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Weed management in conservation agriculture in India

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ABSTRACT

Conservation agriculture (CA) involves minimum soil disturbance, permanent soil cover through crop residues or cover crops, and crop rotations for achieving higher productivity. Even though the adoption of CA in India is still in an early stage, it has been successfully used in the irrigated rice-wheat cropping systems of the Indo Gangetic Plains (IGP) and recently been demonstrated in parts of central India. Increased weed problems during the 'transition period' tends to be the most common hurdle in adoption of CA by farmers. Research has shown that cover crops could play an important role in weed management in CA systems; however, their level of adoption at present is fairly low. Changes in patterns of tillage, planting systems, and other management strategies can alter the soil environment and lead to a major change in weed flora. Herbicide use has been an extremely important component of weed management in CA systems but greater effort is needed to integrate non-chemical weed control tactics with herbicides. Farmer-participatory model of research has proved highly effective in developing CA in rice-wheat system in the IGP. Efforts are required to increase the rate of adoption of direct seeded rice and zero-till wheat throughout the IGP. At present, residue retention on farmer fields tends to be low. Greater awareness of the benefits of residue retention for improved soil health is worthy of an extension campaign in particular and in India in general. Research effort needs to be enhanced to develop CA and promote its adoption in non-rice-wheat cropping systems in India.

Key words: Adoption, Challenges, Conservation agriculture, Future, Opportunities, Socio-economic

Indian agriculture has made significant progress in terms of productivity increase in the last five decades. However, many challenges remain including stagnating net sown area, reduction in per capita land availability, climate change effects and deterioration of land quality. Therefore, a paradigm shift in farming practices is needed to ensure future productivity gains while sustaining the natural resources. Conservation agriculture (CA) has emerged as an effective strategy to enhance sustainable agriculture worldwide. CA has the potential to address the problems of natural resource degradation and environmental pollution, while enhancing system productivity. It is a resource-saving agricultural production system that aims to achieve production intensification and high yields while enhancing the natural resource base through compliance with good production practices of plant nutrition and pest management (Abrol and Sangar 2006).

Cropping system, climate and soils in India

More than half of India's total land mass of 328.7 million hectare (mha) is used for agriculture (Table 1). The net cultivated area increased significantly by about 18% from 119 mha in 1950-51 to 140 M ha in 1970-71 but since then it has been fairly stable, whereas the cropping intensity has increased from 111% to 139%. Irrigated agriculture accounts for 35% of the cropped area and rainfed agriculture is practiced on 65% of the cropped area.

Rice-wheat system is extensive in the sub-tropical areas of the Indo-Gangetic plains (IGP) of India while maize-wheat system is prevalent in tropical, sub-tropical and warm temperate areas. There are mainly three cropping seasons in India: summer (June/July to Sept./Oct.), winter (Oct./Nov. to Feb./Mar.), and spring (Mar./Apr. to May/June). Rice is the main crop in summer while a wide range of crops, including '*Boro*' rice in eastern India, wheat, maize, winter pulses (chickpea, lentil, field

Table 1. Land use statistics in India

Land use	Area (m ha)	Per cent of total land use
Forest area	70.0	22.9
Non-agricultural uses	26.3	8.6
Permanent pastures	10.3	3.4
Fallow land	25.4	8.3
Net sown Area	140.8	46.0
Others	55.9	17.0
Total geographical area	328.7	-
Area sown more than once	54.4	-

Source: www.agricoop.nic.in

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peas), potatoes, and mustard are grown in the winter season. In the spring season, short-duration crops such as maize, pulses (green gram, cowpea), and rice are grown.

In India, the IGP are spread over Punjab, Haryana, Uttar Pradesh, Bihar, and West Bengal states (Woodhead *et al*. 1994, Ali and Pande 1999). The climate of the IGP is continental monsoon type with hot summer season with daytime temperatures reaching as high as 45°C in June or July, and cool, dry winter. Temperature extremes are recorded in the west but the weather tends to be milder in the east. Most of the rainfall (~85%) is received during the summer (June-September). Rainfall is very low in the western part (Punjab, Haryana and Uttar Pradesh) (400–600 mm) and increases towards the east (Bihar and West Bengal), which receives heavy rain (up to 1800 mm). Soils are mainly alluvial in nature. Rice-wheat is the dominant cropping system of the IGP followed by rice-fallow-fallow and maize-wheat; sugarcane, cotton, and potato are also major commercial crops (Table 2). The food legumes are generally grown on marginal land in rainfed areas (Ali *et al*. 2000).

Table 2. Areas occupied by crops in different seasons in IGP in India

Summer season	Per cent of net sown area	Winter season	Per cent of net sown area
Rice	65.5	Wheat	67.2
Maize	11.7	Mustard	1.3
Cotton	1.9	Pulse	4.1
Pearl millet	4.9	Potato	0.6
Perennials sugarcane	5.9	Potato-wheat	1.8
Other crops	1.7	Other crops	6.1
Fallow	7.4	Fallow	15.4

Source: Panigrahy *et al*. (2010)

History of development and adoption of CA in India

According to current estimates, CA is being practiced in about 154.8 mha across the globe (FAO, 2014); the major CA practicing countries are USA (26.5 mha), Brazil (25.5 mha), Argentina (25.5 mha), Canada (13.5 mha) and Australia (17.0 mha). Worldwide, CA has spread mostly in the rain-fed agriculture, but India witnessed its success in irrigated rice-wheat cropping systems of the IGP. However, CA systems have not been promoted or adopted in other major agro-ecoregions of India such as rainfed semi-arid tropics and the arid regions of the mountain agro-ecosystems (Bhan and Behera 2014). In India, CA systems have been advocated since 1970s but it is only in the last 2 decades that the area under CA has increased rapidly. Rapid adoption of CA in India appears to be related to the local development of efficient farm machinery and availability of effective herbicides. Over the past few years, zero tillage and CA has been adopted on more than 1.5 mha of agricultural land in India (Jat *et al*. 2012, www.fao.org/ag/ca/6c.html). Zero-till (ZT) wheat in the rice-wheat (RW) system of the IGP is the dominant CA based technology adopted so far by the Indian farmers. ZT wheat has been widely adopted in the north western IGP in the RW systems, and recently its adoption has also started to increase in the eastern IGP (Malik *et al*. 2014).

In Punjab and Haryana, dry direct-seeding rice in unpuddled fields (DSR) has been introduced recently, on the basis of the findings of a research project funded by the Australian Centre for International Agricultural Research (ACIAR). In Punjab alone, the area under DSR increased from 4200 ha in 2012 to 22,000 ha in 2013 and further to 115,000 ha in 2014; the area under DSR was <1000 ha in 2010, the first year of its introduction in this state (www.tribuneindia.com). Such rapid adoption of DSR clearly highlights the ready acceptance of CA technologies among the farmers in the region. Other CA practices including furrow irrigated raised-bed planting, laser assisted land levelling, unpuddled mechanical transplanting of rice and residue management practices are also being adopted by the farmers of the north-western region (IARI, 2012). The adoption of CA also offers avenues for much needed diversification of the rice-wheat system through relay cropping of sugarcane, pulses, and vegetables as intercrop with wheat and maize. For example, many farmers are now practicing intercropping in raised-bed systems. In this system, wheat is planted on the raised beds and mint or sugarcane in the furrows. Inter-cropping systems such as maize+ potato/onion/redbeets or sugarcane+ chickpea/Indian-mustard are also becoming popular with farmers in western Uttar Pradesh (Gupta and Seth 2007). In India, CA is a new concept and its roots are only now beginning to find ground.

In recent years, the CA technologies have been successfully demonstrated at farmers' field in district Jablapur in Madhya Pradesh under the aegis of ICAR Directorate of Weed Research; the yield enhancement varied from 1.5 to 2 times than under conventional practices (Smart Indian Agriculture, 2015) . These results indicated that the black cotton soils of central India are among the best suited for CA, and it has been the fastest growing cultivation technology in this region. The adoption of CA has advanced sowing time of rice, maize, wheat, mustard crops by 10-15 days enabling the farmers to take third crop of green gram in the summer season which was not possible with conventional practices. Encouraged by the success of these demonstrations, the state agriculture department has started providing subsidy for purchase of CA machinery. The long-term study on different CA based systems, initiated under AICRP-weed management, has shown promising results in case of maize-sunflower in Tamilnadu, pearl millet-mustard in Gujarat, rice-chickpea-green gram in Karnataka pointing towards the possibilities of extending the benefits of CA to central and south India (DWR 2014, AICRPWM 2015)

Challenges associated with herbicide use in CA in IGP

Scarcity of farm labour and increases in their wages across India is being reflected in a greater adoption of pesticides. At present, the use of pesticides in India is quite low and estimated at 0.6 kg/ha as compared to global average of 3 kg/ha (www.ficci.com). Currently, in India, herbicides account for 16% of the total pesticide market, and rice and wheat crops consume the major share of herbicides (www.ficci.com). The shift from conventional to conservation agriculture can be particularly difficult with respect to weed control, particularly during the 'transition period', and increased use of herbicides may be necessary under such situations. With the adoption of no-till or zero-till, producers lose the benefit of weed control offered by tillage from seed burial as well as the option to incorporate soil applied pre-emergent herbicides. Moreover, soil applied herbicides that do not require incorporation can have reduced persistence and efficacy in the presence of plant residue that may intercept and bind the chemical before it reaches the soil surface (Potter *et al*. 2008). This reduced efficacy of pre-emergent herbicides has forced producers wishing to adopt conservation practices to become primarily dependent upon post-emergent herbicides, which reduces their weed control options. To further complicate the situation, adoption of CA can lead to major changes in weed population dynamics due to altered distribution of weed seed within the soil (Buhler 1997); perennial weed species also thrive in reduced-tillage systems and can be difficult to control with available post-emergent herbicides (Swanton *et al.* 1993). For example, after the adoption of DSR in Punjab, weed flora has shifted from typical aquatic rice weeds to aerobic grasses and perennial sedges, which are difficult to control with herbicides recommended in puddle transplanted rice (Bhullar *et al*, unpublished data).

New herbicides are often used in tank-mixes to achieve effective weed control. According to Singh *et al* (2015a), CA practices such as ZT can be an important component of integrated weed management in DSR, provided herbicide efficacy can be maintained by adjusting the rate and timing of herbicide application. Even though there is some evidence that weed control in CA becomes easier over the long-term due to more uniform germination and greater seed predation, there remain serious challenges to weed control in the short-term after the adoption of CA (Murphy *et al.* 2006, Swanton *et al.* 2008).

In India, herbicide use has increased in both CT and ZT systems because it provides cost-effective weed control and saves labor, which has become more scarce and expensive (Rao *et al*. 2007). Although herbicides play an important role in facilitating the adoption of ZT practices, over reliance on herbicides can rapidly lead to herbicide resistance in weeds (CAST 2012, Heap 2012). Additionally, public concerns about the potential adverse effect of herbicides on neighbouring water resources (Spalding *et al.* 2003, Guzzella *et al.* 2006) and human health (Pingali and Marquez 1996, EPA 2007) have increased.

Herbicide resistance is a major problem in wheat in India and could also become a problem in DSR. In wheat, sole dependence on post-applied herbicides for weed control has resulted in the evolution of multiple herbicide resistance in *Phalaris minor*, the single most important weed of wheat (Malik and Singh 1995, Bhullar and Walia 2004a, Chhokar and Sharma 2008, Bhullar *et al.* 2014). In rice, no cases of herbicide resistance have been confirmed yet in the IGP. Lack of herbicide resistance development in rice could be partly due to the integration of multiple tactics such as puddling, transplanting, and continuous flooding used in puddled transplanted rice. However, the adoption of direct seeding could increase reliance on herbicides to compensate for the loss of weed suppression from tillage, flooding, and transplanting. Many of the commonly used post-emergent herbicides for weed control in DSR in the IGP are either acetolactate synthase or acetyl-CoA carboxylase inhibitors (Kumar and Ladha 2011), which are prone to evolution of resistance (HRAC 2012). To expand the adoption of ZT in RW systems while minimizing the risks associated with herbicide use, it is important to develop alternative non-chemical weed management packages.

Management of emerging weed species in CA

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. The shift from conventional puddle transplanted (CT-TPR) to dry direct-seeding (DSR) in rice with reduced or ZT, typically results in changes in tillage, crop establishment method, irrigation practices, and weed management that influence weed diversity and abundance (Kumar *et al*. 2013). Under ZT-DSR, weed flora often shifts towards more difficult to control and competitive grasses and sedges (Kumar and Ladha 2011, Singh *et al*. 2015a). Based on experiences with ZT-DSR in India and other Asian countries, the shift from CT-TPR to ZT-DSR is expected to favour grass weed species including *Dactyloctenum aegyptium*, *Leptochloa chinensis*, *Eragrostis* sp., weedy rice (*Oryza sativa*), along with *Echinochloa crusgalli* and *E. colona*; sedges such as *Fimbristylis miliacea*, *Cyperus rotundus* and *Cyperus iria;* broadleaf weeds such as *Eclipta prostrata* and *Digera arvensis* also increase in DSR systems (Kumar and Ladha 2011, Singh *et al* 2015a, Singh *et al* 2015b). Most of these species are able to germinate over a wide range of temperatures but prefer moist and warm conditions, which makes them well adapted to rice fields. These species are well adapted to establish at or close to the soil surface, where weed seeds in ZT systems typically concentrate (Chauhan and Johnson 2009). The shift from CT to ZT in wheat has resulted in a shift in weed flora. Emergence of *Phalaris minor* is lower under ZT than CT in wheat (Malik *et al.* 2002, Chhokar *et al.* 2007, Franke *et al*. 2007, Gupta and Seth 2007) but higher for some of the broad-leaf weeds, such as *Rumex dentatus* (Chhokar *et al.* 2007).

Weed control in CA is a greater challenge than in conventional agriculture. The behaviour of weeds and their interaction with crops under CA tends to be complex and not fully understood. Weed species in which germination is stimulated by light are likely to be more problematic in CA, where weed seeds are concentrated close to soil surface. Weeds like *Ipomoea* spp. which germinate well in shade, under closed crop canopy, and twin around the crop plants (Bhullar *et al*. 2012) could also be a problem in residue based CA systems. In CA, the presence of residue on the soil surface may influence soil temperature and moisture, which may affect weed seed germination and emergence patterns over the growing season. Soil surface residues can interfere with the effectiveness 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. In the absence of tillage, perennial weeds may also become a more serious challenge in this system. In the past, attempts to implement CA have often caused a yield penalty because reduced tillage failed to control weed interference or crop establishment in CA systems was sub-optimal.

Opportunities for managing weeds in CA

As the density of some annual and perennial weeds can increase under CA, effective weed control techniques are required to manage weeds successfully (Moyer *et al*. 1994). Various approaches, including use of preventive measures, crop residue as mulches, intercropping, competitive crop cultivars, herbicide tolerant cultivars, and herbicides are needed to manage weeds in a CA system.

Preventive measures: Preventing invasive and alien weeds in fields is usually easier and less costly than controlling them after severe infestation, as it is difficult to control weeds once they are established. Some weed preventive measures include the use of clean crop seeds, the use of clean agricultural implements, and managing weeds on bunds and roads. The aim should be to minimize the area of weed infestation and decrease the dissemination of weed seeds from one area to another or from one crop to another. Hand-roguing weeds before seed-shed could be an important tactic in India, where farm size tends to be small. Such a practice would be obviously impractical on large farms in many western countries.

Laser land levelling: Laser land levelling provides uniform soil moisture in the entire field and allows uniform crop establishment and growth leading to a reduced weed infestation. Reduction in weed population in wheat was recorded under precisely levelled fields in comparison to traditional levelled fields (Jat *et al.* 2009).

Stale seedbed: Most of the weed seeds remain in the top soil layer in CA, a flush of weed seedlings appears within a week after irrigation or shower. These weed seedlings can be killed by the application of non-selective herbicides such as glyphosate, paraquat or glufosinate. Stale seedbed significantly reduced weed pressure in ZT-wheat (Mahajan *et al*. 1999). In an ongoing study on DSR in Punjab, stale seedbed reduced weed density by 39% (Manpreet Singh, unpublished data). The fallow period (45-60 d) between wheat harvest and the sowing of rice provides an excellent opportunity to implement stale seedbed for weed management before planting DSR. When stale seedbed practice is used, the crop emerges under weed-free conditions and it will have a competitive advantage over late-emerging weed seedlings. With the limited options available to manage weedy rice in ZT-DSR, the stale seedbed technique is recommended as part of an IWM strategy in many weedy rice-infested areas (Rao *et al.* 2007).

Sowing time, tillage and residue management: In CA, sowing time can be manipulated to favour the crop. In the north-western IGP, sowing wheat 2 weeks earlier than the conventional system has been shown to give the crop a head start over *P. minor*. (Singh *et al.* 1999). Similarly, earlier seeding of spring crops can improve their ability to compete with weeds. Franke *et al.* (2007) observed that the density of all three flushes of *P. minor* in wheat sown on the same date were lower in ZT compared with CT. Zero tillage when combined with residue retention on the surface and early sowing, results in the suppression of *P. minor* and other weeds of wheat. Improvements in planting technology like the shredder-spreader ('Turbo Happy seeder') has made it possible to sow wheat in heavy residue mulch of up to 8 to 10 t/ha without any adverse effects on crop establishment (Sharma *et al.* 2008, Kumar and Ladha 2011). Such heavy mulch has the potential to reduce the establishment of weeds in crops. For example, Singh *et al.* (2013) recorded 48% reduction in weed population in wheat sown with 'Turbo Happy seeder' as compared to conventional till sown wheat in Punjab. Improved weed control with application of rice residues as straw mulch, at sowing time, at 6 t/ha in potato (Bhullar *et al.* 2015) and at 9 t/ha in turmeric (Kaur *et al.* 2008) than without mulch have been reported.

Establishment methods: Zero-till rice can be established either by direct seeding (ZT-DSR) or by transplanting (ZT-TPR) rice seedlings manually or mechanically. Kumar *et al.* (2013) reported that in the absence of weed control measures, yield losses due to weeds were 90% under ZT-DSR, compared with 35 to 42% under ZT-TPR. Where DSR is preferred for saving labor and water resources, ZT-DSR can be rotated with ZT transplanted rice every few years to keep weed pressure under check. Under herbicides and integrated weed management (IWM) treatments, ZT-DSR recorded grain yield similar to CT-DSR and CT-PTR at Ludhiana (AICRP-WM 2014): among DSR methods, under IWM treatment, ZT-DSR with residue retention on the surface recorded 19% higher yield than CT-DSR, however, under herbicides only treatment, CT-DSR recorded 8% higher yield than ZT-DSR. The succeeding wheat crop, sown with CT or ZT with and without residues retention on the surface recorded similar grain yield. Planting wheat on raised beds reduced weed density and biomass as compared to the conventional method of flat seedbed (Dhillon *et al.* 2005).

Seed rate: Weed competition in ZT-DSR can also be reduced by optimizing seed rate and the crop geometry (Chauhan 2012). In the IGP, a seed rate of 20 to 25 kg/ha has been recommended for DSR (Kumar and Ladha 2011, Gill *et al.* 2013) under optimum weed control. However, results of Chauhan *et al.* (2011) suggest that a seeding rate of 95 to 125 kg/ha for inbred varieties and 83 to 92 kg/ha for hybrid varieties is needed to achieve maximum yields in competition with weeds. Reductions in row spacing from 45 to 15 cm had no effect on rice yields under wee-free conditions but increased yields where weeds were present (Akobundu and Ahissou 1985; Chauhan and Johnson 2011b). Even though higher seed rates have been shown to improve crop competitive ability with weeds, local farmers are reluctant to use more than 20 kg/ha seed rate for rice due to concerns about increased cost of production. In ZT wheat also, narrow row spacing (15 cm) reduced *P. minor* biomass by 16% compared with normal spacing of 22.5 cm (Mahajan and Brar 2002). Integrated use of narrow row spacing (15 cm), higher seed rate (150 kg/ha) and 25% lower dose of clodinafop reduced *P. minor* density compared with normal spacing (22.5cm), normal seed rate (125 kg/ha) and field dose of clodinafop (Bhullar and Walia 2004b).

High-residue cover cropping: This practice can significantly improve weed control in CA. Prior to termination, cover crops compete with weeds for resources; cover crops can also release allelochemicals into the soil, which may be detrimental to competing weed species, particularly to small-seeded weeds (Weston 1996, Foley 1999, Price *et al.* 2008). After termination, weed suppression occurs by physical impedance of weed species with cover crop residue as well as continued leaching of allelochemicals into the soil (Weston 1996). Future adoption of these practices will be dependent upon continued research to identify herbicide strategies that can work effectively in high-residue systems. In ZT rice production in IGP, sowing *Sesbania* sp. at 25 kg/ha along with rice has shown promise for suppressing weeds. *Sesbania* sp. is allowed to grow with rice to suppress weeds and is then killed with 2,4-D ester at 25 to 30 days after sowing. Singh *et al.* (2007) reported 76 to 83% lower broad-leaf weed densities and 20 to 33% lower grass weed densities with this practice compared with only a rice crop.

Competitive crop cultivars: Crop cultivars vary in their growth habit, which can substantially affect the crop-weed competitive balance. Cultivars with high early seedling vigor and spreading nature, which cover the ground quickly during the vegetative stage, result in the suppression of weeds. Currently, cultivars that were bred for CT-PTR are being used in ZT-DSR, and very limited efforts have been made to breed more weed competitive rice cultivars suitable for ZT-DSR. However, several existing cultivars exhibiting superior weed competitiveness have been identified (Singh *et al.* 2009). In general, it has been observed that early maturing inbred and hybrids because of their faster early growth and ground cover are more effective in smothering weeds than medium- to long-duration cultivars (Gill *et al.* 2013, Singh *et al.* 2014). A long-duration rice cultivar '*PR 114*' (145 d) having slower initial growth had 26- 31 days longer critical weed free period than for '*PR 115*' (125 d) (Singh *et al.* 2014).

Wheat varieties with faster early growth, earlier canopy formation, spreading habit and greater height are less susceptible to weed competition (Balyan and Malik 1989; Paul and Gill 1979). Under timely planting conditions, wheat varieties '*PBW-343*' and '*WH-542*' were equally competitive (Chahal *et al.* 2003, Kaur *et al.* 2003), but under delayed sowing conditions, '*PBW-343*' was superior to other cultivars against *P. minor* (Kaur *et al.* 2003).

Water and nutrient management: High soil moisture in RW systems favors moisture-loving weeds like *P. minor*, *R. dentatus* and *P. monspeliensis* (Singh *et al.* 1995). Because wheat can germinate under drier conditions than can many weeds (Chhokar *et al.* 1999), sowing under dry conditions can facilitate reduced weed emergence and competition. Water management has been an important component of weed control in conventionally flooded CT-PTR, where flooding is established from the first day of transplanting. The emergence and growth of most of rice weed species is inhibited when fields are submerged shortly after seeding. In ZT-DSR, flooding cannot be applied immediately after sowing because rice seeds cannot germinate and survive under completely submerged conditions. Therefore, many weeds can emerge in DSR before flooding is possible, making weed management difficult (Chauhan 2012). The development of rice cultivars capable of germinating under anaerobic conditions would greatly facilitate weed management via flooding in DSR (Chauhan 2012). This trait would not only help in weed control but also in enhancing the adoption of DSR in both rainfed and irrigated areas because crop establishment will be improved with this trait if untimely rain comes soon after sowing. Similarly, placement of fertilizer in the crop root zone rather than broadcast application can shift weed–crop competition in favor of the crop.

Depleting weed seed banks: Even after practicing weed control, some weeds can escape and produce a large number of persistent seeds, which can reduce yields or increase weed management costs in subsequent seasons. These weeds need to removed/ uprooted before they set seed and this tactic is affordable for most farmers in the IGP. Another approach to depleting weed seed banks involves enhancing weed seed predation and decay. Weed seeds present on the soil surface in CA are most vulnerable to surface-dwelling seed predators and burial makes seeds largely unavailable to them (Hulme 1994). Therefore, seed predation could be important in systems where newly produced weed seeds remain on the soil surface, for example, in no-till systems. Cromar *et al.* (1999) reported post-dispersal predation of *E. crusgalli* reduced seed input from 2000 to 360 seeds/m^2. Therefore, crop management practices such as ZT and residue retention, which are known to enhance the activity of weed seed decay agents, might contribute to reductions in the weed seed bank in the long run.

Crop rotations: Continuous cultivation of a single crop or crops having similar management practices allows certain weed species to become dominant in the system and, over time, these weed species become hard to control. Rotating crops that have dissimilar life cycles or cultivation practices is an effective cultural practice for disrupting life cycles and improving control of problematic weeds such as *P. minor* (Chhokar *et al.* 2008). Malik and Singh (1995) found fewer resistance cases in *P. minor* where growers used sugarcane, sunflower, and vegetables in the rotation rather than a RW cropping system. On heavy soils, infestations of wild oats that dominated in the maize-wheat system were completely eliminated by growing rice instead of maize (Gill and Brar 1975). Diversification and intensification of the RW system by growing a short-duration vegetable crop (pea or potato) followed by late sown wheat can also improve weed control without increasing herbicide use (Chhokar *et al.* 2008). By replacing wheat with alternate crops such as berseem, potato, sunflower, oilseed rape for 2-3 years in RW cropping system, seedbank of *P. minor* was significantly reduced in Punjab (Brar 2002) (Table 3). Diversified crop rotation can be exploited to improve the management of problematic weeds, because the selection pressure is diversified by changing patterns of weed control tactics.

Table 3. Status of *P. minor* seed bank in different crop rotations in Kapurthala and Patiala districts of Punjab

Crop rotation	No. of *P. minor* seeds/kg top soil			
	0-7.5 cm		7.5 - 15.0 cm	
	Kapurthala	Patiala	Kapurthala	Patiala
Rice-wheat	40	30	18	10
Rice-potato-sunflower/wheat	7	0	3	0
Rice-toria (indian rape)-sunflower	0	-	0	-
Rice-berseem (*Egyptian clover*)	0	0	0	0
Rice-gobhi sarson (oilseed rape)	5	-	0	-
Rice-onion-wheat	-	0	-	0

Source: Brar (2002)

Chemical weed control: Herbicides are an integral part of weed management in CA. In CA, the diverse weed flora present in the field before crop sowing must be killed by using non-selective herbicides. Proper selection of herbicide formulations for CA may be necessary to achieve effective weed control because crop residues may intercept 15 to 80% of the applied herbicides (Chauhan *et al.* 2012). For example, pre-emergence herbicides applied as granules may provide better weed control than liquid-formations in no-till systems. The rotation of herbicides with different modes of action may be important in avoiding or delaying the evolution of resistance. Several low-dose, high-potency, selective, post-emergence herbicides and mixtures are presently available in India for effectively managing weeds in major crops such as rice and wheat grown in CA.

Herbicide-tolerant crops provide growers in many countries with a useful tool for managing weeds in CA systems. At present, herbicide tolerant crops are not available to growers in India. There are also some risks associated with the adoption of herbicide tolerant crops. Continuous use of the same herbicide such as glyphosate may result in shifts in weed flora or it may accelerate the development of glyphosate resistance in weeds. Indeed, glyphosate was successfully utilized for over 2 decades before a resistant biotype of rigid ryegrass (*Lolium rigidum*) was identified in Australia in 1996 (Powles *et al.* 1998). However, since the release of herbicide tolerant crops, several resistant weed biotypes have been reported in glyphosate-tolerant systems in as little as 3 years (Green 2007, Duke and Powles 2008). Therefore, herbicide tolerant crop cultivars should not be considered as a stand-alone component of weed management. An integrated weed management strategy should be used to ensure that this important weed management tool remains effective, profitable and environmentally sound over a long period of time.

Integrated weed management: Any single method of weed control used in isolation cannot provide season-long effective weed control because of variations in the growth habit and life cycle of weeds. Therefore, a combination of different weed management strategies needs to be evaluated for widening the weed control spectrum and efficacy for sustainable crop production. Combining good agronomic practices, timeliness of operations, fertilizer and water management, intercropping and retaining crop residues on the soil surface can improve the efficacy of herbicides and crop competitiveness against weeds. The integration of herbicides with intercropping in sugarcane (Bhullar *et al.* 2006) and with nitrogen fertilization in wheat (Bhullar and Walia 2003) improved weed control than sole cropping or herbicides alone. Weeds of secondary importance may emerge as a primary weed problem because of the continuous use of a single herbicide or herbicides with a similar mode of action. This problem can be avoided by adopting an integrated approach that includes herbicide rotation, herbicide combinations and crop rotation to develop sustainable and effective weed management strategies under CA systems.

Socio-economic influences on the adoption of CA

Crop yield: The success of ZT in north-western parts of India has been attributed to the increase in wheat yields following the adoption of ZT in rice–wheat rotations (Gupta and Seth 2007, Bhan and Behera 2014). In a review of ZT in India, Erenstein and Laxmi (2008) found 5-7% increase in wheat yield as compared to the wheat grown in CT. At long-term field sites established in Punjab within the ACIAR project, the average grain yield of ZT-wheat was 5.82 t/ha as compared to 5.42 t/ha for CT-wheat (*i.e.* 7% yield gain) during 2012-13 (Bhullar *et al.* unpublished data). In the eastern IGP, where late planting of wheat is quite common, yield increase due to timely planting in ZT-wheat can be in the range of 400–1000 kg/ha (Gupta and Seth 2007). Research has shown that the zero-till system allows crops to be sown by at least 1 week earlier than CT, thereby reducing yield losses which can range from 1–1.5%/day after the optimum wheat sowing time (Aslam *et al.* 1993, Ortiz Monasterio *et al.* 1994, Mehla *et al.* 2000, Hobbs and

Gupta 2003, 2004). Because of the benefits observed in ZT-wheat, CA technologies have been tried in other cropping systems in India (Jat *et al*. 2011), but there are large knowledge gaps.

The importance of skill development through experiential learning adoption has been confirmed in DSR in a recent farmer survey conducted by the authors in Punjab. DSR was introduced in Punjab and Haryana as an alternative to CT-PTR to reduce the cost of production and water input. The results of the survey clearly indicated presence of some yield penalty in first one to two years of DSR adoption but after that the farmers were able to achieve similar or higher yields under DSR than CT-PTR. Research and farmer experience shows that the productivity of wheat grown after DSR is greater than wheat grown after CT-PTR. In our recent survey in 2012-13, 70% of farmer respondents reported higher grain yield of wheat after DSR (6.0 t/ha) than after CT-PTR (5.54 t/ha) (Bhullar *et al*, unpublished data). According to Boparai *et al*. (1992) and Aggarwal *et al*. (1995), better root development of wheat the main reason for the higher grain yield of wheat following DSR than after CT-PTR.

Economic benefits: Farmer experiences from several locations in the IGP showed that ZT technology in wheat can reduce land preparation costs by about Rs. 2,500 ($41.7)/ha and reduce diesel consumption by 50–60 l/ha (Sharma *et al*. 2005). According to Erenstein and Laxmi (2008), ZT-wheat after rice in India generates substantial benefits at the farm level by enhancing farm income from wheat cultivation (US$97/ha) through the combined effects of yield improvement and cost-saving (Table 4). Similarly Gupta and Seth (2007) reported net benefits of US$ 150/ha with ZT-wheat in India.

According to our own survey of farmers in Punjab, DSR improved net returns in coarse and in scented rice. The net returns from wheat following DSR was higher by Rs 4050/ha than following CT-PTR. The total returns from DSR-wheat system were Rs. 5050- 8100/ha higher than in the PTR-wheat system, indicating that DSR based cropping sequence provides higher economic returns than PTR (Bhullar *et al*, unpublished data).

Impact on the environment: The adoption of CA based technologies have been shown to enhance soil quality (Jat *et al*. 2009, Gathala *et al*. 2011), avoiding crop residue burning reduces loss of nutrients, and environmental pollution, which reduces a serious health hazard (Sidhu *et al*. 2007). With the development of new drills, which are able to cut through crop residue, for ZT crop planting, burning of straw can be avoided, which amounts to as much as 10 t/ha, potentially reducing release of some 13–14 tons of carbon dioxide (Gupta *et al*. 2004). Zero-tillage on an average saves about 60 l of fuel/ha thus reducing emission of CO_2 by 156 kg/ha/year (Gupta *et al*. 2004). The adoption of CA in the long-term should enhance C sequestration and build-up in soil organic matter and should be considered a practical strategy to mitigate Green House Gas emissions (Saharawat *et al*. 2012). For example, continuous submergence of soils in CT-PTR promotes the production of methane by anaerobic decomposition of organic matter. Incorporation of straw increases methane emissions under flooded conditions, but surface management of the straw under aerobic conditions can mitigate these effects. Thus, adoption of aerobic mulch management with reduced tillage is likely to reduce methane emissions from the system.

Table 4. Summary of key impacts of zero tillage in India's Indo-Gangetic Plains

Indicator	Value
Households directly affected (estimate)	620,000
Extent of adoption (zero/reduced tillage, estimate)	1.76 m ha
Production cost saving	US$ 52/ha
Increase in crop yields	5-7% (140-200 kg/ha)
Increase in farm income from wheat production	US$97/ha
Increase in real household incomes	US$180-340/farm
Increase in food production	0.7% (343,000 tons)

Source: Erenstein and Laxmi 2008

Research, development, extension and training needs for weed management in CA

Researchable issues

- Developing package of practices for IWM involving crops, tillage, residues, modified planting methods and herbicides in CA to reduce use of herbicides and to minimize cost of production.
- Understanding weed dynamics, their interference potential and suitable management practices with low-cost herbicides in CA. This will help in making weed control timing decisions and maximizing the effectiveness of both chemical and non-chemical weed control tactics.
- Quantifying the effects of different crop residue mulches on different weeds and how much residue of these crops is required to achieve optimum suppression of different weeds without affecting crop establishment.

- Quantifying short- to long-term effects of inclusion of cover crops in the systems on weed suppression during cover cropping and after its termination in succeeding crops, for possible reductions in herbicide inputs for adequate weed control under CA.
- Developing weed-competitive crop cultivars for CA. In case of rice, cultivars with anaerobic germination and iron efficient traits so that early flooding can be used in ZT-DSR for weed suppression.
- Estimating season-long seed predation potential under conventional and conservation agriculture and mechanisms by which seed predation can be enhanced.
- Developing management strategies for emerging problematic weed species.
- Improved understanding of the interactions between retained crop residues and herbicides, and degradation pathways, adsorption-desorption and transport processes of herbicides under CA. Further research on herbicide mixtures for delaying resistance, reducing the cost of weed management, and improving the weed control spectrum is needed.

Policy issues

- Developing and implementing appropriate legislation on prevention and monitoring of crop residue burning through incentives (e.g. carbon credits) and penalties.
- Support the development of CA machinery and ensure its availability at affordable prices through subsidies and promoting custom hiring systems.
- Support for the adoption of CA technologies in local environments by improving the availability of critical inputs.
- Classifying crop residues as amendments (similar to lime or gypsum) and their use in agriculture should attract a subsidy as is the case for fertilizers or soil amendments.

Capacity building

- Capacity building of under- and post-graduate students and training of farmers. Every agricultural university should have courses in CA both at under- and postgraduate levels. Capacity building of farmers to acquire, test and adopt technologies through participatory approach will enable them to identify suitable CA practices for their farms and thus they can reduce their production cost and combat production constraints.
- Establishing self-help groups and encouraging unemployed youths to take up custom hiring of CA machinery as a profession.
- Including CA in the soil health card for proper monitoring of crop residues retention/burning and its impact on soil health.
- Training personnel at the KVKs and the state agricultural departments for awareness generation and adoption of CA by the local farmers.

Extension activities

- Each university, research institute and NGO committed to sustainable development of agriculture should start working directly with farmers. Their experience should be used for improving the CA technology and overcoming its constraints to make CA a success.
- Organizing farmers' field days, holding of field demonstrations, cross-farm visits of extension experts and effective use of mass media for the transfer of CA technology could play a major role in promoting CA to the farming community.
- Improvement in the coordination among various stakeholders (research, extension service, farmers, service providers, agricultural machinery manufacturers, etc.) for more effective transfer of technologies will play a pivotal role in accelerating the adoption of new interventions.

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