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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 e*x-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

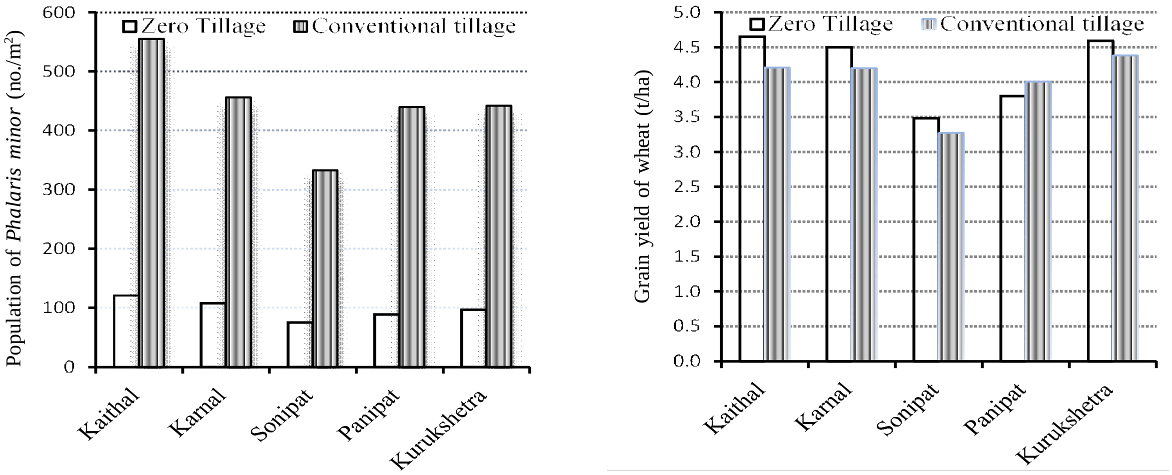

Fig. 1. Effect of tillage on wheat yield and population of *Phalaris minor* at different locations in Haryana

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

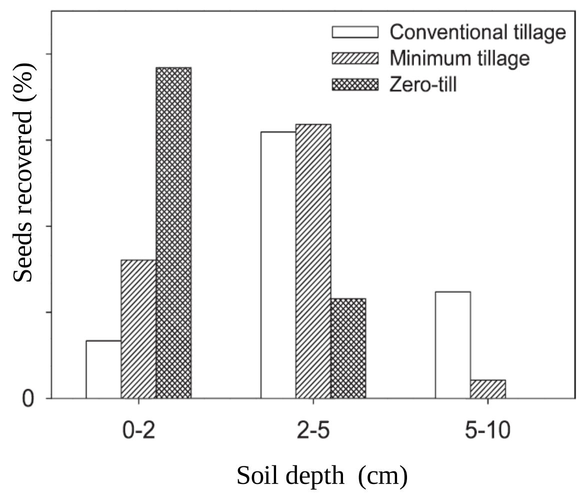

Fig. 2. Effect of tillage systems on vertical distribution of weed seeds

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.

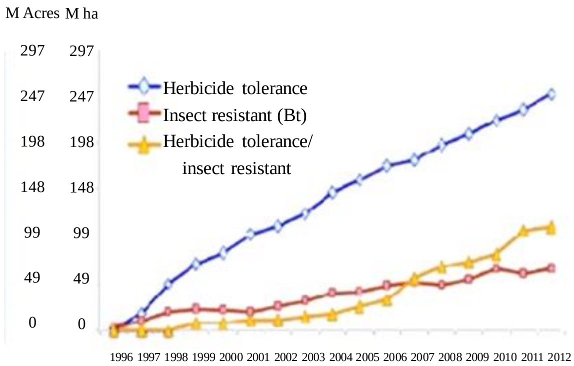

Fig. 3. Global area of biotech crops by trait

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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