were found at double the recommended dose (Janaki *et al.* 2012). Bromacil and diuron residues at 3 kg/ha persisted on top 2.5 cm of the soil profile even after eight months (Leela 1984). Kulshrestha *et al.* (1977), Sandhu *et al.* (1994), Sondhia (2001, 2002), and Nag and Das (2009) and Janaki *et al.* (2012) reported that more than 95 percent of atrazine dissipated from the field at the time of crop harvest. The half-life values were found to be 9.38-21.54 days in soil. Pre-emergence applications of atrazine and simazine at 1.5 kg/ha persisted up to 47 and 83 days, respectively (Sharma and Angiras 1997). Kausik and Moolani (1974) reported 97% atrazine dissipation from the soil within 4 months in which maize plants were growing whereas about 83% atrazine dissipated from un-cropped soil. The persistence of fluazifop-p-butyl at two rates of application and at three temperature level revealed fast degradation in soil to corresponding acid, fluazifop-p-butyl as only 2% fluazifop-p-butyl was recovered after 24 h. The acid form of the herbicide had a half life of 19.8-23.9 days. Persistence was inversely related to the soil temperature (Raut and Kulsh-restha 1991). The residue level of fluazifop-p in soil was found 0.051 to 0.079 µg/g at 125-500 g/ha application rates in soybean field (Sondhia 2007).

Sondhia *et al.* (2006) reported rapid dissipation of butachlor in rice field as compared to laboratory conditions with half-life of 18.1-23.0 days at 1.0 -2.0 kg/ha. The butachlor degradation in soils were mainly influenced by soil organic matter and moisture and rapid disappearance was noticed at field capacity followed by submergence and air dry conditions in all soils. 2, 4-D at 0.4 kg/ha alone and in combination with anilofos persisted up to harvest with half-life of 18-22 days (Jayakumar and Ramulu 1993). Clodinafop-propargyl ester generally convert to acid (a major metabolites) and which is also responsible for herbicidal action. It was found that dissipation of clodinafop was not affected by specific soil pH and soil type. Residues of clodinafop in soil was found 0.093 to 0.081 µg/g in alluvial, red and black soil (Roy and Singh 2006, Sondhia and Mishra 2005). Fentazamide residues at 240 g/ha application rate were found 0.03 to 0.04 mg/kg in soil of rice field in a three year study with a half life of 20 days, however residues were below the detection limit in rice husk and straw (Tandon *et al.* 2012). Chloropheny-ltetrazoline and cyclohexyl ethylamine have been identified as major and minor metabolites of fentazamide in soil (Mukherjee and Gopal 2005). In a monitoring study of four herbicides, butachlor residues alone contributed 61% followed by pendimethalin (36%), and fluchloralin (3%). Alachlor was not detected in all the locations. The total range of herbicides was <0.01 to 1.46 ng/g with a mean of 0.21 ng/g. The individual concentration of herbicides ranged 0.03-1.28 ng/g (pendimethalin), 0.02-1.22 ng/g (butachlor), 0.01-0.25 ng/g (Kumar 2011). The residues of pretilachlor dissipated to below detection limit within 30 days after application when applied with green manure, while at 0.75 to 1.5 kg/ha rates, it persisted up to 45 days with a half-life of 3.9 to 10.0 days (Dharumarajan *et al.* 2008).

Sorghum and cucumber plants were found very sensitive bioassay plants for metribuzin and could detect residues even at 0.010 and 0.046 mg/kg in the post harvest soil of potato crop (Sondhia 2005). At harvest no detectable residues of fenoxaprop-ethyl or acid were detected in soil, wheat grain and straw samples at recommended doses (Sondhia 2007, Singh *et al.* 2013). In paddy field benthiocarb residue dissipated to 90% within 30 days in soil and no residues were detected in soil as well as in straw, grain and husk samples at harvest when applied at 1500 to 3000 g/ha in transplanted paddy field (Aktar *et al.* 2007). However, Kumar (1993) reported lower temperature and higher concentration resulted in greater persistence (Jayakumar and Ramulu 1993). Adsorption of alachlor increased with increase in concentration, time of incubation, rise in activation temperature, lowering of pH and increase in the organic matter content (Sethi and Chopra 1975). Sondhia (2002) reported that alachlor and fluchloralin residues were not detected in the soil at harvest at 1.0 kg/ha rate in the soybean field but at 1.2 and 1.5 kg/ha rates, 0.01 and 0.02 µg/g residues were detected at harvest. Whereas in sandy loam soil of Karnataka, alachlor persisted upto 60 days at 1.5 kg/ha application rate applied as pre-emergence in vegetable crops (Leela 1993).

Fluchloralin degraded at faster rate in flooded anaerobic soil than in aerobic soil and amendment of fluchloralin with organic matter enhanced degradation of flooded anaerobic soil and dealkylated fluchloralin, partially reduced fluchloralin and its cyclic product were detected as major degradation products (Singh and Kulshrestha 1995). Patel *et al.* (1996) found that persistence of the pre-plant incorporated fluchloralin at 0.67-1.35 kg/ha application rates was longer in the loamy soil as compared to sandy loam soil with the half-life values in both the soils ranged between 42.4 to 45.6 days. Fluchloralin translocated to leaves and roots of chicory crop and was detected on the 60th day of application and did not found at harvest. Kalpana *et al.* (1999) found that fluchloralin applied at 1.00 kg/ha in a sandy loam soil in onion crop showed first-order rate kinetics in a biphasic mode and residues were not found at harvest.

Dissipation of pendimethalin in the field peas (*Pisum sativum* L.) and chickpea soil followed first-order kinetics showing a half-life of 11.23-19.83 days averaged over all doses (Sondhia 2012, 2013). Kulshrestha *et al.* (2000) reported that repeated application of pendimethalin on the same soil led to rapid degradation of pendimethalin in each successive year with each successive crop. Pahwa and Bajaj (1997) found that persistence of pendimethalin and trifluralin was directly correlated with temperature and application rate. Pendimethalin in a sandy loam soil applied at 1 to 4 kg/ha rates in wheat crop showed persistence up to 200 days and caused phytotoxicity to the succeeding sensitive sorghum crop at higher dose (Yadav *et al.* 1995). Pendimethalin was found to be persistent in the soil of cabbage field however residues did not translocated to plant parts (Arora and Gopal 2004). Persistence of some herbicides under Indian tropical conditions in soil is given in Table 3.

Goyal *et al.* (2003) reported that intermittent wetting and drying resulted in a very high persistence (90-99%) of trifluralin whereas with continuous ponding, the persistence of trifluralin decreased to 22-40% in alluvial soil. Sondhia (2006) reported 0.008 µg/g imazethapyr residues at harvest in the soil of soybean crop at 100 g/ha application rate. Sondhia (2006, 2008) reported 0.002, 0.006, 0.0075 and 0.010 µg/g residue of imazosulfuron in the soil of transplanted rice field after 60 days at 30-60 g/ha application rates, however no residues were found after 90 and 120 days. Sulfosulfuron followed first order dissipation kinetics in soil at 25-50 g/ha application rates and residues were not detected in the soil at harvest under wheat cropping system (Ramesh and Maheshwari 2003, Sondhia and Singh 2008). However after150 days residues were found below 0.001 µg/g in soil samples collected from 25 to 50 g/ha treated plots (Sondhia and Singhai 2008).

The adsorption–desorption revealed strong adsorption of dithiopyr in alluvial soil with K_d values ranging from 3.97–5.78 and Freundlich capacity factor (K_F) of 2.41. The leaching studies carried out under saturated flow conditions revealed that dithiopyr was highly immobile in alluvial soil. Strong adsorption of dithiopyr may cause a greater persistence in the soil (Gupta and Gajbhiye 2002). Singh and Kulshrestha (2006) reported dissipation of triasulfuron at 15 and 20 g/ha in soil under wheat crop with half-

Table 3. Persistence of some herbicides under tropical conditions in soil

Herbicide	Persistence in soil (days)	References
Atrazine	45-90	Kulshrestha *et al.* (1977), Sandhu *et al.* (1994), Sharma and Angiras (1997), Nag and Das (2009)
Alachlor	60-80	Leela (1993), Sharma (2002)
2,4-D	45-90	Kumari *et al.* (2004), Sushilkumar *et al.* (2008)
Butachlor	100	Sondhia *et al.* (2006)
Dithiopyr	90-150	Gupta and Gajbhiye (2002)
Fluzifop-p-butyl	30-90	Leela (1993), Sondhia (2007)
Isoproturon	90-120	Yaduraju *et al.* (1993), Sondhia and Singh (2006)
Imazosulfuron	60	Sondhia (2006, 2008)
Metoxuron	80	Randhawa and Sandhu (1997)
Metribuzin	20-100	Sondhia (2002)
Oxadiazon	56-125	Leela (1993), Raj *et al.* (1999)
Pyrazosulfuron-ethyl	35-60	Mukherjee *et al.* (2010), Naveen *et al.* (2012), Sondhia *et al.* (2013)
Pretilachlor	30-60	Dharumarajan *et al.* (2008), Kumar (2011), Sondhia (2012)
Pendimethalin	60-200	Yadav *et al.* (1995), AICRP Annual report (1999), Kalpana *et al.* (1999), Rai *et al.* (2000), Gowda *et al.* (2002), Sondhia (2012, 2013)
Tralkoxydim	28-45	Srivastava *et al.* (1995)
Thiobencarb (benthiocarb)	28-60	Jayakumar and Ramulu (1993), Aktar *et al.* (2007)
Oxyflourfen	60-80	Devi *et al.* (1998)
Imazethapyr	90-240	Rana and Angiras (1993), Sondhia (2007, 2012)
Metolachlor	40-190	Devi *et al.* (2000), Sanyal and Yaduraju (2008)

life of 5.8 and 5.9 days. Isoproturon degraded to non-detectable level within 60 days at 0.94 kg/ha rate in Ludhiana, it took 75 days in Badrukha, Kum Kalan and Chakkar district for its complete degradation (Walia *et al.* 2000). Isoproturon applied at 1.0 kg/ha rate in wheat crop degraded completely at harvest in black soil of Jabalpur (Randhawa and Sandhu 1997, Sondhia 2002, Sondhia and Singh 2006). Isoproturon residues at 0.5 and 1.0 kg/ha application rates were found 0.0213 mg/kg after 70 days and 0.0201 mg/kg after 120 days in soil of potato crop (Yaduraju *et al.* 1993). Gupta *et al.* (2001) found that flufenacet dissipated to about 98% in soil after 60 days and no residues were detected after 90 days under submerged conditions than field capacity. Sondhia (2002) reported that metribuzin applied at 0.85 and 1.20 kg/ha persisted up to harvest in black soil in potato crop in Jabalpur. Rai *et al.* (1997) found rapid degradation (40-61%) of anilofos after 30 days of incubation under flooded than non-flooded conditions. Anilofos at 0.4 kg/ha application rate persisted up to 56 days in direct seeded rice field (Radhamani *et al.* 1997).

Sondhia and Khare (2014) demonstrated sorption of cyhalofop-butyl in sandy clay loam and clayey soils using a batch equilibrium method. Adsorption of cyhalofop-butyl was found positively related with clay and organic carbon content and cyhalofop-butyl was highly adsorbed in clayey than sandy clay loam. Adsorption isotherm suggested a relatively higher affinity of the cyhalofop-butyl for the adsorption sites at low equilibrium concentrations. Metolachlor applied as pre-emergence at 1-2 kg/ha application rates was dissipated almost 100 % in the soil at harvest under field condition (Singh *et al.* 1997). Dissipation of metolachlor occurred in two distinct phases. The initial slow rate could be due to degradation and adsorption on soil. After one month herbicide dissipated rather rapidly (Singh *et al.*1997). Sanyal *et al.* (2000) demonstrated moderate persistence of metolachlor with a half-life of 27 days in the field conditions and leached to a depth of 15-30 cm in soil. It was found that fungi *Aspergillus flavus* and *Aspergillus terricola* rapidly degraded metolachlor applied at 10 kg/ha up to 92% and 87% after 20 days in sterile and non-sterile soils, respectively (Sanyal and Kulshrestha 2003). Following the first order kinetics, the diclosulam dissipates in soybean crop soil with half-life values ranging between 5.28-8.36 days in three consecutive seasons, irrespective of the doses (Bhattacharyya *et al.* 2012).

Herbicide residues in cereals

The analytical results of herbicide residues in various crops indicated global presence of residues but below the alarming level. Using the latest hi-tech analytical devices, the presence of herbicide residues can be easily detected at ppb level. Based on extensive herbicide residue work conducted at Directorate of Weed Science Research, Jabalpur, All India Coordinated project on Weed Control (AICRP-WC) and various sources in India, in about 80 percent samples, residues were found below detection limit (BDL), 13.4 percent below maximum residue limit (MRL) and 6.6 percent residues were found above MRL values.

Rice: Sondhia and Dixit (2012) demonstrated that ethoxysulfuron dissipated at faster rate in soil and plants and residues were found below 0.001 μg/g in grains and straw at harvest at 15-20 g/ha application rates. Imazosulfuron residues were found to be 0.009 and 0.039 μg/g at 50 and 60 g/ha rates, respectively in rice and residues were not detected at 30-40 g/ha in rice grains and straw (Sondhia 2007, 2008). The residue level of butachlor in rice grain and straw samples were found 0.029 and 0.042 μg/g, respectively (Sondhia *et al.* 2006). Harvest time samples of paddy grains, rice bran and straw, treated with butachlor showed residues below the detectable levels in rice, 0.002 mg/kg in bran, 0.009 mg/kg in straw and 0.006 mg/kg in rice grains at 1.0 kg/ha and at 2 kg/ha, the residues were 0.001, 0.005, 0.010 and 0.025 mg/kg in rice, bran, straw and paddy grains, respectively (Reddy *et al.* 1998). Deka and Gogoi (1993) found 0.012 and 0.007 mg/kg residues in rice grains and straw after treatment with butachlor at 2.0 kg/ha rate.

In paddy straw 0.01-0.03 μg/g oxyfluorfen residues were detected at 240-500 g/h arates. Residues were 0.028-0.03 μg/g in soil when oxyfluorfen was applied at 240-500 g/ha rates. However, in rice grains, 0.018-0.106 μg/g of oxyfluorfen residues were detected in 240-500 g/ha treated plots (Sondhia 2009). Residues of metsulfuron-methyl and pretilachlor in rice grains and straw at harvest were found below 0.001 μg/g (Dharumarajan *et al.* 2008, Sondhia 2009). In plant foliage collected at harvest traces of atrazine residues were detected in few samples in first year but in the second year's residues were not detected (Nag and Das 2009). Fentazamide residues were below the detection limit in rice husk and straw at 240-420 application rates. Chlorophenyltetrazoline and cyclohexyl ethylamine have been identified as major and minor metabolites of fentazamide in soil (Mukherjee and Gopal 2005). Butachlor dissipated with half life varied from 12.5 to 21.5 days at 1.0 and 2.0 kg/ha application rates under with and without organic manures conditions. Low levels of residues were detected in rice grain (Rao *et al.* 2012). Devi *et al.* (1997) and Jayakumar and Sankaran (1995) reported that butachlor and anilofos residues in rice crop were found below the maximum permissible residue limit (0.25 mg/kg) in soil. Sondhia *et al.* (2004) reported that butachlor residues were not detected after 120 days in clay loam soil applied at 1.0 kg/ha in transplanted rice crop. The pre-emergence application of anilofos and thiobencarb applied at recommended doses continuously for four seasons in rice crop showed residues in soil, rice grains and plant parts below the maximum allowable level (Balasubramanian *et al.* 1999).

Wheat: In a field experiment, residues of isoproturon were found to be 0.006, 0.041 and 0.022 μg/g in post-harvest soil, wheat grain and straw, respectively, while 0.021 and 0.096 μg/g residues of clodinafop was present in soil and grain at higher level of application (Arora *et al.* 2013). At harvest, no residues of metsulfuron-methyl were detected in wheat grains at 3-4 g/ha rates. However 0.002 μg/g residues were detected in wheat straw at 5-8 g/ha application rates (Sondhia 2008). In wheat field soil, residues persisted beyond 30 days with a first order rate kinetics biphasic dissipation with initial faster dissipation followed by a slower dissipation during later period. Wheat grains, straw and soil collected at harvest (112 days) contained residues below detectable limits (Singh and Kulshrestha 2006). In a three year field trials revealed no detectable amount of tralkoxydim in treated samples of soil, wheat grain and straw at harvest of wheat (Srivastava *et al.*1994, Srivastava *et al.* 1995).

Clodinafop residues were not detected in the wheat grain and straw at doses 60-120 g/ha however 0.0089 mg/kg residues were detected in wheat grains at 240 g/ha treatment (Sondhia and Mishra 2005). Sulfosulfuron residues were not found in wheat grains, straw and subsequent vegetables in natural ecosystem as well as in model ecosystem at recommended rates in wheat crop (Ramesh and Maheshwari 2003, Sondhia *et al.* 2007, Sondhia and Singhai 2009). Isoproturon dissipated by 120 days in the soil of wheat crop applied at 1.0 kg/ha and residues were not detected in wheat grains and straw at harvest (Sondhia and Singh 2006). Persistence of clodinafop-propargyl evaluated at Ludhiana showed that it degraded to safe level by 60 days at 0.03 to 0.04 g/ha application rates and at higher doses, *viz.* 11 and 22 g/ha, residues persisted for more than 80 days. Whereas Singh *et al.* (2004) reported that clodinofop at 60 and 120 g/ha rates in wheat crop degraded completely by harvest and hence residues of clodinofop were not detected in wheat grains and soil at harvest. Metribuzin residues were not found in the soil, grains and straw following an application at 210 -420 g/ha in wheat crop at Pantnagar (Dubey *et al.* 1998). Fenoxaprop residue in the soil of wheat field was found 0.0004-0.0011 µg/g at 70-400 g/ha application rates (Sondhia 2006). In an experiment initially 0.0434, 0.0888 and 0.1661 µg/g residues of fenoxprop-p-ethyl, carfentrazone and pinoxaden were detected in the wheat soil which dissipated to 0.0026 µg/g at 30 days. At 90 days fenoxaprop-p-ethyl, carfentrazone and pinoxaden residue were in wheat soil were found to be <0.001 µg/g. Half life of fenoxaprop-p-ethyl, carfentrazone, and pinoxaden in the soil of wheat field was found 16.61, 9.15 and 8.62 days (Sondhia 2014). Herbicide residues in crop plants at harvest are given in Table 4.

Herbicide residues in pulses: Terminal residues of pendimethalin were monitored in the green field peas (*Pisum sativum* L.) and chickpea (*Cicer arietinum* L.) applied as pre-emergence herbicide at 750-185 g/ha rates. Low pendimethalin residues were found in mature pea grains (0.004-BDL µg/g), and straw (0.007-0.001 µg/g) at 750-185 g/ha treatments, respectively (Sondhia 2013). Pendimethalin residues were 0.025, 0.015, <0.001 µg/g in chickpea grains at 750 to 185 g/ha treatments. Much lower pendimethalin residues, *viz.* 0.015 to <0.001 µg/g were found in straw at 750, 350 and 185 g/ha treatments, respectively (Sondhia 2012). Mandal *et al.* (2014) and Mukhopadhyay *et al.* (2012) demonstrated that at harvest, the residues of quizalofop ethyl on black gram seed, foliage and soil were found to be below the detection limit of 0.01 mg/kg following a single application of the herbicide at 50-100 g/ha for both the periods. In another study persistence and degradation kinetics of trifluralin applied as pre-emergence in black gram at 1.0 to 2.0 kg/ha for the control of broad leaf weeds was conducted. The dissipation at 90 days was found approximately 97% and followed first order kinetics with the half life 23.3 to 26.2 days. Irrespective of any dose, no residues of trifluralin were detected in black gram crop soil and plant samples at harvest (Aktar *et al.* 2009).

Herbicide residues in oilseed crops: In a three seasons field trial conducted under West Bengal conditions, diclosulam residues were found to be below detectable level (BDL) in soybean plant samples irrespective of the treatment doses and the days in all seasons (Bhattacharyya *et al.* 2012). The residues of imazethapyr in soil, soybean grains and straw were found 0.008, 0.102 and 0.301 µg/g, respectively at 100 g/ha application rate (Sondhia 2008). Fluazifop-p-butyl, applied to soybeans, at 0.25 and 0.50 kg/ha at New Delhi, dissipated to 0.1 mg/kg in 30 days from both the dosages and was below detectable limits (0.08 mg/kg) in 60 days (Singh *et al.* 1999). Fluazifop-p-butyl can leach up to 15 cm soil and at harvest 0.012-0.036 mg/kg residues were found in the soil of soybean crop with 0.250-0.500 kg/ha rates, application and fluazifop-p-butyl at 0.5 kg/ha rate resulted in the translocation of 0.005 and 0.001 mg/kg residues to soybean grains and cake, respectively (Kulshrestha *et al.* 1995). The residue level of fluazifop-p in soil was found to be 0.051 to 0.079 µg/g at 125 to 500 g/ha applied rates. Residues of fluazifop p-butyl were 0.472, 0.554 and 0.702 µg/g in soybean straw and 0.297, 0.300 and 0.312 µg/g in soybean grains at 125,

Table 4. Residues of some of the herbicides in the soil, food grain and straw

Herbicide	Crop	Dose (g/ha)	Residues (µg/g)			References
			Soil	Grain	Straw	
Ethoxysulfuron	Rice	15-18.7	<0.001	<0.001	<0.001	Sondhia and Dixit (2012)
Butachlor	Rice	1000	0.005	0.025-0.002	0.029-0.006	Deka and Gogoi (1993), Reddy *et al.* (1998), Sondhia *et al.* (2006)
Sulfosulfuron	Wheat	25	BDL	0.010- BDL	0.004- BDL	Ramesh and Maheshwari (2003), Sondhia *et al.* (2007)
Metsulfuron-methyl	Rice	4-4	BDL	BDL	0.002	Sondhia (2008)
	Wheat	4-8	BDL	BDL	BDL	Sondhia
Isoproturon	Wheat	1000	0.006-0.032	0.035-0.041	0.065-0.022	Sondhia and Singh (2006), Arora *et al.* (2013)
Oxyfluorfen	Rice	150-250	BDL	0.018	0.106	Sondhia (2009)
Imazethapyr	Soybean	100	0.016	0.210	BDL	Sondhia (2007, 2008), Patel *et al.* (2009)
Imazosulfuron	Rice	30-40	BDL	BDL	BDL	Sondhia (2008)
		50-60	BDL	0.006-0.009	0.009-0.039	Sondhia (2008)
Fentazamide	Rice	240-420	BDL	BDL	BDL	Mukherjee and Gopal (2005)
Anilofos	Rice		<MRL	<MRL	<MRL	Jayakumar and Sankaran, (1995)
Fluazifop-p-butyl	Soybean	500	0.012-0.036	0.005	0.001	Kulshrestha *et al.* (1995)
Clodinafop	Wheat	240	0.021-BDL	0.096-BDL	BDL	Singh *et al.* (2004), Sondhia and Mishra (2005), Arora *et al.* (2013)
Tralkoxydim	Wheat	250-800	BDL	BDL	BDL	Srivastava *et al.* (1994)

250 and 500 g/ha, respectively (Sondhia 2007). Patel *et al.* (2014) evaluated effect of imazethapyr and varying level of fertilizers on soybean grain quality with respect to oil and protein percentage applied in soybean crop under long-term fertilizer experiment. The maximum protein content (39.54 %) and oil content of 19.47 percent was observed in 100% NPK+ FYM+ imazethapyr treatment. While, the lowest value of protein and oil contents we recorded in treatment with no fertilizer + imazethapyr application at recommended dose. The result of the study imply that the use of balance rate of minerals fertilizer in combination with organic manures along with herbicide must form part of soil management practices for the intensively cultivated soil to sustain soil health, productivity and crop quality.

Herbicide residues in vegetables: Terminal residues of pendimethalin applied as pre-emergence at 1 kg/ha in tomato, cauliflower, and radishes were studies under field conditions. At harvest, 0.008, 0.001, and 0.014 µg/g residues of pendimethalin were found in tomato, cauliflower, and radishes, respectively (Sondhia 2013). Terminal residues of oxyfluorfen applied at 150 to 300 g/ha in direct seeded onion crop at 90 days (green onion) and at 130 days (mature onion bulbs) were monitored in green onion, dry onion bulbs and soil samples under field condition at Jabalpur. The residues of oxyfluorfen in the green onion and mature onion bulbs were 0.041- 0.063 and 0.0034-0.0460 µg/g at 150–300/ha rates. Residues of oxyfluorfen applied in mature onion were below the maximum residue limit (0.05 µg/g) (Sondhia and Dixit 2007, Sondhia 2009). A pre-harvest interval of 118 days for onion crop after the herbicide application was suggested (Sondhia 2010). Residues of pendimethalin, fluchloralin, and oxadiazon were found below the maximum residue limit in onion bulbs at harvest (125 days after spraying) at Anand. At harvest, 0.009 and 0.006 mg/kg terminal residues of fluchloralin applied at 0.75 and 1.50 kg/ha, respectively were found in stover and grains (Saikia and Pandey 1999). Sondhia and Dubey (2006) did not find pendimethalin residues at mature stage, however 0.007 µg/g pendimethalin residues were detected in green onion at 1.0 kg/ha application rate. Similarly 0.005 and 0.003 µg/g haloxyfop residues were detected in the green and mature onion bulbs collected at 50 days and at harvest (129 days), respectively (Sondhia 2006). Oxyfluorfen residues applied to cabbages at 0.1 to 0.4 kg/ha application rates were not found in soil at harvest (Sundararajan *et al.* 1993). The half-life of pendimethalin in onion plants and soil varied from 11.8- 15.5 days and 14.9-15.1 days, respectively (Sinha *et al.* 1996).

Field experiment was conducted to study the persistence of pendimethalin and oxyfluorfen in soil and its residues in edible parts of radish. At harvest in both the seasons more than 98% of initial deposit of pendimethalin was dissipated with half-lives in radish field were 6.45 days and 10.03 days at 0.5 and 0.75 kg/ha applied rates, respectively. More than 60 per cent of the initial deposit of oxyfluorfen was dissipated at the time of harvest of crop and 6.96 days and 12.26 days of half-life was observed at 0.1 and 0.15 kg/ha of oxyfluorfen application, respectively. In radish tubers the residues of pendimethalin and oxyfluorfen were below maximum residue limit (Sirestha *et al.* 2011). Samples of onion bulbs collected at 30, 60 and 90 days after spray and at uprooting stage showed no residues of oxyfluorfen and pendimethalin in onion bulbs (Kaur *et al.* 2010). Dissipation of haloxyfop in onion leaf and soil followed first order kinetics with the DT_{50} values in onion leaf ranged from 3.24-6.71 days whereas 3.78-6.96 days for soil following application 100-400 g/ha. No residue could be detected in bulb at harvest irrespective of doses (Chakraborty *et al.* 2005). At harvest the level of pendimethalin, fluchloralin and oxadiazon residue applied pre-emergence at 1.0-0.5 kg/ha in onion bulbs ranged from 0.003 to 0.021, 0.004 to 0.036 and 0.080 to 0.104 µg/g, respectively. Marginal increase in the residue was observed with increased FYM application (Raj *et al.* 1999).

Herbicide residues in maize: Atrazine applied at 1.0 kg/ha rate in maize crop degraded by harvest and residues were not detected in maize grains but at 2.0 kg/ha rate, 0.088 mg/kg of residues were detected (Sondhia 2000).The residual effect of atrazine (1.0-2.0 kg/ha) was studied on the succeeding crops of chickpea and Indian mustard, where fluchloralin was applied at 0.75 kg/ha. Atrazine was degraded to undetectable levels at all doses by the time the maize crop was harvested (90 days). The average half-life of atrazine varied from 23 to 25 days in the first year and 26 to 31 days in the second year. In chickpea and Indian mustard, low levels of fluchloralin residues were detected in soil at 150 days (64-85% and 69-82% losses, respectively). However, the magnitude of flucloralin persistence was not affected by preceding atrazine treatments applied to maize. The maize yield declined with an increase in atrazine dose and was lowest at 2.0 kg/ha (2.48 and 1.63 t/ha in 1994 and 1995, respectively, compared to 3.20 and 2.52 t/ha in the hand-weeded treatment). However, atrazine had no significant residual effect on chickpea or Indian mustard yields (Saikia *et al.* 2000).

Herbicide residues in tea/plantation crops: India is the highest producer of tea in the world. In India tea is being cultivated mainly in north-east. Tea (*Camellia sinensis*) is a perennial crop grown on wide variety of soil types and climatic conditions. It is the healthiest drinks and second most consumed beverage after water. Napropamide was rapidly dissipated in soil following the first-order kinetics with half-lives in the range of 12.54-27.87 days. The initial deposit of napropamide in tea cropped soil was found in the range of 1.18-1.49 and 2.08-2.90 µg/g at recommended dose (1.125 kg/ha) and double the recommended dose (2.25 kg/ha), respectively irrespective of any season and doses. At 30 days after application of the herbicide, more than 50% of the residue was dissipated. The residue declined below detectable limit in the tea soil on day 60–90 day in X and 2X doses irrespective of season. The dissipation of napropamide in tea cropped soil followed the first-order kinetics with the half-life values varied from 12.54 to 27.87 days irrespective of doses and seasons in south India. In made tea the initial concentration of napropamide was found in the range of 0.14–0.20 µg/g in recommended dose and 0.35–0.44 µg in double the recommended dose in three seasons (Biswas *et al.* 2013).

Herbicide residues in non-cropped areas: Glufosinate ammonium at 0.45- 0.90 kg/ha application rates applied as post-emergence to cotton degraded to safe level by 20 day at Ludhiana. At Anand, pendimethalin applied at 0.6-0.9 % to tobacco recorded 0.198 to 0.376 mg/kg residues in tobacco leaves and 0.72 mg/kg residues in leaves treated with 0.5 % pendimethalin and 0.04-0.079 mg/kg residues treated with 0.25% pendimethalin (Parmar *et al.* 1998). Sushilkumar *et al.* (2008) evaluated persistence of glyphosate in non-crop area and found that residues were not detected after 45 days at 2.0-2.5 kg/ha application rates however at 3.0 kg/ha glyphosate persisted up to 60 days in black soils of Jabalpur.

Herbicide residues in other crops: Pendimethalin residues at 0.5 kg/ha application rate were not detected in the soil of lucerne crop at Anand. Alachlor residues were found at trace level in cotton plant, cotton lint and oil, water and fish at 2.5 and 5.0 kg/ha application rates under field conditions at Chennai (Ramesh and Maheshwari 2004). It was found that 2,4-D residues at 0.06 mg/kg level caused malformation in leaves (Kathpal *et al.* 1980). Metamitron persisted in sugar beet crop plant up to 15 days while up to 30 days in soil. On day 90, metamitron was detected in the soil at 7.0 kg/ha treated plots (Janaki *et al.* 2013). Application of pendimethalin, trifluralin and resulted in below detectable limit residues (0.02 mg/kg) in celery seeds (Kaur and Gill 2012). In cucumber, anilophos (ND–0.042 mg/kg) in onion, fluchloralin (0.012–0.065 mg/kg), and anilophos (ND–0.033 mg/kg) were detected (Srivastava *et al.* 2011). At Anand, pendimethalin applied at 0.6-0.9% to tobacco recorded 0.198 to 0.376 mg/kg residues in tobacco leaves and 0.72 mg/kg residues in leaves treated with 0.5% pendimethalin and 0.04-0.079 mg/kg residues treated with 0.25% pendimethalin (Parmar *et al.* 1998).

Herbicide residues in water system: With the increasing use of herbicides for weed control, the applied herbicide may find it way into streams and underground water sources by runoff, drift and leaching mechanism (Sondhia 2008, 2009, 2013). Many herbicides are routinely detected from the surface and ground water sources in developed countries like, USA, New Zealand, Australia, Canada, Japan and European countries. The most often detected herbicides above the prescribed maximum residues limits are 2,4-D, atrazine, cyanazine, carbaryl, simazine, bromacil, diuron, diazinon, prometon, metolachlor, dinoseb, picloram, metribuzin, metsulfuron, glyphosate, metolachlor, propanil, butachlor, pendimethalin, oxyfluorfen *etc*. Many herbicides are strictly banned or restricted such as butachlor, atrazine, pendimethalin, and paraquat in USA, and European countries due to their high concentration in the ground and surface water and potential health hazards to aquatic, animal and human lives.

In India, reports on monitoring and detection of herbicide residues in water are limited as compared to developed countries. Pyrazosulfuron-ethyl residue level of 0.0154 mg/kg on 21st day and of 0.0023 mg/kg on 35th day were detected in the underground water (Naveen *et al.* 2012). Persistence and mobility of 2,4-D were found to be dependent on soil water content (Gupta *et al.* 2012).The water samples collected from Singoor reservoir, Hyderabad were found contaminated with residues of atrazine (BDL-1.056 µg/L). The concentration of atrazine residues in Osmansagar water was 0.056 µg/L during post-monsoon November 2005 and total pesticide residues together 3.369 µg/L (Reddy and Reddy 2010). Residues of alachlor were detected up to 60 days in acidic, neutral and basic buffer solution fortified with 0.5 and 1 µg /g and residue were below the detection limit after 140 days in water different soils and no residues were detected after 80 days.

The studies conducted at AICRP weed control in water system revealed that butachlor residues were ranged between 0.001 to 0.093 mg/L in the water of rice field (AICRP 2009). Residues of paraquat were not detected after 20 days at 0.80 kg/ha application rates to control *Eichornia* but application of 1.8 kg/ha showed 0.069 and 0.028 mg/L residues in pond and canal water, respectively. 2,4-D increased pH, EC, carbonates and free CO_2 increased after treatment at 1.0-2.0 mg/kg dose but the dissolved oxygen decreased and the 2,4-D residues become non-detectable after 42 days. 2,4-D residues at lower level than the acceptable daily intake (0.01 mg per kg body weight) were detected in fish samples at Thrissur at recommended rate of application at all the sampling interval and at higher dose, *viz*. 2.0 or 4.0 kg/ha waiting period of more than 4 months was suggested. Paraquat residues in the fish samples were detected below the acceptable daily intake of 0.002 mg per kg body weight. It is reported that only 0.80 to 1.11 % of the applied paraquat remained in the sediment fraction however paraquat at 0.8- 3.2 kg/ha application rates increased the pH and electrical conductivity of water. It is reported that isoproturon residues were not present in the ground water in all the water samples collected from different districts of Hisar.

Leaching results indicated that imazethapyr could leach in clay loam soil up to the depth of 70 cm applied at 100 and 200 g/ha (Sondhia 2013). Sondhia (2009) demonstrated that residues of sulfosulfuron were significantly higher in surface soil at higher dose compared to sub-surface soil at lower dose up to 150 day at 25-100 g/ha in wheat under field conditions. Initial concentration of sulfosulfuron residues in the surface soil (0-15 cm) were 0.229, 0.967 and 1.038 µg/g, which dissipated to 0.003-0.005 µg/g at 25-100 g/ha doses by 100 days. However, at 0 days sulfosulfuron residues in sub-surface soil were 0.136-0.065 µg/g in 25-100 g/ha doses. Sulfosulfuron residues were not detected after 200 days in surface and sub-surface soils in all the doses. Pendimethalin could leach in clay loam soil up to the depth of 55 cm in 200 mm rainfall (Sondhia 2007). High mobility of metsulfuron-methyl was found under continuous saturated moisture conditions (Sondhia 2009).

Khare and Sondhia (2014) demonstrated cyhalofop-p-butyl mobility in a sandy loam soil and subsequent distribution of residues at 0-150 cm depths under field conditions. Cyhalofop-p-butyl application at two rates and subsequent precipitation had a significant impact on soil physico-chemical properties and herbicide mobility. Precipitation caused substantial mobility of cyhalofop-p-butyl in the soil and 1.1 to 7.6 µg/L of cyhalofop-p-butyl was found in leachates. Cyhalofop-p-butyl three transformation products, *viz.* cyhalofop acid, diacid, and phenol were also detected.

A laboratory experiment was conducted to study the persistence of pretilachlor in water at acidic, neutral and alkaline pH by incubating for 60 days. Irrespective of pH, pretilachlor residues were detected up to 15 days after application and were below the detectable limit on 30^{th} day. The half -life of pretitachlor in different pH water varied from 3.05 to 3.30 days and there was not much difference in half- life due to increase or decrease in pH of irrigation water (Deepa and Jayakumar 2006).The total mean concentration of atrazine ranged from 0.72 to 17.3 µg/L whereas 0.91 to 40.97 µg/L were recorded as the mean concentration of simazine in groundwater samples collected from Delhi (Aslam *et al.* 2013).

In fishes: In a study, Yadav *et al.* (2013) revealed the genotoxic potential of butachlor even at low dose level (1.0 mg/kg) and suggested that butachlor interferes with cellular activities in fishes at genetic level inducing chromosomal aberrations and suggested a serious concern towards the potential danger of butachlor for aquatic organisms. On comparing the effect of different herbicides, it was observed that the fish mortality was more with 2,4-DEE and paraquat than with glyphosate (Muniappa *et al.* 1995). To evaluate the possible bio-accumulation of sulfosulfuron in the fishes, an experiment was conducted in glass aquarium for 90 days. Sulfosulfuron was applied to the aquariums at 25-100 g/ha. Residues of sulfosulfuron in the fishes were found 1.09- 3.52 µg/g after 10 days and by 90 days residues in the fishes were below the MRL (Sondhia 2008, Sondhia 2008). In another indirect effect of herbicides on fishes, mortality was more with butachlor, followed by anilofos and oxyflourfen (Sondhia 2012). Pretilachlor, penoxsulam and pyrazosulfuron-ethyl residues ranged between 0.0133, 0.0189 and 0.063 µg/g at 30 days and dissipated to <0.001, 0.017 and 0.010, respectively at 60 days respectively in fishes (Sondhia 2012, 2013, 2014). In another study, fishes (*Channa punctata*) were exposed for 10 days to sub lethal concentration ($1/5^{th}$of static LC_{50}) of butachlor. Residue of butachlor after 10 days were 0.1255 mg/kg in gills, 0.3515 (bloch) liver in (bloch) liver, 0.3145 mg/kg in kidney and 0.2350 mg/kg in brain traces muscle of *Channa punctata*. The results revealed that prolonged exposure to sub lethal concentrations led to increase in the accumulation of residues. The residues are accumulated in different tissues, causing toxicity to the fishes which ultimately resulted in biomagnifications through the food chain (Tilak 2007). The *Tilapia mossambica* were exposed to sub lethal concentration (66 mg/L) for 24, 48, and 72 hrs respectively to assess toxic effect of the metribuzin on the biochemical aspects such as total protein, carbohydrate and cholesterol in liver, muscle, kidney and gills. All bio chemical parameters were found to be decreased in all tissues in comparison to control (Saradhamani and Selvarani 2009).

Similarly, dissipation of sulfosulfuron in natural water and its bioaccumulation in fish was conducted at two different concentration levels 1 and 2 mg/L. The dissipation data in water showed the DT_{50} and DT_{90} values 67-76 and 222-253 days and followed first order kinetics. Bioaccumulation of sulfosulfuron in fish was conducted under static conditions exposing the fish at one-tenth of sub-lethal concentration 9mg/L and at double the concentration 18ml/g, for a period of 56 days. Accumulation of sulfosulfuron in fish in the range 0.009-0.496 µg/g was found. Both in water and fish samples, metabolites of aminopyrimidine, desmethyl sulfosulfuron, guanidine, sulfonamide, ethyl sulfone and rearranged amine were found. One of the metabolite aminopyrimidine was identified at higher concentration levels (0.01-0.1 µg/mL) in comparison to other metabolites (Ramesh *et al.* 2007, Sondhia 2008). The calculated DT_{50} and DT_{90} values for aminopyrimidine dissipation in water were found to be 66-68 days and 218-226 days, respectively with a complete demineralization after three hundred days.

Recently, Sondhia *et al.* (2014) demonstrated a water quality index (WQI) to see the suitability of water in term of its quality for fishery after application of metsulfuron-methyl. The WQI proposed in the study was composed of eight measurable major environmental parameters, *viz.* herbicide residue, pH, total dissolve solids (TDS), dissolved oxygen (DO), biological oxygen demand (BOD), free ammonia, chloride and temperature. Concentrations of these eight variables were normalized on a scale from 0 (zero) to 100 and translated into statements of water quality (excellent, good, poor, very poor and unsuitable). Based on WQI, water quality of adjacent pond was derived as category I (excellent) to category II (good), and found suitable for fish farming.

Metabolites / transformation products

In an experiment, the photo stability of sulfosulfuron was studied after irradiation under sunlight. Under alkaline condition, sulfosulfuron yielded 1-(2-ethylsulfonylimidazo[1,2-*a*]pyridin-3-yl-3-(4,6-dimethoxypyrimidin-2-yl) amine, and under acidic condition it degraded to 1-(2-ethylsulfonylimidazo[1,2-*a*] pyridine)-3-sulfonamide and 4,6-dimethoxy-2-aminopyrimidine. Photodegradation included breaking of a sulfonylurea bridge, as in the case of acidic hydrolysis and contraction of the sulfonylurea bridge was the major pathway of alkaline hydrolysis (Saha and Kulshrestha 2002). The sulfisulfuron degraded within 50 days on topsoil but the residual concentrations were localized at depth 30-45 cm depths this might be due to leaching property of the sulfosulfuron. The absence of sunlight, considerably lesser availability of microbial population and organic carbon content also participates in the stability in subsoil. Desmethyl sulfosulfuron, rearranged amine, sulfonamide and guanidine were identified as breakdown product of sulfosulfuron in the subsurface soil. From the results the calculated DT_{50} value for sulfisulfuron were around 105 to 147 days and the DT_{90} values around 349 to 488 days (Ramesh *et al.* 2007, Sondhia 2008).

Metabolites of pyrazosulfuron were detected from soil and pond water which were identified by LC/MS/MS. Three major transformation products of pyrazosulfuron-ethyl detected from rice field as ethyl-5-[(4,6-dimethoxypyrimidin-2-ylcarbamoyl) sulfamoyl]-1-methylpyrazole-4-carboxylic acid; ethyl 1-methyl-5-sulfamyl-1H-pyazole-4-carboxylate and 4,6-dimethoxypyrimidin-2-amine, 1-methyl-5-sulfamyl-1H-pyazole-4-carboxylic acid (Sondhia *et al.* 2013, Wassem and Sondhia 2014). *Penicillium chrysogenum* and *Aspergillus niger* were found as potent pyrazosulfuron-ethyl degrading fungi (Sondhia *et al.* 2013). Major degradation products of penoxsulam in field soil were identified as 1,2,4 triazolo-[1,5-c] pyrimidin-2 amine, 5,8 dicarboxylic acid; 2-(2,2-difluoroethoxy) -6 (trifluromethyl) benzenesulfonamide ; 3-[[[2-(2,2-difluoroethoxy)-N-[1,2,4] triazole [1,5c]-6-trifluromethyl) benzene sulfonamide carboxylate (Rajput and Sondhia 2014). Major metabolites of cyhalofop-butyl in soil and leachates were detected by LC/MS/MS as (R) -2-4(4-amino 2-fluoro phenoxy) phenoxypropanoic acid (cyhalofop acid) and (R) -2-4(4-caboxyl-2-flurophenoxy) phenoxypropanoic acid (cyhalofop-diacid), and cyhalofop-phenol (Sondhia and Khare 2014).The major photoproducts of metsulfuron methyl were identified as methyl-2-sulfonyl-amino-benzoate, 2-amino-6-methoxy-4-methyltriazine and saccharin (O-sulfobenzoimide). These metabolites were also identified from metsulfuron methyl treated wheat field soil. Stability test for pinoxaden and its metabolite NOA 407854(8–(2,6-diethyl-4-methyl-phenyl) -tetrahydropyrazolo[1,2-d][1,4,5]oxadiazepine-7,9-dione) in wheat for a period of 30 days showed that the compound remained stable and the degradation observed was only 6.5% at the end of storage period. This shows slow dissipation of pinoxaden metabolites at 20±1° C. Residues of pinoxaden and its metabolites were found below the detectable limit (<0.01 mg/kg) (Dixit *et al.* 2011).

Seven major degradation products of pretilachlor in field soil were identified by LC/MS/MS as 2,6-diethyl-N-(propoxyethyl)acetanilide; 2,6-diethyl-N-(propoxyethyl)aniline;2,6-diethyl-N-(2-hydrox-yethyl) aniline; 2,6-diethyl-N-(ethyl)aniline; acetanilide; 2-

chloro-2,)1–hydroxyethyl, 6ethyl)-N-(2-propoxyethyl acetanilide; and 2-chloro-1(-9-ethyl-3-hydroxy-2,3,4,5-tetrahydro-1H-1benzazapin-1-yl) ethanone (Sondhia 2014).

Herbicide and human heath effect implications

Indirect effects of herbicides on human are not common in India. However increasing incidences of acute herbicide self-poisoning by butachlor, fluchloralin, paraquat, 2,4-D, pendimethalin, glyphosate *etc*. are a significant problem in parts of Asia (Senarathna *et al.* 2009). Due to paraquat low vapour pressure and the formation of large droplets, inhalation of paraquat spray used in the open environment has not been shown to cause any significant systemic toxicity; however, inhalational exposure to paraquat in confined spaces, such as a greenhouse, is known to be associated with fatal pulmonary disease. Irrespective of its route of administration in mammalian systems, paraquat is rapidly distributed in most tissues, with the highest concentration found in the lungs and kidneys. The compound accumulates slowly in the lungs via an energy dependent process. Excretion of paraquat, in its unchanged form, is biphasic, owing to lung accumulation and occurs largely in the urine and, to a limited extent, in the bile (Suntres 2002). Poisoning with paraquat leads to both local and systemic effects.

Paraquat poisoning is an uncommon entity in India, and is associated with a high mortality rate (Agarwal *et al.* 2005, Kondle *et al.* 2013). These cases are reported in India to highlight the high mortality rate associated with paraquat poisoning in spite of advances in treatment and supportive care (Khosya and Gothwal 2012). The oxidative role of butachlor in intracellular ROS production, and consequent mitochondrial dysfunction, oxidative DNA damage, and chromosomal breakage, which eventually triggers necrosis in human PBMN cells is also reported (Dwivedi *et al.* 2012).

In an experiment, cultured human lymphocytes were exposed to three different concentrations (2.5, 5.0 and 10.0 µg/ml) of fluchloralin for 24 and 48 h to assess chromosomal aberrations. A significant dose-dependent increase of chromatid type aberration was observed in these cells. Multiple aberrations (MA) were scored at all concentrations after 48 h treatment. Higher concentrations of fluchloralin (20, 40 and 50 µg/mL) resulted in a significant dependent increase in number of micronucleated cells and showed genotoxic effects of fluchloralin in human cells (Panneerselvam *et al.* 1995). Nair *et al.*(2005) demonstrated that 2,4-D is capable of inducing higher DNA damage as well as chromosomal aberrations in human lymphocytes. In an Indian series of 17 patients of herbicide poisoning, the most common symptoms were vomiting (100%), followed by altered sensorium (59%), oral ulceration or dysphagia (53%), dyspnea (41%), or loose stools (24%) (Sandhu *et al.* 2003). Acute respiratory distress syndrome because of paraquat usually appears 24–48 h after ingestion (Singh *et al.* 1999). Common symptoms of acute poisoning by some of the herbicides and cases of poisoning are listed in Table 5 and 6.

Table 5. Some herbicides which caused direct adverse effects on human beings

Herbicide	Bioactivity	Adverse effects on human beings
Butachlor	It controls annual grasses and some broad-leaved weeds in transplanted and direct-seeded rice. It is applied as pre-emergence in EC formulations and as early post-emergence in the form of granules.	Weight loss, weight changes in internal organs, reduced brain size together with lesions.
Isoproturon	It is used to control annual grass weeds in wheat, rye and barley.	Isoproturon appears to be a tumour promoter rather than a complete carcinogen.
Paraquat	It is used as a plant desiccant effective against grasses.	Parkinson's and Alzheimer's diseases.
Simazine and atrazine	These are persistent soil acting herbicides which in high concentrations acts as total weed killer and in lower concentrations is used for selective control of germinating weeds in a variety of crops - maize, sugarcane, pineapple, sorghum. It is also used for long term control of annual grass and broad-leaved weeds in crops like citrus, coffee, tea and cocoa.	Cancer of testes
Trifluralin	It is used for the control of annual grasses and broad leaved weeds in a wide range of crops cotton, groundnuts, soybeans, brassica, beans and cereals.	Prolonged or repeated skin contact with trifluralin may cause allergic dermatitis. Other effects include decreased red blood cell counts and increases in methemoglobin, total serum lipids, triglycerides, and cholesterol. It has been shown to cause liver and kidney damage in other studies of chronic oral exposure in animals.

Table 6. Cases of intentionally herbicide poisoning in human beings in India

Poisoning	Total patients	Death	Amount taken (mL)	Reference
Paraquat			Unknown	Attar *et al.* (2009), Khosya and Gothwal (2012), Kondle *et al.* (2013)
Rajasthan and Maharastra	04	03	10-50	
North India	05	03	Unknown	Agarwal *et al.* (2006)
Himachal Pradesh	02	02	Unknown	Raina *et al.* (2008)
Karnataka	06	04	Unknown	Saravu *et al.* (2013)
Haryana	01	-	Unknown	Ghosh *et al.* (2012)
Pendimethalin (Uttar Pradesh)	02	02	20-100	Kumar and Verma (2012)
Glyphosate	02	-	100-150	Das *et al.* (2012)
2-4-D ethyl ester	03	02	100 g	Singh *et al.* (2008)

Herbicide poisoning: a diagnostic challenge

Hemoperfusion using activated charcoal has been shown to decrease paraquat level, but data to support survival benefit in humans is insufficient. It is only effective if initiated within 4 h of ingestion, as peak paraquat concentration in the lung is achieved in 5–7 h (Sandhu *et al.* 2003). Hemodialysis is used as a support of acute renal failure, but it does not increase clearance of the substance as it is rapidly distributed to the lungs and other organs. Immunosuppression with combination of cyclophosphamide and methylprednisolone was shown to be beneficial in moderate-to-severe cases by prevention of ongoing inflammation (Agarwal *et al.* 2005). Unfortunately, none of the studied treatments, including controlled hypoxia, superoxide dismutase, vitamins C and E, N-acetylcysteine, desferrioxamine, and nitrous oxide, has been proven to be effective (Suntres 2001, Eddleston *et al.* 2003).

Conclusion

Herbicide residues after recommended use for control of weeds are relatively high initially; however, the levels are reduced rapidly, and residues are often not detectable after a few days or weeks or at harvest. The soil acts as an important buffer governing the persistence and fate of most herbicides in the environment. As long as soil system remains healthy, possible adverse effect from herbicides in the environment probably can be minimized. Herbicides in most instances when applied at recommended doses have not been detected in food chain or in soil at level that should cause concern. Data on the occurrence of herbicide-related sickness among defined populations in developing countries are scanty. To conclude based on limited data of direct and/or inferential information, the domain of herbicide illustrates a certain ambiguity in situations in which people are undergoing life-long exposure. Further, the persistence and half-life period of many herbicides were found to be less in Indian tropical conditions. This could be one of the reasons for the presence of low level of residues. It can be concluded that in India herbicide contamination of soil, plants and natural waters occurs infrequently and at low levels. With few exceptions aquatic herbicides do not accumulate and persist in fishes. Though some reports of herbicide poisoning are reported though data on the occurrence of herbicide-related illnesses among defined populations in human, the domain of herbicide illustrates a certain ambiguity in situations in which people are undergoing life-long exposure.

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Herbicide–tolerant GM crops in India: challenges and strategies

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ABSTRACT

Crops made resistant to herbicides by biotechnology are being widely adopted in various parts of the world. Those containing transgenes that impart resistance to post-emergence, non-selective herbicides such as glyphosate and glufosinate will have the major impact. These products allow the farmer to more effectively use reduced or no-tillage cultural practices, eliminate use of some of the more environmentally suspect herbicides and use fewer herbicides to manage nearly the entire spectrum of weed species. In some cases, non-selective herbicides used with herbicide resistant crops reduce plant pathogen problems because of the chemicals' toxicity to certain microbes Herbicide tolerant crops can be produced by either insertion of a "foreign" gene (transgene) from another organism into a crop, or by regenerating herbicide tolerant mutants from existing crop germplasm. Biotech crops reached 160 million hectares, up 12 million hectares on 8% growth, from 2010 and 94 fold increase in hectarage from 1.7 million hectares in 1996 to 160 million hectares in 2011, makes biotech crops the fastest adopted crop technology in the history of modern agriculture. From the genesis of commercialization in 1996 to 2011, herbicide tolerance has consistently been the dominant trait. In 2011, herbicide tolerance deployed in soybean, maize, canola, cotton, sugar beet and alfalfa, occupied 59% or 93.9 million hectares of the global biotech area of 160 million hectares. Over the past few years, several herbicide resistant crops (HRCs), both transgenic and non-transgenic, have become available in many countries for commercial cultivation. But in India, the technology of herbicide tolerant crops is in initial stage of field evaluation.

Key words: Challenges, GM crops, Herbicide-tolerant, Strategies

Non-selective herbicides such as glyphosate and glufosinate aid in broadening the spectrum of weeds controlled, which is particularly important in no-till systems, and those "weedy" fields. Genetically modified herbicide tolerant maize and spring oil seed rape cultivars tolerant to glufosinate ammonium, were used which gives post-emergence broad spectrum control of annual grasses and broad-leaved weeds (Firbank 2003). In general, glyphosate is the most widely used herbicide in the world and literature about its use and characteristics is extensive (Woodburn 2000).

Experimental results revealed that application of glyphosate 2700 g/ha recorded lower weed density, dry weight and higher weed control efficiency when compared to other doses of glyphosate and hand weeding method (Table 1) in cotton. According to Franz *et al.* (1997), the systemic activity of glyphosate also helped in control of perennial weeds and their perennial vegetative structures such as stolons and rhizomes. Keeling *et al.* (1998) also observed that, weed control is often excellent (95%) with the application glyphosate as post-emergence in cotton. Post-emergence application of glyphosate at 900, 1800 and 3600 g/ha registered lower weed density, dry weight and higher weed control efficiency in transgenic Hishell and 900 M Gold corn hybrids in the maize trial I (Table 2) and post emergence application of glyphosate at 900 and 1800 g/ha registered lower weed density, dry weight and higher weed control efficiency in transgenic 30V92 and 30B11 corn hybrids in the maize trial II compared to their state and national checks (Table 3). Grichar *et al.* (2004) who had found that single application of glyphosate as early or late post emergence effectively controlled the broad spectrum of weeds.

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Carry-over effect of herbicides

Glyphosate and glufosinate have almost no soil residual activity because they are tightly bound to the organic particles in the soil. Hence, there are few restrictions for planting or replanting intervals or injuries to the subsequent crops. This trait facilitates crop rotation by providing flexibility in selection of potential rotation crops. HTC will not cause any residual effect on succeeding crops (AICRPWC 2011).

Succeeding crops like sunflower, soybean and pearlmillet has been sown after cotton crop in the treatment blocks to assess the carry over effect of potassium salt of glyphosate (MON 76366). Observations

Table 1. Effect of glyphosate on WCE and seed cotton yield in transgenic cotton

Treatment	2009-10		2010-11	
	WCE (%)	Seed cotton yield (t/ha)	WCE (%)	Seed cotton yield (t/ha)
Glyphosate. 900 g/ha	93.4	2.61	91.3	2.47
Glyphosate 1350 g/ha	95.0	2.84	92.4	2.57
Glyphosate 1800 g/ha	98.0	2.98	95.1	2.85
Glyphosate 2700 g/ha	98.4	3.19	96.3	3.09
Glyphosate 3600 g/ha	98.4	3.11	97.3	3.02
Glyphosate 5400 g/ha	100.	2.85	97.8	2.75
HW on 15 and 30 DAS	95.5	2.50	74.9	2.32
Unweeded check	-	0.84	-	0.71
LSD (P=0.05)	-	0.32	-	0.29

Table 2. WCE and grain yield in transgenic corn (mean of four seasons)

Treatment	WCE (%)	Grain yield (t/ha)
T_1- Hishell POE glyphosate 900 g/ha	93.8	9.91
T_2- Hishell POE glyphosate 1800 g/ha	96.7	10.34
T_3- Hishell POE glyphosate 3600 g/ha	97.1	10.69
T_4- 900 M Gold POE glyphosate 900 g/ha	94.4	9.95
T_5- 900 M Gold POE glyphosate 1800 g/ha	95.4	10.46
T_6- 900 M Gold POE glyphosate 3600 g/ha	97.7	10.66
T_7- Hishell PE atrazine 0.5 kg/ha+ HW+ IC	91.5	9.23
T_8- 900 M Gold PE atrazine 0.5 kg/ha+ HW+ IC	88.4	8.77
T_9- Proagro PE atrazine 0.5 kg/ha+ HW+ IC	84.8	7.43
T_{10}- CoHM 5 PE atrazine 0.5 kg/ha+ HW+ IC	82.9	7.08
LSD (P=0.05)	-	1.68

Table 3. WCE and grain yield in transgenic corn hybrids (*Kharif* 2010)

Treatment	WCE (%)	Grain yield (t/ha)
T_1- 30V92 HR glyphosate 900 g/ha	98.6	11.10
T_2- 30V92HR glyphosate 1800 g/ha	99.5	12.21
T_3- 30V92HR (weedy check)	0.0	8.84
T_4- 30B11HR glyphosate 900 g/ha	97.7	10.97
T_5- 30B11HR glyphosate 1800 g/ha	99.0	11.98
T_6- 30B11HR (weedy check)	0.0	9.12
T_7- 30V92 PE atrazine 0.5 kg/ha + HW+ IC	72.6	10.23
T_8- 30B11 PE atrazine 0.5 kg/ha + HW+ IC	70.3	9.76
T_9- BIO9681 PE atrazine 0.5 kg/ha +HW + IC	68.7	8.00
T_{10}- CoHM5 PE atrazine 0.5 kg/ha + HW + IC	68.6	7.33
LSD (P=0.05)	-	0.84

T_1, T_6= Transgenic

were recorded on germination percentage, vigour, plant height and yield for all the treatments. Treatment differences found to be insignificant for all the parameters hence there was normal growth and development of succeeding crops (Table 4). The results were in line with the findings of Nadanassababady *et al.* (2000) who had reported that bioassay of herbicide residues indicated that none of the herbicide evaluated for the chemical control of weeds in cotton persisted in the soil to the level of affecting the germination and growth of succeeding crops like fingermillet and cucumber.

Post-emergence application of glyphosate in transgenic maize hybrids did not affect the germination per cent, vigour and yield of succeeding green gram in both the transgenic maize trials. Franz *et al.* (1997) reported that crops can be planted or seeded directly into treated areas of glyphosate because it has no pre-emergent activity even when applied at high rates.

Reduced crop injury

Various post-emergence type herbicides used for weed control in soybean, canola, or corn can cause crop injury and ultimately yield loss. Crop injury is more severe when the crop is under stress or unfavourable environmental conditions occur. In contrast, crop injury is reduced with the use of herbicide tolerant crops. The phytotoxicity symptoms were not observed in cotton with glyphosate at lower doses, *viz.* 900, 1350, 1800 and 2700 g/ha. Higher doses, *viz.* 3600 and 5400 g/ha were noticed with phytotoxicity symptoms at early stages of herbicide application (Table 5). Glyphosate cause almost no crop injury, compared to some traditional herbicides (e.g., lactofen, chlorimuron), especially when applied to cotton. The greatest benefit to growers is the broad-spectrum weed control with post-emergence application of glyphosate to cotton without crop injury as earlier reported by Wilcut *et al.* (1996).

Regarding transgenic maize hybrids, there was no phytotoxic symptom observed in transgenic maize hybrids due to application of various doses of glyphosate at 900, 1800 and 3600 g/ha at throughout the crop growth in both the trials.

Use of environmentally safe herbicides

In general, glyphosate and glufosinate have lower toxicity to humans and animals compared to some other

Table 4. Residual effect of herbicides on yield (t/ha) of succeeding crops grown after transgenic cotton

Treatment	2009-10			2010-11		
	Sunflower	Soybean	Pearlmillet	Sunflower	Soybean	Pearlmillet
Glyphosate 900 g/ha	1.34	1.49	0.85	1.36	1.48	0.80
Glyphosate 1350 g/ha	1.36	1.57	0.89	1.38	1.56	0.83
Glyphosate 1800 g/ha	1.40	1.57	0.87	1.43	1.54	0.84
Glyphosate 2700 g/ha	1.43	1.50	0.86	1.47	1.52	0.85
Glyphosate 3600 g/ha	1.38	1.53	0.86	1.41	1.54	0.82
Glyphosate 5400 g/ha	1.46	1.61	0.90	1.40	1.63	0.81
HW 15 and 30 DAS	1.32	1.48	0.83	1.34	1.49	0.76
Unweeded check	1.29	1.42	0.82	1.32	1.47	0.74
LSD (P=0.05)	NS	NS	NS	NS	NS	NS

Table 5. Per cent rating of phytotoxic effects in herbicide tolerant transgenic cotton

Treatment	2009-10			2010-11		
	7 DAHS	14 DAHS	21 DAHS	7 DAHS	14 DAHS	21 DAHS
Glyphosate 900 g/ha	0.0	0.0	0.0	0.0	0.0	0.0
Glyphosate 1350 g/ha	0.0	0.0	0.0	0.0	0.0	0.0
Glyphosate 1800 g/ha	0.0	0.0	0.0	0.0	0.0	0.0
Glyphosate 2700 g/ha	0.0	0.0	0.0	0.0	0.0	0.0
Glyphosate 3600 g/ha	3.0	3.0	2.0	3.0	3.0	2.0
Glyphosate 5400 g/ha	4.0	4.0	3.0	4.0	4.0	3.0
Hand weeding on 15 and 30 DAS	0.0	0.0	0.0	0.0	0.0	0.0
Unweeded check	0.0	0.0	0.0	0.0	0.0	0.0

DAHS = Days after herbicide spray

herbicides. Since they are absorbed by the organic particles in the soil and decompose rapidly, they pose little danger for leaching and contamination of ground water or toxicity to wildlife (Knezevic and Cassman 2003). Glyphosate applied at lower doses like 900, 1350, 1800 and 2700 g/ha recorded with more number of bacteria, fungi and actinomycetes. In transgenic maize hybrids, POE application of glyphosate at lower doses like 900 and 1800 g/ha recorded with more number of bacteria, fungi and actinomycetes population compared to atrazine applied treatments (Table 6). This might be due to glyphosate applied directly on the weeds that added organic material to the soil, during decomposition of organic material microbial population might have been increased. Haney *et al*. (2000) who had reported that glyphosate was available to soil and rhizosphere microbial communities as a substrate for direct metabolism leading to increased microbial biomass and activity. Higher doses of glyphosate with 3600 and 5400 g/ha led to slight reduction in microbial population as observed at initial stages and recovered within 45 days. The results corroborate with the observations of Weaver *et al*. (2007) who had reported that glyphosate had only small and transient effects on the soil microbial community, even when applied at greater than field rates.

Mode of action for resistance management

Since the discovery and report of triazine resistance almost 40 years ago, weed resistance to herbicides has been well documented. For example, there are 40 dicot and 15 monocot species known to have biotypes resistant to triazine herbicides. Also, at least 44 weed species have been reported to have biotypes resistant to one or more of 15 other herbicides or herbicide families (Heap 2001). The list of herbicide-resistant weeds will continue to grow, especially with repeated use of herbicides with the same mode of action. Many of the selective herbicides in corn and soybean have similar or identical mechanisms of action such as the inhibition of enzyme acetolactate synthase (ALS) or the inhibition of acetyl-co-enzyme-A-carboxylase (ACCase). Therefore, herbicide tolerant crops particularly cotton (e.g., glyphosate and glufosinate) can provide a new mode of action when used in an IWM program as an aid in resistance management.

Crop management flexibility

The herbicide tolerant technology is simple to use. It requires neither special skills nor training. The technology does not have major restrictions and is flexible, which is probably one of the reasons for such wide adoption by producers. In particular, crops that are tolerant to broad-spectrum herbicides such as glyphosate extend the period of herbicide application for effective weed control, which is helpful in dealing with rainy and windy days during the optimal periods for weed control measures. In contrast, poor weather during the critical period for weed control can greatly limit the effectiveness of more selective herbicides

Table 6. Effect of glyphosate on soil microbes in transgenic corn (*Kharif* 2010)

Treatment	Bacteria ($x10^{-4}$ CFU/g)	Fungi ($x10^{-4}$ CFU/g)	Actinomycetes ($x10^{-4}$ CFU/g)
T_1- 30V92 HR glyphosate 900 g/ha	41.9	27.3	12.9
T_2- 30V92HR glyphosate 1800 g/ha	39.8	28.5	13.3
T_3- 30V92HR (weedy check)	43.7	28.3	14.1
T_4- 30B11HR glyphosate 900 g/ha	40.2	29.6	12.4
T_5- 30B11HR glyphosate 1800 g/ha	39.1	28.6	12.9
T_6- 30B11HR (weedy check)	42.9	29.1	13.7
T_7- 30V92 PE atrazine 0.5 kg/ha + HW + IC	30.5	26.3	11.2
T_8- 30B11 PE atrazine 0.5 kg/ha + HW + IC	31.1	26.8	11.7
T_9- BIO9681 PE atrazine 0.5 kg/ha + HW + IC	28.3	26.0	11.6
T_{10}- CoHM5 PE atrazine 0.5 kg/ha + HW + IC	27.1	25.6	11.8
LSD (P=0.05)	7.61	4.29	1.18

(Peterson *et al.* 2002). According to AICRPWC (2011) trials, total weed density was significantly lowered with post-emergence application of glyphosate in transgenic cotton and corn hybrids when compared to hand weeding plots in transgenic cotton and national and state checks in transgenic maize. Keeling *et al.* (1998) also observed that, weed control is often excellent (95%) with the application glyphosate as post emergence in cotton.

Increased yield and income

Cotton crop being slow in its initial growth and is grown with wider spacing, is always encountered with severe weed competition during early stage, which results in low yield. A broad spectrum of weeds with wider adaptability to extremities of climatic, edaphic and biotic stresses are infesting the cotton fields. High persistence nature of weeds is attributed to their ability of high seed production and seed viability. Hand weeding or hoeing twice is the most commonly adopted method of weed control in cotton. However, complete weed control could not be achieved by using any single method alone. Herbicidal weed control seems to be a competitive and promising way to control weeds at initial stages of crop growth.

Higher yield of herbicide tolerant transgenic cotton recorded with glyphosate at 2700 g/ha over hand weeding twice during both the seasons during winter 2009-10 and winter 2010-11 (Table 1). It could be attributed to efficient control of weeds during the cropping period. The findings are in accordance with observation of Main *et al.* (2007) who had earlier reported that Roundup Ready Flex cotton could provide producers with acceptable weed control without compromising cotton yield. Glyphosate at 2700 g/ha recorded with higher gross and net returns and B:C ratio in herbicide tolerant transgenic cotton.

Higher grain yield was recorded with POE application of Round up at 900, 1800 and 3600 g/ha in Hishell and 900 M Gold transgenic hybrids (Table 2), even though higher and comparable weed control and yield were obtained with glyphosate at 900 and 3600 g/ha, higher net return and benefit cost ratio was recorded in glyphosate at 1800 g/ha in transgenic 900 M Gold in all the four seasons in trial I. Post-emergence application of glyphosate at 900 and 1800 g/ha registered higher grain yield in transgenic 30V92 and 30B11 corn hybrids in the maize trial II compared to their state and national checks (Table 3). Average yield obtained in transgenic hybrid was 10 t/ha and conventional transgenic maize hybrid was 8 t/ha. The findings are in accordance with observation of Tharp *et al.* (1999) who had earlier reported that maize yields of herbicide resistant hybrids were maximum with glyphosate at 0.84 kg/ha of glyphosate when applied at fifth leaf stage of maize.

Conclusion

Herbicide tolerant crops are strongly impacting weed management choices. In many crops their use will decrease the cost of effective weed management in the short to medium-term. However, they offer the farmer a powerful new tool that, if used wisely, can be incorporated into an integrated pest management strategy that can be used for many years to more economically and effectively manage weeds. In maize and cotton transgenic crops, post-emergence weed management with glyphosate proved to be the better management option for the control of weeds.

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Predicting invasive plants using weed risk assessment

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ABSTRACT

Seeds and planting materials of different plant species are being imported into India. Many of these plants have the potential to become agricultural or environmental weeds and this risk needs to be assessed before allowing their entry. Weed risk assessment is a question based scoring system, containing 49 questions about the species. The questions include details of the plant's climatic preferences, biological attributes, dispersal methods and reproduction. A minimum number of questions must be answered before an assessment is made. The weed risk assessment uses responses to the questions to generate a numerical score that is positively correlated with weediness. The assessment method was tested against 170 plants representing both weeds and useful plants from agriculture and environment. The method was judged on its ability to correctly reject weeds and accept non weeds. A total of 40% plants were classified as serious weeds, 30% as common weeds and remaining 30% were non weeds. The system is designed to be operated by plant quarantine officers. The weed risk assessment system with explicit scoring of biological, ecological and geographical attributes is a useful tool for detecting potentially invasive weeds in other areas of the world.

Key words: Plant Quarantine, Score, Seeds, Weed, Weed risk assessment

The implementation of new policy on 'Seed Development' by the Government of India has provided stimulus for the import of seeds of various crops from all over the world. This has increased the risk for the introduction of exotic weeds into India. Weeds have major impacts on economies and natural environments worldwide including India. Many of these weeds have been purposely introduced as new crops or as ornamentals. To counter the threat to agriculture or the environment from new plants, regulatory authorities have a statutory responsibility to ensure that all plants proposed to be imported, which are not already established, be evaluated for their potential to damage the productive capacity or environment of the country. Quarantine in India officially came into operation with the passing of the Destructive Insects & Pests Act (DIP Act) in 1914. Plant Quarantine Order 2003 (regulation of import into India), of the Destructive Insects and Pests Act (1914) provides a legislative framework for the application of measures to prevent the introduction or spread of insect, disease and weed pests affecting plants. Effective plant quarantine is important for the protection of the biodiversity of the natural environment and agricultural productivity. Infestation of agricultural system has the potential not only to incur costs in controlling pests and losses in production, but also to restrict access to export markets, if the pest has the potential to contaminate the marketable product. There are many approaches to predicting weed potential (Mack 1996), but there is an urgent need of an objective, credible and publicly acceptable risk assessment system to predict the weediness of the new plant introductions.

An acceptable weed risk assessment system should satisfy a number of requirements. It should be calibrated and validated against a large number of plants already present in the recipient country and representing the full spectrum of plants likely to be encountered as imports into that country. It must discriminate between weeds and non-weeds, such that the majority of weeds are not accepted, non-weeds are not rejected, and the proportion of plants requiring further evaluation is kept to a minimum. As international trade agreements require that prohibited plant should fit in the definition of a quarantine pest before they can be excluded by quarantine regulations (Singh *et al.* 2005), the system must be passed on explicit assumption and scientific principles so that country +cannot be accused of applying unjustified non-tariff trade barriers. Ideally, the system should be capable of identifying which land use system the plant is likely to invade, to assist in an economic evaluation of its potential impacts. Finally, the system must be cost

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effective. This 'weed risk assessment' (WRA) system for India is designed in consultation with the weed scientists of Australia, University of Queensland, Brisbane.

Methodology of weed risk analysis (WRA)

The WRA system is designed to run on Microsoft Excel 2007 in MS Windows operating system. The basis of the WRA is to answers 49 questions (Table 1) based on the main attributes and impacts of weeds. These are combined into scoring system which in the absence of any evidence to the contrary, gives an equal weight to nearly all questions (Tabel 2). These cover a range of weedy attributes in order to screen for plants that are likely to become weeds of an environment and/or agriculture. The questions are divided into three sections producing identifiable scores that contribute to the total score (Table 2). Most questions are answered, as yes, no or don't know. Biogeography consists the documented distribution, climate preferences, history of cultivation, and weediness of a plant elsewhere in the world, *i.e.* apart from the proposed recipient country. Weediness elsewhere is a good predictor of a plant becoming a weed in new areas with similar environmental conditions (Forcella and Wood 1984). The questions concerning the history of cultivation recognizes the important human component of propagule pressure (Williamson and Fitter 1996), but such data are obviously never available for the proposed new country. The global distribution and climate preferences, where these are available, are used to predict a potential distribution in the recipient country. Undesirable attributes are characteristics such as toxic fruits and unpalatibility, or invasive behavior, such as a climbing or smothering growth habit, or the ability to survive in dense shade. Biology and ecology are the attributes that enable a plant to reproduce, spread and persist (Noble 1989) such as whether the plant is wind dispersed or animal dispersed, and whether the seeds would survive through passage of an animal's gut. Availability of information is often very limited for new species which can restrain the utility of screening systems. To ensure that at least some questions were answered for each section, the WRA system requires the answer to two questions in Section-A, two in Section- B and six in Section-C before it will give an evaluation and recommendation. The recommendation can be compared with the number of questions, answered as an indication of its reliability which obviously improves as more questions are answered.

Answers to the questions provide a potential total score ranging from -14 (benign plant) to 29 (maximum weediness) for each plant. The total score is partitioned between answers to questions considered to relate primarily to agriculture, to the environment, or common to both (Table 1). The total scores are converted to one of the three possible recommendations by two critical score settings. The lower critical scores 0, separates 'acceptable' plants from those requiring 'evaluation', and the higher critical score, 6, separates plants requiring 'evaluation' from those that should be 'rejected'. Evaluation could mean either obtaining more data or re-running the system, or undertaking further investigations such as field trails (Mack 1996). The model was run to assess the weed potential of plants ranging from beneficial plants to serious weeds.

Interference of results of WRA

The answer to most of the questions in WRA is yes (y), *no* (n) or don't know (leave blank or?). The system translates these responses into a numerical score.

A typical score for a question is Yes=1 point, No= -1 or 0 and don't know/? =0

The questions in Sections- 2 and -3 (climate and weed elsewhere) of the questionnaire differ from the typical scoring in that they generate a score by a weighting system. The score given for questions 2.01 and 2.02 is used to weight the scores for 'yes' answers in the weed elsewhere questions (3.01 to 3.05). The quality of climate data greatly affects the climate match. A good climate match increases the probability that a weedy species will behave the same way in India as it does overseas. The weediness score also increases if the information used to produce the climate match is not comprehensive, due to the greater uncertainty introduced by this data.

Two other questions do not fit into the standard scoring system:

1) A score of 'no' for question 3.01, whether a plant has naturalized overseas, is modified by the score to question 2.05, its history of repeated export species with repeated introductions outside of their native range that have not established are a lower risk.

2) Questions 6.07, the minimum generative time, require the input of a numerical score. This generative time is standardized by the use of correlation factor as shown in table.

Reproduction	Scores
< 1 to 2 years	1
Between 2 to 4 years	0
Greater than or equal to 4 years	-1

Table 1. Weed risk assessment system question sheet

Botanical Name:	*Phalaris paradoxa*	Outcome:	Reject
Common Name:	Paradoxa grass	Score:	12
Family Name:	Poaceae	Your name:	M.C. Singh

Section	Weed Type	S.no.	a Question	b Response	c Score	d N Score	e Y Score
Domestication/ cultivation							
A	Common	1.01	Is the species highly domesticated? If answer is no go to question 2.01	N	0	0	-3
A	Common	1.02	Has the species become naturalised where grown?			-1	1
A	Common	1.03	Does the species have weedy races?			-1	1
Climate and distribution							
A		2.01	Species suited to Indian climates (0-low; 1-intermediate; 2-high)		2		
A		2.02	Quality of climate match data (0-low; 1-intermediate; 2-high)		2		
A	Common	2.03	Broad climate suitability	N	0	0	1
A	Common	2.04	Native or naturalised in regions with extended dry periods.	N	0	0	1
A		2.05	Does the species have a history of repeated introductions outside its natural range?				
A	Weed elsewhere						
A	Common	3.01	Naturalised beyond native range	Y	2		
A	Environmental	3.02	Garden /amenity / disturbance weed	N	-1		
A	Agricultural	3.03	Weed of agriculture /horticulture / forestry	Y	4		
A	Environmental	3.04	Environmental Weed	N	-1		
A	Common	3.05	Congeneric weed Undesirable				
Undesirable traits							
B	Common	4.01	Produces spines, thorns or burrs	N	0	0	1
B	Common	4.02	Allelopathic	N	0	0	1
B	Common	4.03	Parasitic	N	0	0	1
B	Agricultural	4.04	Unpalatable to grazing animals	N	-1	-1	1
B	Common	4.05	Toxic to animals	N	0	0	1
B	Common	4.06	Host for recognised pests and pathogens			0	1
B	Common	4.07	Causes allergies or is otherwise toxic to humans	N	0	0	1
B	Environmental	4.08	Creates a fire hazard in natural ecosystems	N	0	0	1
B	Environmental	4.09	Is a shade tolerant plant at some stage of its life cycle			0	1
B	Environmental	4.10	Grows on infertile soils			0	1
B	Environmental	4.11	Climbing or smothering growth habit			0	1
B	Common	4.12	Forms dense thickets plant type	N	0	0	1
Plant type							
C	Environmental	5.01	Aquatic	N	0	0	5
C	Common	5.02	Grass	Y	1	0	1
C	Environmental	5.03	Nitrogen fixing woody plant	N	0	0	1
C	Common	5.04	Geophyte			0	1
Reproduction							
C	Common	6.01	Evidence of substantial reproductive failure in native habitat			0	1
C	Common	6.02	Produces viable seed	Y	1	-1	1
C	Agricultural	6.03	Hybridises naturally			-1	1
C	Common	6.04	Self-fertilisation	Y	1	-1	1
C	Common	6.05	Requires specialist pollinators	N	0	0	-1
C	Agricultural	6.06	Reproduction by vegetative propagation	N	-1	-1	1
C	Common	6.07	Minimum generative time (years) (Answer between 1,2, 0r 4 value)	1	1		
Dispersal mechanisms							
C	Agricultural	7.01	Propagules likely to be dispersed unintentionally	N	-1	-1	1
C	Common	7.02	Propagules dispersed intentionally by people	Y	1	-1	1
C	Agricultural	7.03	Propagules likely to be disperse as a produce contaminant			-1	1
C	Common	7.04	Propagules adapted to wind dispersal	Y	1	-1	1
C	Environmental	7.05	Propagules buoyant			-1	1
C	Environmental	7.06	Propagules bird dispersed	Y	1	-1	1
C	Common	7.07	Propagules dispersed by other animals (externally)	N	-1	-1	1
C	Common	7.08	Propagules dispersed by other animals (internally)	Y	1	-1	1
Biological attributes							
C	Common	8.01	Prolific seed production	Y	1	-1	1
C	Common	8.02	Evidence that a persistent propagule bank is formed (> 1 year)	Y	1	-1	1
C	Agricultural	8.03	Well Controlled by herbicides	Y	-1	1	-1
C	Agricultural	8.04	Tolerates or benefits from multilation, cultivation or fire			-1	1
C	Common	8.05	Effective natural enemies present in India	N	-1	-1	1

Result

Weed Type	
Agricultural	5
Environmental	6
Common	22

Excluding common weed and comparing agricultural and environmental weed towards the higher side leads to the conclusion of environmental weed

Section Attended	
A	7
B	8
C	18
Total	33
Outcome:	Reject

Table 2. Weed risk assessment system question sheet

Section	Weed Type	a Question	b Response [1]	c Score [2]	d N Score	e Y Score
	C	1.01			0	-3
A	C	1.02			-1	1
A	C	1.03			-1	1
A		2.01				
A		2.02				
A	C	2.03				
A	C	2.04				
A		2.05				
A	C	3.01				
A	E	3.02				
A	A	3.03				
A	E	3.04				
A	C	3.05				
B	C	4.01			0	1
B	C	4.02			0	1
B	C	4.03			0	1
B	A	4.04			-1	1
B	C	4.05			0	1
B	C	4.06			0	1
B	C	4.07			0	1
B	E	4.08			0	1
B	E	4.09			0	1
B	E	4.10			0	1
B	E	4.11			0	1
B	C	4.12			0	1
C	E	5.01			0	5
C	C	5.02			0	1
C	E	5.03			0	1
C	C	5.04			0	1
C	C	6.01			0	1
C	C	6.02			-1	1
C	A	6.03			-1	1
C	C	6.04			-1	1
C	C	6.05			0	-1
C	A	6.06			-1	1
C	C	6.07				
C	A	7.01			-1	1
C	C	7.02			-1	1
C	A	7.03			-1	1
C	C	7.04			-1	1
C	E	7.05			-1	1
C	E	7.06			-1	1
C	C	7.07			-1	1
C	C	7.08			-1	1
C	C	8.01			-1	1
C	C	8.02			-1	1
C	A	8.03			1	-1
C	A	8.04			-1	1
C	C	8.05			-1	1

Response for these questions is 2 unless a climate analysis is done. (Questions 2.01–2.05)

Refer to lookup table (Questions 3.01–3.05)

Lookup table for section 3.
Locate value of inputs and lookup output for each question

Yes to question 3.01 – 3.05										default
Inputs	2.01	0	0	0	1	1	1	2	2	2
	2.02	0	1	2	0	1	2	0	1	2
Results	3.01	2	1	1	2	2	1	2	2	2
	3.02	2	1	1	2	2	1	2	2	2
	3.03	3	2	1	4	3	2	4	4	4
	3.04	3	2	1	4	3	2	4	4	4
	3.05	2	1	1	2	2	1	2	2	2

No to question 3.01-3.05				
Input	2.05	?	N	Y
Results	3.01	-1	0	-2
	3.02-3.05	0	0	0

Procedure

1. Record appropriate responses in column b.
2. Look up score in columns d & e and record result in column c.
3. Calculate total score.
4. Lookup and record recommendation
5. Verify that minimum number of questions from each section is answered.
6. Compute Agricultural (A& C) and environmental (E& C) scores: If either score is less than 1, the outcome pertains to the other sector.

Lookup table for 6.07

years	1	2	4
score	1	0	-1

Score	Outcome
<1	Accept
1 -6	Evaluate
< 6	Reject
Section	**Minimum # question [5]**
A	2
B	2
C	6
Total	10

Total Score [3]	
Outcome [4]	
Agriculture [6]	
Environment [6]	

Weed Type	
A	Agricultural
E	Environmental
C	Common

The WRA compares the total score for a species to the critical values to determine the recommendation for the species. The threshold values for the system are shown as follows:

If the plant scores less than 1	Accept the plant
if the plant scores greater than 6	Reject the plant
if the plant scores between 1 to 6	Plant requires further evaluation

The species used for the calibration of the system ranged from severe agricultural and environmental weeds to benign and beneficial plants. The WRA tallies the number of questions answered in each section. The WRA allows for a minimum number of questions in each of its three different categories. The minimum number of questions for each section is: 2 for Section- A, 2 for Section- B and 6 for Section- C. When using the; Excel Spreadsheet', if the minimum number of questions is not completed, a message that more information is required is posted by the system. The WRA has some capacity to suggest the type of ecosystem likely to be affected by the plant assessed. The WRA indicates if the plant is more likely to be a specific weed of agriculture or the general environment, once it has assessed the plants potential to become a weed in India. A species may be assessed to be a weed of both categories. The partitioning helps to identify areas most at risk from the characters assessed for the species. The assessment method was tested against 170 plants representing both weeds and useful plants from agriculture and environment. The method was judged on its ability to correctly reject weeds and accept non weeds. A total of 40% plants were classified as serious weeds, 30% as common weeds and remaining 30% were non weeds.

The system identifies a wide range of weeds, and does not accept plants known to be major weeds in India. By splitting the total scores the model also allows an estimate of whether the weed is more likely to impact on agricultural or natural environment systems, which may assist regulatory authorities in making a recommendation. These features suggest that the system could be altered and still be expected to produce satisfactory results in other bio-climatic regions of the globe where protocols are lacking (Ruesink *et al.* 1995). As the system is simple and spreadsheet based, it can be used by lay people who wish to import plants and it has an educational role because it shows the effect of individual questions on the total score. The system distinguishes between many useful and non useful plants, but some useful plants can be rejected. This is to be expected, because planned introductions are chosen for their ability to survive (Ruesink *et al.* 1995), and the questions asked by the system are based primarily on biological and ecological criteria which identify attributes common to both useful agricultural plants and weeds (Lonsdale 1994). These may differ only in a small number of characteristics within any single life from (Perrins *et al.* 1992). Where a plant may have significant economic benefits, a further evaluation of its weediness potential may include experimental studies (Williamson, 1993, Scott and Panetta 1993). Economic value should be scored in a transparently separate exercise and balanced against weediness in appropriate risk assessment evaluations (Singh *et al*. 2005).

It is concluded that the Weed Risk Assessment System with explicit scoring of biological, ecological and geographical attributes is a useful tool for detecting potentially invasive weeds in other parts of the world and should be used in Indian Plant Quarantine to assess the plants before issue of the *Import Permit.*

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Living with weeds - a new paradigm

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ABSTRACT

Some people, particularly in developed countries, have strong negative attitudes towards weeds, and a tendency to label potentially useful plant resources as invasive 'aliens', which are to be controlled at any cost. This undesirable attitude ignores the considerable evidence of beneficial uses of weed species to many societies, over a long period of human history. The recent application of 'species-focused' weed risk assessments have contributed to the maligning of many plant taxa as 'invaders' in the public's mind, undermining their worth as biological resources. Some of the methods used in the blitz against weeds, including the excessive use of herbicides, have resulted in undesirable consequences, such as herbicide resistance, and negative impacts on biodiversity in farming landscapes. Weeds maintain the biological diversity of farming landscapes, providing food and shelter for a variety of animals. Insects, which pollinate crops, extensively use weeds as a source of nectar, when crops are not in flower. Weeds also attract crop pests; and there is evidence that pest populations in some crops are much lower in 'weedy fields' than in 'weed-free' crops. As many of our primary crops have 'weedy-relatives', the genes present in weeds appear crucial for future evolution of crops, particularly to confer 'hardiness' (ability to tolerate variable environmental conditions). Some weed species contribute to aesthetic pleasure, as part of 'wild nature', while others provide culinary delights for humans, and are important as food sources for both vertebrate and invertebrate animals. Many weeds with medicinal values continue to be used either as traditional 'herbal' remedies, or extracted for secondary metabolites. The colonising strengths of several species are being used in the remediation of water and terrestrial environments to scavenge soil pollutants. Globally, there is considerable interest in using the large biomass produced by these species as raw materials for countless household products, including bricks, paper and furniture; and as future bio-fuels.Therefore, within the field of weed science, a fresh look at weeds is essential. Perhaps, a new and bold paradigm should be 'co-existing' or 'living with weeds', recognising their intrinsic worth as part of biodiversity, and the many possible uses as bio-resources.

Key words: Beneficial effects of weeds, Colonising species, Utilization of weeds, Weeds as biological resources

Negative impacts of weeds are wellknown. Many weeds compete aggressively with crop plants, reducing yields and crop quality, and take the space of native bushlands or garden plants. Some can also taint milk, and others are poisonous to humans and domestic animals. Still others have attributes like thorns and spines, which cause physical injury. Some weeds may act as host plants for parasitic insects or diseases, while yet others can be parasitic on other plants. Through these direct or indirect effects, weeds often increase the cost of farming and decrease the value of agricultural land and produce. In some circumstances, they may even threaten the biodiversity of landscapes, national parks, conservation areas, aquatic habitat and waterbodies.

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In US agriculture, weeds cause a reduction of 12% in potential crop yields. In economic terms, this represents about US$ 33 billion loss in crop production annually, based on the crop potential value of all US crops of about US$ 267 billion/year (Pimentel *et al.* 2000). In Australia, the cost of weeds to Australia's primary industries in lost production and weed control exceeded Aus$ 4 billion per year (Sinden *et al.* 2005). In India, weeds cause about 30% losses in potential crop production, which is worth about US$ 90 billion/year in reduced crop yields (Pimentel *et al.* 2000). These are highly significant figures. Our dislike for weeds is also reflected in the global figures from agrochemical sales. Globally, we spent US$ 35.8 billion and $39.4 billion in 2006 and 2007, respectively, on agrochemicals, of which 40% ($14.3 billion) and 39% ($ 15.5 billion), respectively, were for herbicides

(Grube *et al.* 2007). It was estimated that herbicides of worth ` 11,600 crores or 116 billions will be required annually to control *Parthenium hysterophortus* infested in an area of about 35 million hactares land in India (Sushilkumar and Varsheny 2010).

Given the negative impacts that weeds may have on agriculture, environment, and to human societies in general, it is essential to understand these plants better. Some plant species become weeds because they are competitive, adaptable, highly fecund, and are capable of exploiting naturally disturbed or man-made habitats. As humans manipulate our surroundings to fulfil our needs, we provide an environment suitable for certain plant species, which may thrive under those circumstances. They are not ecologically 'plants out of place', as some older definitions have suggested. In fact, in an ecological sense, the opposite is true. Weeds are just opportunistic species or '*pioneers of secondary succession*' (Bunting 1960), that are well adapted to grow in locations where disturbances have opened up space (Grime 1979).

In many ways, humans may also be regarded as 'weeds', because we are highly adept at disturbing and colonising landscapes, as well as perpetuating our species. As Harlan and de Wet (1965) wrote: *"…The word weed is taken to mean a species or race, which is adapted to conditions of human disturbance. By this definition…..animals such as the English sparrow, the starling, the "statuary" pigeon, the house mouse, Drosophila melanogaster, and others are especially fitted to environments provided by human disturbance. Indeed, perhaps no species thrives under human disturbance more than Homo sapiens himself. In this ecological sense, man is a weed…"*

A set of common biological characteristics allows weeds to colonise disturbed habitats, to form extensive populations, and often, to dominate landscapes. These include high fecundity (numbers of individuals produced), the ability to germinate and grow rapidly, and tolerance of a wide range of environmental conditions (Baker 1965). However, a species may initially colonise, and then become an invader of landscapes only if a chance combination of circumstances makes its attributes particularly advantageous to its growth and survival (Naylor and Lutman 2002). In many cases, this opportunity arises because of lack of natural enemies, specific parasites or herbivores, which gives them an advantage over crops and native flora. Various features of the plants themselves (such as phenotypic plasticity, and ability to produce chemical defences to deter herbivores) would assist the colonisation process. However, in the right place, many of these extraordinary plants can provide benefits that can be exploited for human welfare. If evolutionary success means continuing a genetic line over time, and in terms of the Darwinian concept of the struggle for existence, many weeds must rate amongst the most successful plants that have evolved (Auld 2004).

A recent trend has been to refer to the growth of weeds in disturbed habitats as an 'invasion' of natural or man-made habitat by some introduced 'aliens'. This rather xenophobic view, and the resultant 'War on Invasives' is full of 'scientific' theories, scaremongering and far-reaching policies, based on highly subjective opinions of 'good' plants verses 'bad' plants. The effect has been that governments, various corporations, organizations and the pubic spend billions of dollars trying to control the 'fugitive' plants! This war was created by the belief that a new, 'exotic' plant species entering a 'native' ecosystem is always harmful to the surrounding inhabitants. Several major publications have highlighted the issue of significant negative impacts of invasive specieson the local environment (Vitousek *et al*. 1996, Mack and D'Antonio 1998, Groves and Willis 1999, Richardson *et al*. 2000, Groves *et al.* 2005). Whilst this may be true in some cases, the overuse of herbicides, destructive land clearing and indiscriminate weed removal policies and practices, and a hate mentality that maligns species do more damage to native habitats and ecosystems. Over-reacting on this issue with badly planned and indiscriminate weed control actions also divert vast resources that could be better spent on more useful measures, such as preventing land clearing and habitat destruction, preservation of biological diversity, studying plant medicines, renewable resources, and educating the public on the values of weeds as part of nature.

It is clear that weeds were here before us; and will be here after us! Therefore, instead of engaging in an 'unwinnable war', a fresh look at the potential of 'co-existing' with weeds and using them as resources is overdue, given their biodiversity and environmental values, and many possibilities of utilization that can be demonstrated (Jordan and Vatovec 2004, Kim *et al*. 2007, Varshney and Sushilkumar 2009). In many cases, the focus of Weed Research is on managing problematic species in specific situations, rather than on their well-known beneficial impacts in agro-ecosystems, or potential for utilization. However, if farmers and land managers can be led to appreciate the extraordinary strengths of colonising taxa, this will allow a better integration of these species into our economies and overall farm productivity. Improved understanding of the causes of biological invasions will also reduce the current confusion and negative attitudes towards invasive species. The purpose of this paper is to discuss the above viewpoints and argue that: *not all weedy taxa are bad all the time, just because they may interfere, under certain circumstances, with human interests*.

Are all weeds really bad?

Ralph Waldo Emerson, the American Naturalist, had the right idea. His 1873 quote: "…*What is a weed? A weed is a plant whose virtues have not yet been discovered*" expressed a positive view of weeds and their intrinsic worth (virtues), as opposed to negative impacts (Emerson 1873). In Jack Harlan's opinion(1975): "..*Weeds are adapted to habitats disturbed by man. They may be useful in some respects and harmful in others. They may be useful to some people and hated and despised by others...*"Ehrenfried Pfeiffer (1970) elegantly mused as follows: "…*Weeds are only weeds from our egotistical point of view, because they grow where we do not want them. In nature, however, they play an important and interesting role. They resist conditions, which cultivated plants cannot resist, such as drought, acidity of soil, lack of humus and mineral deficiencies, as well as a one-sidedness of minerals. They represent human beings' failure to master the soil, and they grow abundantly wherever people have made mistakes – they simply indicate our errors and nature's corrections...*"

These well-known, sympathetic views of weeds provide the basis for a re-appraisal of our attitudes. *Are weeds really bad?* The answer may depend on an individual's perceptions, but for ecologically-minded Weed Scientists, interested in creating a food-secure society in productive, but sustainable and ecologically-healthy landscapes, it must be a resounding: *No*. Taken individually by species, or collectively as a group - weeds are the most fascinating and extraordinary plants in the world. They are top-notch, skilled survivors, often thriving in inhospitable environments and extreme conditions, where otherspecies would fail. Much of the time, they appear to mock our unsuccessful attempts to eradicate them! They can teach us – animals -how to survive and make the best of any situation. As humans face significant uncertainty in a relatively unstable future climate, brought about by our own actions (and inactions), the strategies for survival demonstrated by weeds would be great lessons to learn.

Weeds do not ask for much; they may take some of the earth's resources for their growth and survival; they may also make humans toil a bit more, farmers in particular, but they give back a lot more than we realise (Pfeiffer 1970). In a rapidly changing world, with limited resources and a burgeoning human population, weeds tell us how to share those limited resources, *differentiate our ecological niches*, and co-exist. If we have an enlightened attitude towards weeds and understand them better and apply those ecological principles, it would do well for the survival of our species.

For all other animals, except humans, weeds are undoubtedly a great resource. Most animals cannot be choosy, and they are generally adept at exploiting any resource available for food and shelter. Nearly all insects, fish, birds and foraging herbivorous animals use colonising plants as resources. Birds, bees, ants and other insects derive sugary food from the flowers and fruits of species, such as Lantana (*Lantana camara* L.), consideredan obnoxious pest (Gosper and Vivian-Smith 2006). Similarly, bumblebees, the great pollinator of field crops, rely heavily on weeds for sugary nectar. Macro invertebrates and small fish, living in our streams, thrive on food in the root zones of large macrophytes, such as *Typha angustifolia* L. and *Phragmites australis* (Cav.) Trin. ex Steud (common reed), which are also often regarded as problematic aquatic weeds. Such multi-faceted interactions in the Natural World are quite fascinating, and should be much more meaningful for Weed Scientists to study than spending countless hours researching only the harmful effects of weeds and how to control them.

Weeds and crops are close relatives

"…*There are weed races of most of our field crops and these interact genetically with cultivated races as well as truly wild races. This interaction probably results ultimately in better crops and more persistent weeds. Although some weeds have evolved elegant adaptations under the influence of man, many had weedy tendencies before man existed. Weeds are products of organic evolution; they exist in intermediate states and conditions. They are also genetically labile and phenotypically plastic*" (Harlan 1975).

The interaction between humans and weeds has been going on for millennia, and probably date back to domestication of plants about 12,000 years before present. As suggested by Jack Harlan, firstly in 1975 (quote above), many species that became crop plants have 'weedy' relatives, and several have actually evolved from weeds. Therein lays our first and the most significant interaction with weeds: based on plenty of scientific evidence, almost all of our major food crops originated from relatives who might be considered 'undesirables' in today's context! The co-evolution between weeds and crops is an on-going process (Harlan 1965, 1975), and genetic exchanges between related species are part of natural evolution.The accepted view (Baker 1974, 1991) is that many weeds of today are as old as agriculture itself and have substantially evolved with adaptations and characteristics that enable them to grow, flourish, invade, and dominate cropping fields, which arehuman-disturbed environments. Once evolved in agricultural habitat, the same attributes of survival, spread, fast growth and persistence, allowed many weeds to exploit other relatively undisturbed, more natural systems, where vacancies and opportunities existed.

There is also general consensus that most cosmopolitan weeds across the globe originated in the agricultural fields of one kind or another. These plant species represent a significant component of the agro-ecosystem, resulting from the continuous selection pressure imposed on them by man, his tools, agricultural practices, and methods of weed control. 'Agrestals' or, wild plants growing within or adjacent to agricultural fields, have long been exposed to both natural and human breeding and selection systems that enabled them to survive and insure their future generations. They have also proved to be excellent invaders into human-made habitats, taking advantage of all measures that man imposed to eliminate or to keep them fully under his control.

Weeds are much maligned, but not all weeds are 'bad' all the time

Weeds are the most maligned group of plants in the world, certainly in developed countries. The Weed Science literature is full of books, review papers and reports that highlight negative aspects of weeds in cropping and non-agricultural landscapes. The recent species-focused 'Weed Risk Assessments' have created a pervasive myth: an impression that most introduced species are undesirable in any new habitat, and are likely to be problematic. Even if we understand the imprecise idea of '*border protection*' with regard to the deliberate and unnecessary introductions of potentially invasive species from one part of the globe to another, isn't it another human folly to assign a '*guilty until proven otherwise*' tag to many useful plants?

The term '*invasive plants*' refers to '*any naturalised species that has a capacity to expand their geographic range and spread in the area to which it has been introduced,* and have detrimental impacts (Richardson *et al*. 2000). They are, therefore, *a subset of non-native species that cross a threshold for disproportionate negative impacts in an ecosystem*, and this distinction is considered vital. The definition recognises that: (a) Introduced species could become 'naturalised' in areas where they did not exist before, and 'invade' or gain geographical territory, with or without human assistance; and (b) Such species often cause harm to the environment, economy, or human health. Somewhat implicit in the definition is the view that *not all exotics are invasive, but all invasives are exotic*.

It is important to note that most exotic species, which may be naturalized and reproduce self-sustainably, represent a small fraction of the community in which they are introduced and typically have negligible influence on plant communities they inhabit. On the other hand, a few species, which have high rates of population growth and spread, may become dominant members of plant communities; have a negative influence on native species; and may alter the functioning of ecosystems. Good examples are: *Lantana* in India and Australia; Mesquite (*Prosopsis* spp.) and Prickly Acacia (*Acacia nilotica* (L.) Delile) in Australia. Many recent publications have highlighted the dangers posed by 'environmental weeds' and 'sleeper weeds', which may impact adversely on natural landscapes (Mack and D'Antonio 1998, Richardson *et al.* 2000, Williams and West 2000, Groves *et al*. 2005). Environmental weeds are usually non-native, but naturalised plants, which could have a negative impact on native species diversity. It should be noted that some native plant species that are invasive beyond their indigenous range can also become environmental weeds; an example is: Golden Wreath Wattle (*Acacia saligna* (Labill.) H.L. Wendl.), indigenous to Western Australia, but is naturalised and considered a major problem in the Eastern States of Australia. 'Sleeper weeds' are a sub-group of plants that arrive at a region, naturalise (*i.e*. establish and self-reproduce), and remain localized for a long period, usually greater than about 50 years, before they become seriously invasive (Groves 1999). The single species focused risk assessments' mind-set has created a dubious list of maligned species, which is already quite impressive and is dangerously growing longer.

'Weediness' is in the eye of the beholder

After much debate in the 1980s, the Weed Science Society of America (WSSA) defined a weed as: '*a plant growing where it is not desired*'. The European Weed Science Society (EWSS) extended this to include: '*any plant or vegetation, excluding fungi, interfering with the objectives or requirements of people*'. The Australian definitions have a strong slant towards the European version, *i.e.* '*a weed is a species that adversely affects biodiversity, the economy or society*' (Groves *et al.* 2005) or '*a weed is a plant, which has, or has the potential to have, a detrimental effect on economic, conservation, or social values in Australia*' (ARMCANZ 1999). These definitions are only partially true; by effectively removing man's culpability, they miss the essential point that *weeds are a symptom of a man-made crisis, but not the cause of it.*

However, even plants with strong colonising attributes are of value in various situations, at different times, or to different people (Chandrasena 2007). Therefore, developing countries will do well to broaden the common definition to capture the idea that weeds present problems to some people, and certainly not to all people; at all times or at all places. In that regard, Kloot's (1987) definition from Australia that a weed, '*is a plant that may interfere with human activity in one way or another and, thus, has come to be regarded negatively by at least part of the society*' is a reasonable one to consider.

Five decades ago, Bunting (1960) had already clarified that '…*weeds are pioneers of secondary succession, of which the weedy arable field is a special case*…' and they specialize in the occupation of ground stripped of plants by landslides, floods, fires, or by man's activities. Largely agreeing with Bunting, Baker (1965) defined a weed as: '…*a plant if, in any specified geographical area, its populations grow entirely or predominantly in situations markedly disturbed by man, (without, of course, being a deliberately cultivated plant)*…' Zimdahl (1999) favoured the view that weeds are: '…*those plants that are successful in disturbed environments, are fast growing, and, are often, but not always herbaceous*…' These well respected definitions emphasize the human connection and man's own role in creating disturbed habitats. Bunting (1960) also said, '…*an essential feature of all of man's activities, in agriculture or otherwise, is the production of open, or at least disturbed, habitats*…' Downplaying man's role in creating much of the disturbance to which colonising plants naturally respond has led to misconceptions, and, over time, to the hardened attitude towards 'weedy' taxa. Most people, growers, farmers, biologists, and even politicians will agree that weeds can be are useful resources, at various times. This word 'weed' - *an epithet of human invention and a dubious 'cultural construct'* - has caused so much confusion within the field of Weed Science. In the world of plants, it simply does not exist. As Plato said in 300 BC - '…*beauty is in the eyes of the beholder*…'; 'Weediness' is definitely in the eyes of the beholder; in my view, much of the time this human perception is subjective and flawed.

Weeds or useful plants - a matter of opinion and circumstances

Grice and Brown (1996) highlighted the dilemma of labelling a weed in relation to managing Australian rangelands. From a conservation perspective, a species may be called a weed because it is non-native; from a land use perspective, a native or an introduced species may be labelled a weed because it is toxic to livestock, or reduces agricultural productivity. From an ecological point of view, a species may be called a weed, because it changes the structure of a plant community, or modifies some attribute of an ecosystem, such as the local hydrology.The same species may be identified in another situation by different users, as a useful plant. There are many examples, which demonstrate the tenuous nature of the human judgement on the virtues of a species, whether it is a weed or a useful plant. Clearly, *this is a matter of opinion, largely based on human needs, wants, and perceptions, at a particular time, place, or circumstances*. Such opinion is highly subjective, easily swayed by the needs of a situation, short-term gains, and profit motivation, and there is room for significant error.

Until about the 1970s, weed issues were discussed only from the perspective that they were problems to crop production. In subsequent decades, attention turned to weeds as environmental fugitives affecting our landscapes. Weeds are now projected as major 'villains and thugs', who affect all aspects of our daily lives! Much energy and resources are spent fighting them. However, *is the problem really weeds? Or is it our perception of them*? Weed occurrence is inevitable, because man's activities will continue to disturb environments, and movement of people across continents will exacerbate introductions into new areas. There is no simple remedy for the weed problems in their many manifestations. Prevention of introduction of species to where they did not exist before is strategically the best approach. Sometimes it may be possible to eradicate a relatively small population of a potentially invasive species from a given area, but more often than not, eradication is a flawed approach in most ecosystems. This is because of secondary effects of eradication of a target species (i.e. creating more disturbances, whether by the use of herbicides or physical removal), to which other species will respond. In many ecosystems, there are likely to be compensatory increases of other colonising species, making use of new opportunities.

Therefore, whilst continuing to study the reasons why colonising species sometimes come to dominate landscapes, the best management strategy would be to use several control tactics in an integrated manner, but with heightened emphasis on prevention. Management approaches must attempt to prevent new introductions to disturbed areas, rehabilitate disturbed areas as soon as possible, and to minimise the undesirable impacts where conflicts exists between man and weeds. However, a proper ecological understanding, and a balanced view of economic implications are essential for this. taxa.

Beneficial effects of weeds

The negative connotations associated with colonising species are of such magnitude that for some people it may seem paradoxical that weeds are actually beneficial. Prior to launching major offensives against weeds, all Weed Scientists and Weed Managers should recognise the positive and redeeming values of weeds and properties of these plant species that are highly beneficial to human societies. This recognition requires a conceptual change in direction, and an *acceptance* of the fact that *weeds are beneficial in the right place, under the right circumstances*. The primary objective of this essay is therefore to highlight some of the beneficial effects of these much demonised, wrongly accused group of plants, and highlight the possibilities of human societies 'living with weeds'. Several other publications have already emphasized various beneficial effects of weeds (Altieri 1988 1995, 1999, Marshall 2001 and references therein), and these support why a conceptual change is necessary. Some of the positive aspects of weeds have been extensively canvassed in a monograph, edited by Kim *et al.* (2007), and more recently, in a National Consultation on 'Weed Utilization' held in October 2009 in India (Varshney and Sushilkumar 2009, and references therein).

Weeds as components of biodiversity and wild nature: Weeds are beneficial not just because of the potential utilization value as various raw materials; or as food and shelter for humans and animals, but also for their innate abilities and ecological and biological roles in natural and man-made ecosystems(Marshall 2001, Marshall *et al.* 2003, Storkey and Westbury 2007, Kim *et al.* 2007). There is also a moral and ethical imperative to value weeds as part of 'wild nature', which is under threat, as a result of burgeoning human populations in several countries, and over development in the creation of 'humanised space'. In many situations, weeds are not the problem; the real culprit is man and his limitless greed, and over-exploitation of resources that has placed the sustainability of the earth's ecosystems in jeopardy.

The term 'biodiversity' describes the biological diversity; or assemblages of organisms that have evolved together to exploit the resources of an environment, in ways that maximises the cycling of energy and nutrients within that area: *i.e.* an 'ecosystem'. By their nature, ecosystems are dynamic and they change in response, both to environmental changes and due to the adaptive evolution of their constituent species. As primary producers,plant sare key components of such systems, with different species occupying various ecological niches, filling a variety of roles (Jordan and Vatovec 2004, Kim *et al.* 2007). Colonising plants are important in many ecosystems, primarily because they are more effective at exploiting available resources and would fill many niches that slow-growing plants are not able to occupy; for the provision of various ecosystem services; and also as primary producers. However, in many instances, weeds may only be a relatively small fraction of the total biodiversity of an ecosystem, although they are roundly condemned for a variety of negative impacts.

Agroecological benefits of weeds: Biodiversity in Agroecosystems responds to changes in agricultural management.Many studies in Britain and Western Europe have clearly identified serious declines in the populations and ranges of birds, and declines in populations of mammals, insects, soil organisms, and plants, associated with arable lands (Marshall 2001, 2002, Marshall *et al.* 2003). As a result, the current European Union (EU) policy is to encourage farmland biodiversity through less intensive farming, which is to be achieved by: (a) Reducing the area cultivated; and (b) Less intensive management. Weeds are increasingly recognised as valuable *'indicators of biodiversity'*, because if they are present, they would provide food and shelter for a wide variety of animal species, increasing the abundance of organisms inhabiting agricultural landscapes. Given the imperatives of *sustainability*, agriculture in some countries are changing, accepting certain levels of weeds adjacent to field crops, often along boundaries, or as wind-breaks (Marshall 2001). Weedy strips are either planted, or allowed to flourish, encouraging a greater abundance of farmland insects and birds. Weeds can draw pests away from crops. Others can provide habitat and floral resources for natural enemies that control pests, for pollinator species that provide crop pollination (Altieri 1988, 1995, 1999, Marshall 2001, 2002, Marshall *et al.* 2003).

A principle in integrated pest management (IPM) is to broadly increase the biodiversity in agroecosystems, so that there will be increased interactions between organisms (*i.e.* herbivores, predators, detrivores, and decomposers). The premise is increased interactions would lead to efficient nutrient transformations, and energy recycling through ecosystems, and self-regulation of populations. The role of colonising species in such key roles needs to be better understood not just within the agroecosystems, but also in farming or non-farming landscapes, so that they can be effectively integrated into sustainable agriculture and healthy environments.

In both agricultural and non-agricultural landscapes, weed cover reduces soil erosion; conserves soil moisture; reduces the loss of nutrients from soil, as well as add nutrients and organic matter into soils of poor quality. Moreover, there is increasing evidence of positive impacts of weeds on soil structure, and the functioning of beneficial soil organisms, including soil microbes, involved in nutrient cycling. Fast-growing, colonising plants are crucial as 'living mulches' and cover crops for the conservation of soil, water and organic matter (Altieri 1995). Many sterile annual grasses (*Lolium* spp., *Poa* spp., *Echinochloa* spp.) are deliberately sown in western countries, as cover-crops, to protect bare soil on road verges, and rehabilitate 'disturbed' areas. As pioneers of secondary succession, these weeds grow fast and proliferate on soils with low fertility, and many decompose readily, adding organic matter and nutrients to soil. Some examples are fast growing legume vines, such as *Pueraria* spp., *Stylosanthes* spp.,*Calapogonium mucunoides* and *Macroptilium artropurpureum*. These colonisers are particularly important as ground cover-crops in tropical plantations and orchards. In other situations, they serve as forage for animals and are also used for pasture improvement. Sometimes, their rampant growth may require management, so as to derive benefits, and not add to problems. However, the potential for using such species with colonising attributes in sustainable agriculture cannot be disputed.

The search for self-sustaining, low-input, diversified, and energy-efficient agricultural systems is now a major worldwide concern. A key strategy in sustainable agriculture is to restore both the structural heterogeneity at the different spatial scales of field, farm, and landscape; and the functional biodiversity of the landscapes (Altieri 1995, 1999). This can be achieved in time through age-old practices like crop rotations and sequences, and in space in the form of cover crops, inter-cropping, agroforestry, and crop/livestock mixtures. Plants with colonising abilities need to be recognized as an integral part of such conservation farming approaches. Weedy species add much to biotic interactions by way of their highly developed chemical defenses, and they perform a variety of ecosystem services. Creation of appropriate biologically diverse cropping and non-cropping landscapes is likely to result in: (a) Increased pest regulation through restoration of natural control of insect pests, nematodes and pathogenic fungi, bacteria and viruses; and (b) Optimal nutrient recycling, by activating soil biota. All of these factors should lead to more sustainable farms and yields, better energy conservation, and less dependence on external inputs. However, the challenge is the extensive adoption of such approaches, and success will depend on the demonstration of the synergies of biodiversity conservation and the economic profitability of farming.

Weeds as repositories of valuable genes for crops: Genetic diversity within populations is the basis of evolution; biodiversity in any given area encompasses the genetic diversity of organisms. As apparent in many examples of weeds and their crop relatives (see Harlan 1965, 1975), the gene pool and genetic diversity of weeds appears crucial in the future evolution of crops. This, I suggest, is another crucial reason for accepting the idea of 'living with weeds'. Weed populations, exhibiting the widest diversity of heritable traits, would be far better equipped to cope with and survive any future environmental changes. Crops, with 'weedy-relatives' would surely benefit from the exchange of genes. The best examples of plant families and genera that demonstrate the closeness of crops and wild species come from the Poaceae (grasses) with all of our major cereals having evolved from wild grass relatives. Other families, such as Solanaceae (nightshades family), Brassicaceae (mustard family), and Cucurbitaceae (gourd gamily) also have numerous examples of wilder, weedy relatives, which are also edible, and domesticated plants that have been cultivated over millennia.

Other beneficial uses and impacts of weeds: Beyond biodiversity values, agro-ecological values and being part of wild nature, the colonising power of plants has been harnessed extensively by societies for a variety of uses, over millennia. The beneficial uses include exploitation as food, medicines, raw materials for industry, animal fodder, and for improvement of water resources and landscape health. There is much to be gained by re-iterating these values, as discussed below, to demonstrate that 'living with weeds' is not incongruous with sustainable agriculture, healthy environments and lifestyles, which are attuned with nature.

Edible weeds: Many weeds are edible, serving as traditional food every day for people all over the world, as discussed in many publications (Holm *et al.* 1977, Duke 1992, Lee *et al.* 2007, Abeysekera and Herath 2007, Bakar 2007, Maneechote 2007, Morita 2007, Varshney and Sushilkumar 2009). More importantly, some are true culinary delights in Asian cooking. Amongthe three topexamples of edible weeds are: *Alternanthera sessilis* (L.) R. Br. (Mukunu-wenna); *Centella asiatica* (L.) Urb. (Asian Pennywort), and *Ipomoea aquatica* Forssk. (Kang Kung) (Chandrasena 2007). Leaves and young shoots are the most commonly used parts of the weeds. In the Asian-Pacific region, more than 150 weed species are considered edible (Kim *et al.* 2007). These include various *Amaranthus* spp., *Taraxacum officinale* Webb. (Dandelion), *Rorippa palustris* (L.) Besser (Water Cress), and *Portulaca oleracea* L. (Purslane).

Medicinal weeds: Weed species form a substantially higher proportion of source plants in pharmacopoeias than would be expected from their proportion in the general flora (Stepp 2004, Stepp and Moerman 2001, Voeks 2004). The possible reasons are related to the life cycle of most (annual) weeds being ephemeral, successional, or *r*-selected species. The opportunistic, short-lived species appear to rely heavily on qualitative toxic chemical defensesto deter herbivores, rather than quantitative compounds (Coley *et al.* 1985). These are secondary metabolites, which accumulate on leaves, shoots, flowers and fruits. They are glycosides, alkaloids, and terpenoids, which are all low molecular weight, often toxic at small doses, and highly biologically active. As a result, a large variety of weeds are used in traditional medicine and pharmaceutical industry as sources of therapeutic compounds. Many have healing effects, which include diuretic, choleretic, anti-inflammatory, anti-oxidative, anti-carcinogenic, analgesic, anti-hyperglycemic, anti-coagulatory and pre-biotic effects, and are used in the treatment of a wide variety of diseases. Among the best examples of weeds commercially important in western medicine are: *Digitalis purpurea* L. (Foxglove) from which digitalin, a group of cardiac-active glycosides is extracted;and *Catharanthus roseus* (L.) G.Don (Madagascar Periwinkle) from which an anti-cancer alkaloid - vincistrine, is extracted. The lists compiled by Bakar (2007), Abeysekera and Herath (2007), Maneechote (2007) and others, demonstratethe medicinal values of a large number of weed species, commonly usedin the Asian-Pacific region in traditional medicine, including Ayurveda and Chinese medicine.

Weeds as fodder for animals: In terms of quantities used, perhaps this category is important, although unremarkable. Many fast-growing species, annuals and perennials, including the previously mentioned legumes and grasses, which produce abundant biomass, provide the fodder required for rearing of animals, such as cattle, goats, pigs, sheep and even horses, ducks and geese. The aquatic weed, *Eichhornia crassipes* (Mart.) Solms (Water hyacinth) is a good example of a strong coloniser, which provides nutritious fodder (Kim *et al.* 2007, and references therein). There is also evidence that some species, deliberately introduced from one region to another as fodder crops, have subsequently become major invaders, requiring costly management.Two examples are *Pennisetum polystachyon* (L.) Schult. (Mission Grass); and *Andropogon gayanus* Kunth (Gamba grass), both introduced as fodder in Australia during 1940s and are currently spreading fast in Northern Australia.

Weedy residues as compost and mulches: The biomass of almost any weed can be composted, as most breakdown quickly; these may not serve as good mulches. On the other hand,biomass of some weeds, which breakdown slower, can be useful mulches. The large sized grasses, *Panicum maximum* Jacq. (Guinea grass), *Imperata cylindrica* (L.) Beauv. (cogon grass); *Urochloa mutica* (Forssk.) T.Q. Nguyen (para grass); and some of the fast-growing legumes, mentioned previously, are good examples. There is also significant interest in converting large amounts of weed biomass into valuable, nutrient-concentrated, odour free compost using worms (vermi composting). Many studies have demonstrated the benefits of harvesting even strong weeds, such as water hyacinth (Gupta *et al.* 2007, Gunnarsson and Peterson 2007) and *Parthenium hysterophorus* L. (Yadav and Garg 2010, Varshney and Sushilkumar 2009 and references therein) for composting, mulching and fodder.

Weeds as raw materials for thatching, weaving and other products: A large variety of weeds (dried and/ or flattened) provide traditional material forroofing and thatching of for rural dwellings, and also as raw materials that can be woven into household products, such as baskets and mats (Kim *et al.* 2007). Sedges: *Eleocharis sphacelata* R.Br., *Eleocharis dulcis* (Burm.f.) Trin ex Hensch., *Schoenoplectus* spp., *Cyperus papyrus* L., as well as *Typha* spp. and grasses, such as *Phragmites australis* (common reed) (Kiviat and Hamilton 2001) are the best examples of this category. The dried stalks of Water hyacinth are also popular for decorative weaving, for a variety of products with global appeal, including furniture (Kim *et al.* 2007 and references therein).

Weeds as raw materials for paper-making and other industrial products: A large variety of colonising species, particularly grasses, are suitable for extraction of high quality lingo-cellulose fibre and other materials. Examples are: *Spartina alternifolia* Loisel. (Cord Grass), *Erianthusarun dinaceus* (Retz.) Jeswiet (wild sugarcane), *Saccharum arundinaceum* Retz. (Hardy Sugarcane), *Saccharum spontaneum* L. (kans grass), *Phragmites australis* Steud. (common reed), and *Miscanthus sacchariflorus* (Maxim.) Hack. (amur silver grass). In addition, the stems of *Chromolaena odorata* (L.) King and H.E. Robbins. (siam weed) and *Ageratum aadenophora* (Spreng.) King and H.E. Robbins. (crofton weed), which contain large amounts of cellulose, are also used for fibre board manufacture in China (Kim *et al.* 2007). The large biomass produced by water hyacinth is also popular as raw material for paper and pulp industry in several countries in the Asia-Pacific region.

Aquatic weeds: Many aquatic weeds provide natural ecosystem services, such as water purification and aquatic habitat improvement in wetlands and streams, through nutrient accumulations and transformations. The same functions can be exploited for biological removal of pollutants from water, including nutrients and other contaminants. The use of water hyacinth in wastewater treatment systems has been well-established for over 40 years in several countries, including USA, China, India, and others (Vietmeyer 1975, Tiwari *et al*. 2007). Other examples of aquatic weeds that have been used in pollution removal include: *Typha* spp. (Taylor and Crowder 1983), *Phragmites australis, Bolboschoenus fluviatilis* (Torr.) Soják; *Schoenoplectus* spp., *Cyperus papyrus* L. (papyrus), and several other species of the sedge family (Cyperaceae).

Use of colonising species in phytoremediation of damaged ecosystems: Soils frequently receive a wide range of contaminants from industrial activities, sewage sludge disposal, metal processing, and energy production, and in many cases, remediation is both expensive and intrusive to ecosystems. Phytoremediation is the use of plants and plant processes to remove, degrade, or render harmless hazardous materials, such as nonvolatile hydrocarbons and immobile inorganic matter, including heavy metals, present in the soil or groundwater. The attributes of 'pioneering' species - fast growth and biomass production, wide tolerance of environmental stresses, and capacity to maintain high population densities, make them particularly attractive for use in phytoremediation of contaminated sites, mine-site rehabilitation and stabilisation of roadsides. For instance, Wang and Liu (2002) demonstrated the strong tendency for uptake and hyper accumulation of Cu, Zn, and Chromium (Cr) in heavy metal polluted environments by Water hyacinth, *Amaranthus retroflexus* L. (red root Amaranth), and *Silene vulgaris* (Moench) Garcke (maiden's tears). In a similar study, Wei and Zhou (2004) showed that Dandelion, Nightshade (*Solanum nigrum* L.) and *Conyza canadensis* (L.) Cronq. (Canadian horseweed) strongly tolerated single Cd or Cd-Pb-Cu-Zn combined pollution and exhibited characteristics of hyper-accumulators. Wu *et al.* (2005) also demonstrated the possibilities of using mixtures of weed species to eliminate Pb and other heavy metals from contaminated soils. Numerous other examples are discussed in Kim *et al*. (2007) and references therein.

Weeds as raw material for bio-fuels: Given the large biomass that colonising species can produce, there are significant environmental benefits in utilizing this biomass directly for burning as fuel (primary biofuels), or used as raw material for fermenting to produce bio-diesel, ethanol and methane (secondary biofuels). The possibilities have been demonstrated in China, India, USA and other countries. Examples are *Jatropha curcas* L., *Thlapsi arvense* L., *Arundo donax* L. (giant reed) and others. There is also considerable interest in using the biomass of shrub weeds and medium-sized trees, which have colonised large areas as biofuels. Water hyacinth continues to be of considerable interest, for the combined uses of both phytoremediation of polluted water, and fermentation to produce biogas (Singhal and Rai 2003).

Miscellaneous uses of weeds: A wide variety of colonising plants are used in landscaping; stabilization of slopes and banks and roadsides. Others are important as ornamental plants, handicrafts, and for building human shelters (bricks and roof thatching), as well as for green roofs (Lee *et al*. 2007, and references therein). In addition, several weeds are important as sources of natural, plant-based dyes, and many yield strong allelochemicals, which may be used as biological insecticides (Minggen 2007, Sondhia and Varshney 2009). Some provide useful ingredients of cosmetic products, such as soaps, perfumes, creams and hair oils.

The way forward

Weed Science, as a discipline, has undergone several changes in the past 50 years or so. This essay supports a conceptual change towards 'living with weeds' as another change that might have to be made in the efforts to preserve our environment for the benefit of both the present and future human societies. This view has been canvassed before (Altieri 1988, 1995, Jordan and Vatovec 2004, Kim *et al*. 2007), and needs to be part of a wider discourse within the field of weed science.

Understanding human culpability for promoting weed abundance: Firstly, let us be clear about man's culpability with regard to weeds. It would not be too imprecise to say human 'create' weeds: we certainly create lists and label them as 'unwanted' from our perspectives; we lay the land bare of plant cover with excessive clearing, disturbing the environment, 'creating' niches that colonising species take up; we arrest ecologically succession by turning vast swathes of land into cropping fields, although more than 50% of our species go to bed hungry each night; and we deliberately introduce organisms from one location to another for profit! Need any more be said about human culpability?

It is important for weed scientists to recognise that the aim of mechanized, large-scale, modern agriculture, as opposed to subsistence agriculture, is to export nutrients and energy from an area. Therefore, there is a natural antithesis between agriculture and conservation of biodiversity - we can never completely reconcile the two, but can we minimise the conflict? With mechanized agriculture and cropping, practiced on the scale that we are witnessing, combined with deforestation and land clearing, *humans present the greatest threat to nature, wilderness and biodiversity*, of which both people and colonising species are constituent parts. This message needs to be part of the discourse between weed scientists, ecologists, and the public, so that we may aspire to achieve a better balance between human greed, genuine development aspirations of nations, and global biodiversity. There are strong moral, aesthetic, social and economic reasons for protecting biodiversity. As Marshall (2001) pointed out: "*a culture, which encourages respect for nature and wildlife is preferable to one that does not*".

It has been argued strongly in numerous publications that colonising species threaten biodiversity. However, it should be evident that they also provide benefits that are not yet fully understood (Marshall 2002, Marshall *et al*. 2003). A key message from Agroecology (Altieri 1988, 1995, 1999) is that, if correctly assembled in time and space, biological diversity, including weeds, is capable of repairing landscapes, sponsoring soil fertility, protecting crops, and increasing productivity. Moreover, the evidence available supports the view that given the opportunity, colonising species will be at the forefront of remediation of damaged ecosystems and rehabilitation of land that had once supported large forests.

Will there be a change in attitude?: The hardened attitude towards weeds in developed countries is largely related to the profits that can be made by individual landholders through farming. Many farmers resist change because of personal learning experiences and property-related economic factors. Shifting the emphasis of weeds from totally undesirable to useful resources requires strong campaigning. This attitude change may come with time, but this can be hastened by economic incentives to manage biodiversity within farmlands, and landscapes, as has been done in EU countries. It can also be hastened by august Societies, such as the Indian Society of Weed Science, or the Asian-Pacific Weed Science Society making a conceptual shift and taking a stand decisively to encourage their constituency to consider accepting the reality of 'living with weeds'.

Many of the developed and affluent nations have been built on technology, which resulted from the industrial revolution of the past two centuries. Accumulation of material wealth is deeply entrenched in such societies. They place little emphasis on the collective 'traditional wisdom' upon which sustainable societies are usually based. A good example is Australia, which was colonized by Europeans only 230 years ago. From the first fleet, which arrived in 1788, the new colonisers introduced many European herbs and wild plants into Australia, and many are now considered invasive species. The European colonisers and subsequent waves of white immigrants then developed an attitude of resisting others from entering the country, a kind of xenophobia. Many pioneer farmers, with deeply ingrained perceptions, often mistrust alternatives. As a result, except for a few 'enlightened' people, farmers generally malign weeds, because weeds are erroneously perceived as the most significant factor, which reduces the profitability of human endeavours. The lack of discussion on beneficial effects of weeds in agricultural landscapes and utilization possibilities contributes to the prevailing view that most weeds are of no value. There is also a perception in developed countries, where every human action needs to be justified based on cost, that utilization of weeds, such as harvested aquatic weeds, is costly and, therefore, not economically worthwhile. Nevertheless, the question needs to be asked: *Should human endeavour always be measured in monetary terms?* Investing in utilization of weeds is justified not just because it is common sense and a good management practice, but also because provides a positive, cultural message of sustainable living for human societies.

Creating a 'weed-literate' society: Making the case for utilization of weeds is not difficult, but creating a more 'weed-literate' society, overcoming the bias against weeds, is more difficult. The compilation of existing knowledge from different cultures should assist this task, and, in this sense, there is much to learn from economic botany and ethnobotany 'bodies of knowledge'. One way of promoting weed-literacy even among weed scientists is to invest in investigating the ecological role of weeds in agro-ecosystems and the environment in any project, bearing in mind that they have both negative and positive impacts.

A set of mandatory question in any new weed science grant application should be:

"*Have you considered the values of the weeds you are targeting for control? Explain*"

"*Have you considered the likely environmental impact (benefit or otherwise) of your proposed weed management actions? Explain*"

"*What are the risks and benefits of your proposed weed management actions? explain*"

The answers should reflect thoughtful, ecological considerations bythe proponents on theintrinsic values of the species and populations they are attempting to manage, as well as on the unintended impacts or non-target effects (*e.g.* herbicide or pesticide spray drifts, or soil disturbances) on multiple interactions of species through food webs, *etc*. The proponents should also clarify why some levels of pioneering species could not be tolerated. August weed societies should also lead by creating the theme 'utilization of weeds as bio-resources' or 'beneficial impacts and uses of weeds' as part of their future mandate, encouragingtheir members, associated innovators, entrepreneurs and farmers to explore more broadly theopportunities presented by weeds.

Weeds will always present a stimulating challenge

Without doubt, weeds have contributed enormously to the development of human innovations. From the earliest developments of agriculture to the modern agricultural revolutions, they have challenged our way of living. This has led to inventions from the earliest digging sticks to sophisticated machinery, and to the development of agronomy, irrigation, surveying, and eventually the agrochemical industry. The development of genetically modified crops by multi-national biotechnology companies during the last two decades also falls into this category. Weed scientists have been involved in the development of glyphosate-resistant cotton and soybean by Monsanto, glufosinate-resistant cotton and soybean by Bayer; these are already in the market. There are other products, which are in the pipeline (*i.e.* dicamba-resistant crops by Monsanto; 2,4-D resistant corn and soybean by Dow). The advances in biotechnology that have created modified organisms that can be grown and harvested on a large scale to feed growing populations must rate high in the continuum of human innovation. The stimulus that profits can be made from such innovations came from the challenge offered by weeds.

Colonising species will always be the ultimate survivors in the conflict with man. Rather than a zero tolerance towards particular taxa, it would seem reasonable to propose 'ecological management' of problematic populations, with an eye on their potential benefits, on a 'case-by-case' basis. This requires synecological models that capture all of the key factors that govern the dynamics of populations in a given location. synecology is the branch of ecology that deals with the structure and development of entire ecological communities, their interactions with the chemical and physical environment, and the complex interrelationships between all plants and animals within them. These differ from autecological, 'species-led' approaches that are more concerned with the reactions of single species. The agroecology approaches (Altieri 1988, 1995, 1999) are invaluable ecological risk management models in the sense that the practices promoted have long-proven benefits in ecosystems. They also encourage positive thinking, linking people with nature, and stimulate people to closely integrate with all components of biological diversity, including 'colonising species.

An ethno-biological perspective -link between plants and humans: As discussed in this essay, humans have for long used colonising species as foods, medicinal plants, animal feeds, housing materials, and raw materials for handicrafts, ornaments, etc. Before these beneficial uses are forgotten, priority should be given to investing and recording of the ways in which traditional cultures have used weeds. To achieve this objective, more cooperative research funding is needed to consolidate our knowledge of their ecological roles, and on utilization of weeds as resources.

Discussing the relative variety and intensity of uses of common reed, *Phragmites australis* by human groups, Kiviat and Hamilton (2001) concluded that the utility value of a plant to humans is related to: (1) abundance and distribution of the plant; (2) length of time the plant and a human group have been in contact; (3) invention or transmission of traditional ecological knowledge of the plant; (4) ease of managing, acquiring, and processing the plant; (5) its physical and chemical qualities (*e.g.* pharmaceutical or toxicological properties, fiber characteristics, nutritional values); and (6) availability and quality of alternate species. Discussion of such ethno-biological perspectives is essential to building better relationships of plants by humans, particularly where the conflicts between the two are more profound.

The importance of traditional cultures, their wisdom and sustainable interactions with plants and animals are routine subject matter in anthropology, and social science. Interactions between the humanities and a discipline like weed science are not strong; and hence, both sides may gain from a closer exchange of views. Journals dedicated to ethnobotany, and economic botany, often carry articles relating to human uses of colonising plants. Increased appreciation of plant resources can be achieved by studying these ethno-biological appraisals. Improved understanding of plants of value to humanity will also assist 'weed risk assessments' when people are asked to decide whether or not to list particularly resourceful taxa as 'invasive'. *Applying 'a guilty until proven innocent' approach to taxa with colonising abilities, as currently practiced, belies common sense, is disrespectful to nature, and will not be tenable in the long-term*.

In contrast to the negative attitude towards weeds prevalent in highly industrialised countries, traditional societies all over the world have used plants and weeds wisely and have 'co-existed' with them. Are there not lessons from previous generations and indigenous cultures that plant resources should be respected rather than maligned? In the attempt to maximise agricultural production, anything other than the crop plant whose yield brings profit is regarded as undesirable. This flawed view is not sustainable under the commonly accepted principles of ecologically sustainable development, to which, paradoxically,even affluent nations have beencommitted.

Perhaps the 'paradigm shift' required in the field of weed science in the 21st Century is to recognise the potential of colonising plants as 'bio-resources' and to find ways to integrate them into our lifestyle rather than over dramatising the negative aspects of plants regarded as weeds, the weed science community needs to bring about a balance and to emphasize the utilitarian value of colonising plants, with their tenacity and vitality, and to reconsider the advantages of putting these into practical use. Utilization, instead of attempts to eradicate, will lead to more effective management of weeds in most situations, where undesirable effects of a large population are untenable.

By 2025 AD the global population is expected to reach 8.5 billion, of which 83% will be living in developing countries. As a consequence, two of the greatest challenges facing mankind are to increase food production in landscapes where productivity has declined, and to achieve this while not degrading the environment. The real challenge is to increase food and fiber production in a sustainable manner, while maintaining the biodiversity, component ecosystems and landscapes for future generations. Therefore, particularly in the less affluent countries, a negative attitude towards any group of plants, including those that sometimes interfere with human affairs is unwarranted, and making such a mistake is not affordable. The examples discussed show why this is so.

In order to alleviate socio-economic hardships, and to conserve biological and cultural diversities, it is necessary to build stronger links between people and biological resources. The level of success of this depends on accommodating local knowledge, aspirations and priorities of communities, including indigenous people and farmers, with some trade-offs between development and conservation. The ultimate goal must be for the present generation to be 'custodians of landscapes', instead of being exploiters, and this task requires a proper appreciation of plant resources, including weeds.

Conclusions

As Harlan (1992) observed: "*...Weeds have been constant and intimate companions of man throughout his history and could tell us a lot more about man, where he has been and what he has done, if only we knew more about them...*". The colonising species, disparaged as 'damned weeds' were here on earth before us; and they will be here after us. They are simply an essential part of the earth's rich biological diversity, just as much as we humans are, wherever or whenever a natural disturbance occurs, or when humans disturb a habitat, colonising plants will be among the first to make use of the opportunity of available space and resources. They will always shadow humans.

In the contest with other plants, those with colonising attributes will always win. This ecological emphasis has been downplayed in a large number of publications, because the focus during the past 100 years or so has been so much on weed control, due to their negative impacts on agricultural production. *Weeds are not the culprits*; *they are just a symptom of the real cause*, which is ecologically destructive land-use practices by humans, including land clearing, monoculture cropping, overgrazing, and introductions of species for short-term profit. If weeds are to be better managed, land management practices must improve, and more broadly, all natural resources must be better managed. In natural systems, or man-made ecosystems, colonising plants serve valuable ecological functions, and these need wider and deeper recognition. Weed Scientists should focus their attention on exemplifying the complex biological interrelationshipscolonising plants have with other biota and the environment, such as providing resources for wildlife, slowing erosion, building soil, and generally enriching biological diversity through genetic exchanges. The future of humankind will surely depend on how well we manage our relationships with nature, and particularly, plants - our primary producers of food. It is a responsibility to manage weeds effectively, and efficiently, whilst appreciating their intrinsic worth and potential as bio-resources.

Many species of plants are currently considered as invasives that may not have much use for humanity; this attitude must change. Much of the time, publicity in developed countries, driven by media interests, gives exaggerated accounts of negative attributes of weeds. This has led to a blitz against weeds, overemphasizing the conflict man has with some species. The fact that so many colonising species grow and coexist in the same environments with native species, as well as crops, tends to be overlooked. Because of their adaptability, weeds will always compete with other plants, like crop plants, or slow-growing perennials. Whilst the economic consequences of this interference with crops are reduced yields and quality of crop produce, whether colonising species will always cause negative ecological consequences is uncertain. Some generalities, such as weeds reduce biodiversity and the regeneration of native species, are unproven across different landscapes. For instance, a study in Canada found that introduced species were no more likely to dominate wetland ecosystems than native species; and the proportion of dominant exotic species that had a significant negative impact on wetland biodiversity was the same as the proportion of native species with a significant negative effect (Houlahan and Findlay 2004).

The widely held belief that weedy, colonising species will always threaten ecosystems overlook the fact that weeds also are part of the same biological diversityin any geographical region, area, or cropping field, enriching and stimulating biotic interactions all the time. Given that most weed invasions can never be reversed, they can only be managed by reducing their populations to a level that might be acceptable. The challenge is to deliberately and effectively managethe negative impacts of weeds in agroecosystemsor non-agricultural landscapes with the tools humans have invented, whilst reaping the ecological benefits of having some levels of weed populations.

In a strategic approach to managing weeds, the utility of these plant resources needs to be highlighted, within the field of weed science, and to do this a conceptual shift towards 'living with weeds' appears necessary. People should be encouraged to explore different ways of using weeds. The summary condemnation of plant taxa,just because someone may not like to have them in particular situations is not a sensible way to approach complex biological interactions, exacerbated by human disturbances and greed. A much broader appreciation of the useful attributes of plants and their applications in improving the human condition should be a high priority for the future generations of weed scientists. As demonstrated in this essay, the features that confer superior colonising ability and competitiveness to these plants can be very useful, not just in repairing damaged ecosystems, but also in providing future food, fibre, medicinesand other necessitiesfor all animals, including humans.

As human enterprises expand, populations increase and the pursuit of material wealth continues, the mode of existence of some colonising plant taxa will increasingly clash with our existence. It is through no intrinsic fault of these plants. The same attributes that make a plant 'invasive' will be sought after under a different set of circumstances. Acknowledging both sides of the argument, the way forward is to broaden our understanding of their crucial role as integral parts of biological communities, learn from their resilience, tenacity, and capacity to adapt to environmental disturbances. Perhaps this would help modify our attitudes, allowing us to avoid creating conflicts with plant taxa, and getting into battles that we cannot win.

As in many other fields, it is necessary from time to time, to realign the focus of a scientific discipline, and weed science may have reached that stage again. As pointed out by Harada (2001), whilst there is a vast amount of weed science literature dealing with weed management, what the future requires is a 'body of knowledge' of beneficial effects of weeds and their utilization potential to be established, so that present and future generations could benefit from that knowledge. My plea is for weed scientists to achieve this in the next decade or so. To end this essay, I would pose the following essential questionto all weed scientists and weed managers; '*Would you live in a world free of weeds*? or, would you cherish the knowledge that a vast multitude of plants, including weeds, and animals inhabit our planet, and our complex interactions with them enrich our lives? *In an environmental ethic that is all too familiar to the sub-continent - that all life is sacred - weeds are no more villainous than man himself*!

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