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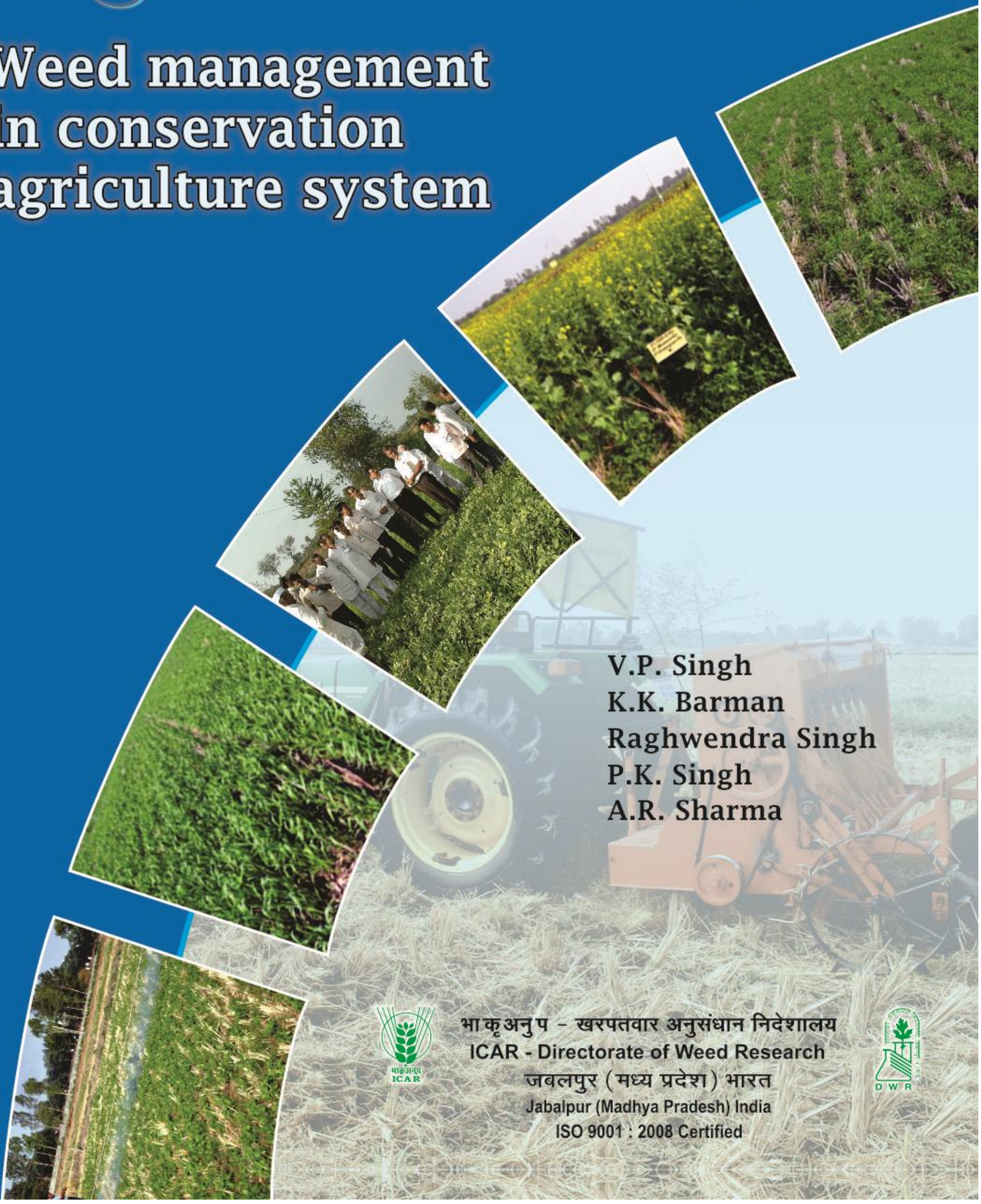
Weed management in conservation agriculture system



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Preface

Conservation agriculture (CA) is a holistic approach towards increased productivity and improved soil health. It does have several advantages over conventional tillage (CT) based agriculture in terms of soil health parameters. However, weeds are the major biotic constraint in CA, posing as a great challenge towards its adoption. Presence of weed seeds on upper soil surface, due to no tillage operation, leads to higher weed infestation in CA, and so far herbicides are the only answer to deal with this problem. Overreliance on herbicide use showed its consequence in terms of environmental pollution, weed shift, and herbicide resistance development in weeds. Growing herbicide tolerant crops using nonselective herbicides is a broad spectrum weed management technique to tackle weed shift, but the same has resulted in evolution of more problematic `super weed'. These observations indicate the need of integrated weed management technologies involving the time tested cultural practices, viz. competitive crop cultivars, mulches, cover crops, intercrops with allelopathic potential, crop diversification, planting geometry, efficient nutrient and water management, etc., along with limited and site specific herbicide application. The modern seeding equipments, e.g. `Happy Seeder' technology, that helps in managing weeds through retention of crop residues as mulches, besides providing efficient seeding and fertilizer placement, holds the promise of becoming an integral part of CA system.

Outcomes of the experiments conducted in farmers' fields and research farm show that the benefits of CA can well be taken in black cotton soils with rice-wheat-moongbean system as weed menace under this system can be managed by integrating suitable herbicides in the weed management programme. However, as this is a highly technology driven agriculture and its very basic principles of sowing seeds in an un-tilled land and without removing crop residues are in sharp contrast to the traditional belief, tremendous amount of efforts will be needed to pursue the farmers' for adoption of this technology. Further, lack of availability of suitable machineries and timely availability of herbicides could be other bottlenecks towards the popularization of CA, which requires administrative intervention.

(Editors)

Content

Weed management in conservation agriculture systems

1. Introduction

The birth of modern (conventional) agriculture coincides with industrial revolution. The identification of N, P and K as critical factors in plant growth led to the manufacture of synthetic fertilizers. While chemical fertilizers and pesticides have existed since the 19th century, their use grew significantly in the early 20th century with the invention of Haber-Bosch method for synthesizing ammonia. The rapid mechanization, especially in the form of tractor and combine harvester, coupled with science-driven innovations in methods and resources led to efficiencies enabling outputs of high quality produce per unit area and time. The contribution of Norman Borlaug and other scientists since 1940s towards development of crops for increased yields further accelerated the modern agriculture and initiated the era of `Green Revolution'. However, the growth of conventional agriculture thus attained was on the basis of capital depletion and massive additions of external inputs, e.g. energy, water, chemicals, etc.

The transformation of 'traditional animal-based subsistence farming' to 'intensive chemical and tractor-based conventional agriculture', have led to multiplicity of issues associated with sustainability of these production practices. Conventional crop production technologies are characterized by: (1) intensive tillage to prepare fine seed- and root-bed for sowing to ensure proper germination and initial vigour, faster absorption of moisture, control of weeds and other pests, mixing of fertilizers and organic manures; (2) monocropping systems; (3) clean cultivation involving removal or burning of all residues after harvesting leading to continuous mining of nutrients and moisture from the soil profile; and bare soil with no soil cover; (4) indiscriminate use of insecticides and pesticides, and excessive and imbalanced use of chemical fertilizers leading to decline in input-use efficiency and factor productivity, and increase in pollution of environment, ground water, streams, rivers and oceans; and (5) energy-intensive farming systems.

Crop residue burning in field

Burnt field

2. Emerging problems

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 concerns, such as:

- Declining factor productivity
- Declining ground water table
- Development of salinity hazards
- Deterioration in soil fertility
- Deterioration in soil physical environment
- Biotic interferences and declining biodiversity
- Reduced availability of protective foods
- Air and ground water pollution
- Stagnating farm incomes

Therefore, 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 needs 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.

3. Conservation agriculture - a new paradigm in crop production

Widespread resource degradation problems under conventional agricultural production system, and the need of reducing production costs, increasing profitability and making agriculture more competitive, made the conservation issues more imperative. Globally innovations of conservation agriculture-based crop management technologies are said to be more efficient, use less input, improve production and income, and address the emerging problems (Gupta and Seth 2007). Additionally, secondary drivers 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 (Jat et al. 2011)

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 (CA) 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, 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).

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 surface)	• Surface retention of residues (permanently covered)
• 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 crop area
• Mono cropping/culture, less efficient rotations	• Diversified and more efficient rotations

• Heavy reliance on manual labor, 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

Tillage is age-old practice of crop production. Jethro Tull (1671-1741), regarded as 'Father of Tillage' came up with a book entitled “Horse Hoeing Husbandry” wherein he propounded a theory that 'Soil particulars are ingested through openings in plant roots due to the processes caused by the swelling of growing roots'. He carried out numerous experiments dealing with cultural practices, leading to development of drill and horse drawn cultivator, and advocated that soil should be finely pulverized to provide proper pebulum for the growing plant. The vulnerability of plough-based agriculture was exposed during Dust Bowl era (1931-39); as wind blew away the precious top soil from the drought-ravaged southern plains of US, leaving behind the failed crops and farms. However, there was no answer then to solve the question of soil degradation. Then what *Nature* magazine termed "an agricultural bombshell" was dropped by Faulkner on July 5, 1943; with the first issue of his masterpiece book `*Plowman's Folly and A Second Look.*' The author opened a new era by simply saying a key sentence “The fact is that no one has ever advanced a scientific reason for plowing.” His idea was in sharp contrast to that advocated by Jethro Tull, and blamed the then universally used moldboard plow for disastrous tillage of the soil. He questioned the use of plough for cultivation of crops, and argued that all standard wisdom used as a rationale for ploughing the soil was invalid. His ideas were considered 'mad' and without merit, until after his death when soil experts and scientists began to admit “We didn't pay attention, and we should have.” Time magazine called this concept “one of the most revolutionary ideas in agriculture history.” He is regarded as one of the first true conservationists. Faulkner's idea received further momentum with the findings of Masanobu Fukuoka, as outlined in his book 'The one straw revolution.' In this book Masanobu Fukuoka presented a radical challenge to the global systems we rely on for our food. At the same time, it is a spiritual memoir of a man whose innovative system of cultivating the earth reflects a deep faith in the wholeness and balance of the natural world. For more than 65 years Masanobu Fukuoka worked to develop a system of natural farming. He did not plow his fields, used no agricultural chemicals or inorganic fertilizers, did not flood his rice fields as farmers have done in Asia for centuries, and yet his yields equalled or surpassed the most productive farms in Japan.

4. Prospects of conservation agriculture

Conservation agriculture has increased crop yields compared with conventional tillage in many countries, viz. USA, Australia, Mexico, Canada and Brazil (Malhi and Lemke 2007; D'Emden *et al.* 2009). For example, sizable yield increases and income stability have led to wide-scale adoption of CA among farming community in Brazil (Saturnino and Landers 2001). Similarly farmers in developing countries, like India and Pakistan, have also started to practice some CA technologies. For example, zero-till (ZT) wheat in the rice–wheat system is currently being practiced on >3 million ha in north-western parts of the Indo-Gangetic Plains. Globally, about 155 million 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. For example, presently resource conservation technologies are practiced in more than 3 million 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 nothing less than the end of an age-old concept, popularly known as “more you till and more you eat”. Adoption and spread of ZT wheat has been a success story in north-western parts of India due to: (i) reduced cost of production (Malik *et al.* 2005; RWC-CIMMYT 2005); (ii) enhanced soil quality, i.e. soil physical, chemical and biological conditions (Jat *et al.* 2009a; Kaschuk *et al.* 2010; Gathala *et al.* 2011b); (iii) increased C sequestration and built-up in soil organic matter (Blanco-Canqui and Lal 2009; Saharawat *et al.* 2012); (iv) reduced incidence of weeds (Malik *et al.* 2005; Chauhan *et al.* 2007b); (v) increased water and nutrient-use efficiencies

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: www.fao.org/ag/ca/6c.html dt. 01.12.2014

(Blanco-Canqui and Lal 2009; Kaschuk *et al.* 2010; Jat *et al.* 2012; Saharawat *et al.* 2012); (vi) increased system productivity (Gathala *et al.* 2011a); (vii) advances in sowing date (Hobbs *et al.* 2008); (viii) greater environmental sustainability (Sidhu *et al.* 2007; Pathak *et al.* 2011); (ix) increased residue breakdown with legumes in the rotation (Fillery 2001); (x) reduced temperature variability (Blanco-Canqui and Lal 2009; Jat *et al.* 2009b; Gathala *et al.* 2011b), and (xi) opportunities for crop diversification and intensification (Jat *et al.* 2005).

The number of tillage operations done under CT (4-6 operation) is much more than under CA (only 1 operation for sowing) thereby saving time and cost. Besides reducing the cost of tillage operation, CA also saves irrigation water and reduces CO_2 emission. For example, wheat under ZT requires 30-50% less water in first irrigation and 15-20% less water in subsequent irrigation resulting in a saving of about 36% water under ZT. It was also noticed that there was about 70-75% reduction in CO_2 emission under ZT wheat than in CT (Table 3).

Table 3. Environmental impact of ZT wheat in Haryana and Bihar

Particulars	**Haryana**		**Bihar**	
	ZT	**CT**	**ZT**	**CT**
Diesel consumption for tillage operation (L ha^{-1})	10.0	39.1	10.0	34.3
Irrigation water use ($m^3 ha^{-1}$)	1710	2150	932	1134
Total CO_2 emission (kg ha^{-1})	21.6	84.5	21.6	74.0

Source: Pal *et al.* (2010)

Conservation agriculture has to addresses the complete agricultural system—the 'basket' of conservation-related agricultural practices. Initially it was considered that the practices of minimal tillage, permanent residue cover and planned crop rotations are to be prescribed simultaneously for making the CA successful (Hobbs *et al.* 2008). However, later on it was advocated to include integrated weed management as another crucial component for successful implementation of CA (Farooq *et al.* 2011a); as weeds are one of the most difficult management issues within this system (Giller *et al.* 2009). For example, adoption of ZT wheat in the rice–wheat system of Pakistan's Punjab province increased during the initial years of its introduction, but later on showed a significant proportion of disadoption due to weed menace (Farooq *et al.* 2007). About 39% ZT users of this region encountered an increase in weed problems due to ZT, with 37% reporting no effect, and 24% a decrease (Tahir and Younas 2004). It was noted that the ZT adopters, non-adopters, and disadopters differ significantly in terms of their resource base; and disadopters also had more problems in controlling weeds. Giller *et al.* (2009) argued that weeds are 'Achilles heel' as they can affect yields and sustainability of CA systems.

5. Crop growth and productivity

Conservation agriculture (CA) systems including new cultivars are more efficient, use less input, improve production and income, and address the emerging problems (Gupta and Seth 2007; Saharawat *et al.* 2009). Improvement of grain and straw production encourages farmers to leave crop residues on their fields, and ensures the long-term benefit of ZT system. Minimum tillage + crop residue has been found to be beneficial for conserving water and improving crop productivity (Saharawat *et al.* 2009; Jat *et al*. 2012). Compared to deep tillage, conservation tillage in maize-wheat cropping system involving minimum tillage (in wheat) with *Lantana camara* (an obnoxious weed) mulch (in standing maize or at its harvest) conserved more moisture, and resulted in higher grain yield of wheat in a hill ecosystem (Sharma and Acharya 2000). The yields of wheat sown in presence of rice residues were always comparable to or higher than yields obtained under conventional sowing (Sidhu *et al.* 2007; Ghosh *et al.* 2010; Mishra and Singh 2012). Similarly, zero-tillage with residue retention showed beneficial effect on growth of other crops like rice, mustard and linseed with a yield increase of 44-63% over conventional tillage (Ghosh *et al.* 2010).

In a study on rice-wheat cropping systems at New Delhi, direct-seeded rice alone gave about 0.5 t ha^{-1} lower yields than transplanted rice (Table 4). However, the loss was compensated when brown manuring with *Sesbania* was done or greengram residues were incorporated in previous summer. Wheat yields were similar under zero-till with rice

Table 4. Conservation agriculture technologies in basmati rice ('PRH 10')- wheat ('HD 2894')-greengram ('SML 668') cropping system at New Delhi

Treatment	Rice grain yield (t ha^{-1})	Wheat grain yield (t ha^{-1})	System productivity (t ha^{-1})	Net returns ($x10^3$ ₹ha^{-1})	Irrigation water productivity (kg rice ha^{-1} mm)
DSR – ZT wheat	4.90	4.62	13.34	112.21	5.97
DSR – ZT wheat + RR	5.15	4.80	13.97	117.50	6.12
DSR + BM – ZT wheat	5.08	4.68	13.72	115.75	5.58
DSR + BM – ZT wheat+RR	5.32	4.88	14.35	121.68	6.20
DSR – ZT wheat - GG	5.18	4.78	15.77	128.42	6.22
DSR – ZT wheat +RR - GG	5.45	4.95	16.56	131.26	6.35
TPR – ZT wheat	5.55	4.88	14.76	120.13	3.75
TPR – CT wheat (Conventional)	5.58	5.07	15.00	122.15	3.66

DSR – Direct-seeded rice, TPR – Transplanted rice, BM – Brown manuring with *Sesbania*, GG – Greengram, ZT – Zero tillage, CT – Conventional tillage, RR – Rice Residues

residues and conventionally-tilled crop. System productivity and net returns were comparable under direct-seeded rice with brown manuring followed ZT wheat with rice residues and conventional practice. However, the highest productivity was recorded under direct seeded rice followed by ZT wheat and followed by greengram cropping system (all key elements of CA). Direct-seeded rice required about 30-40% less water and had 3-times less global warming potential compared with the transplanted rice crop. Direct-seeded rice with brown manuring of *Sesbania*, followed by zero-till wheat with rice residues and zero-till greengram during summer resulted in higher productivity, profitability and environmental sustainability.

6. Energy use-efficiency

Farm mechanization plays a vital role for the success of CA in different agro-ecologies and socio-economic farming groups. It ensures timeliness, precision and quality of field operations; reduces production cost; saves labour; reduces weather risk in changing climatic scenarios; improves productivity, environmental quality, sustainability and generates rural employment on on-farm and off-farm activities (Ladha *et al.* 2009; Saharawat *et al.* 2011). Reduced labour and machinery costs are economic considerations that are frequently given as additional reasons to use CA practices. Adopting conservation agriculture techniques is a holistic approach for management of soil and water resources, and improving efficiency and productivity per unit of C-based energy consumed. Compared to intensive tilled conventional rice-wheat system, ZT systems require much lesser energy and gives higher energy output; input ratio as well as higher system productivity (Gangwar *et al.* 2006). For example, continuous ZT with effective weed management using recommended herbicide + 1 hand weeding was more remunerative and energy efficient in Vertisols of Central India, and it was suggested that conventional till-based rice–wheat system could be replaced with zero-till-based crop establishment method with effective weed control measures to save labor and energy (Mishra and Singh 2012). Similarly, low-cost of cultivation, minimum energy usage, higher water productivity, higher net returns and enhanced energy input : output ratio were reported in ZT maize-wheat cropping system (Ram *et al.* 2010).

7. Soil health

Soil health denotes a state of dynamic equilibrium between flora and fauna and their surrounding soil environment in which all the metabolic activities of the former proceed optimally without any hindrance, stress or impedance from the latter. A healthy soil would ensure proper retention and release of nutrients and water, promote and sustain root growth, maintain soil biotic habitat, respond to management and resist degradation. Soil erosion, organic matter decline, compaction and salinization resulting from the CT based agriculture are the major threats to soil health. Conservation agriculture, which prescribes ZT coupled with crop residue mulching and diversified crop rotation, has come forward as a sustainable management system that could revert physical soil degradation in resource-poor farms across very different agro-ecological conditions (FAO 2012).

Intensive tillage accelerates soil organic carbon (SOC) loss as CO_2 as a result of physical disruption and enhanced biological oxidation. It is estimated that agriculture has contributed 25% of the historical human-made emissions of CO_2 during the past two centuries. Loss of SOC could significantly be reduced by shifting from CT to ZT and other low-disturbance techniques. That's why conservation tillage systems are proposed as a way of achieving SOC sequestration, as relatively higher SOC in the plough layer is noticed under ZT than in CT. It was projected that the conversion of a conventional system to conservation tillage could mitigate approximately 20% of the USA agricultural greenhouse gas emissions (Del Grosso *et al.* 2005), and could result in a 0.50 MT ha^{-1} yr^{-1} C sequestration rate (Lal *et al.* 1998). The principle of maintaining a permanent soil covers either by planting a cover crop or by using crop residues eventually increases the amount of organic matter and available organic carbon in the soil. The benefit of crop residue recycling is higher when used as mulch on ZT soil than its incorporation under CT system. For example, crop residue treatment in ZT soils showed significantly higher amount of SOC than other treatment combinations in the top 15 cm soil depths (Table 5). Crop residue served as a source of carbon especially in upper soil layers. Zero-tillage practice minimizes exposure of SOC from oxidation, and thus ensuring higher SOC content in surface soils of ZT with crop residue application.

Table 5. Effects of tillage and residue treatments on the SOC content (Ghimire *et al.* 2008)

Soil Depth (cm)	Soil organic carbon (kg m^{-3})				LSD
	CT		ZT		
	Mo	M_1	Mo	M_1	
0-5	11.01	12.12	12.73	14.23	1.72
5-10	8.53	10.83	10.08	10.94	1.72
10-15	7.13	9.26	10.11	8.06	1.72
15-30	4.63	5.73	5.80	4.82	1.72
30-50	4.43	4.90	4.69	3.99	1.72
0-50	7.15	8.57	7.81	8.68	0.77

Mo: No crop residue, M_1: crop residue @ 4 tonnes ha^{-1} for each crop in the rotation

In conventional farming crop residues are grazed by livestock, removed for fodder or burnt. Under this condition, bare soils exposed to intense and erratic rain showers and winds, as well as high evapo-transpiration levels result in slaking and crust formation.

Intensive tillage causes the gradual loss of stable soil aggregates leading to soil erosion and compaction (Govaerts *et al.* 2006). Soil compaction in CA is significantly reduced by the reduction of traffic and increased soil organic matter. Soil structures are especially compromised by cultivation, in particular by mouldboard ploughing. It rips apart the soil and also reduces earthworm populations and thus the earthworm tunnels (macropores); discouraging better drainage and improved water retention. Conservation agriculture reduces runoff and topsoil loss, increases infiltration and allows *in situ* moisture conservation, thereby improves crop water availability through the presence (year-round) of a protective soil cover as well as by soil structural improvements (Govaerts *et al*. 2006) through increase in topsoil organic carbon and reduced soil disturbance (Franzluebbers 2002). Soil erosion is a double edged sword, in one hand it causes loss of a virtually non-renewable resource, and on the other hand the soil sediments and 'attached nutrients' can damage aquatic biodiversity by damaging the aquatic habitat in streams and rivers or ponds. Sharratt *et al.* (2006) observed in a 20 years long-term experiment in Alaska that the soil had higher saturated hydraulic conductivity and retained more water against gravitational and matric forces when subjected to ZT. The higher saturated hydraulic conductivity was apparently caused by greater macro-porosity, whereas, enhanced retention of water was caused by an organic layer overlying mineral soil or smaller hydraulic gradients in ZT. Improved drainage achieved through an improved soil structure may also help avoid salinization.

Significant improvement in bulk density, penetration resistance, and aggregation of soil were recorded with 28 years of ZT over CT practices in Ohio, USA (Mahboubi *et al.* 1993). Similarly, Hill (1990) found an increase in soil density and strength with 12 years of ZT versus CT in Maryland, USA. However, some other studies recorded no change in soil bulk density, but did find enhanced aggregate stability with ZT treatment (Anken *et al.* 2004). Improved soil structures achieved through the application of the CA techniques can also reduce run off, thereby reducing pollution from recently applied pesticides. Improved water retention allows natural processes to occur and soil biota to break down pesticides, reducing the pollution caused by leaching.

Soil macroinvertebrates, i.e. termites, ants and earthworms, have been defined as 'ecosystem engineers' due to their role in soil structure formation and maintenance through the creation of continuous macropores (Blanchart *et al.* 2004), stable macroaggregates (Blanchart *et al.* 2004) and organo-mineral complexes (Six *et al.* 2004). Earthworm activity gets stimulated (Castellanos-Navarrete *et al.* 2012) under CA due to the absence of tillage, which strongly reduces direct physical damage to earthworms, and reduced habitat disturbance. Although, along with soil organic matter and root residues, aboveground crop residues constitute a major food source for most earthworm species, residue retention *per se* do not favour earthworm proliferation when incorporated into the soil by CT (Figure 1). Earthworm population was reduced drastically when a permanent pasture was converted to CT cropping than to ZT cropping (Aslam *et al.* 1999), indicating the favourable effect of CA on earthworms. There was also a significant shift of soil microbial dynamics with land-use change. The conversion of a permanent pasture to CT resulted in a marked decline in microbial biomass carbon, microbial biomass nitrogen and microbial biomass phosphorus at 0-5 cm soil depth. In contrast, after two years of continuous cropping with ZT, the microbial biomass nutrient status remained similar to that of the permanent pasture treatment. Reduced tillage has been shown to enhance soil microbial diversity. Soil disturbance by tillage was a major factor affecting biodiversity due to desiccation, mechanical destruction, soil compaction, reduced pore volume and disruption of access to food resources. When farmed without tillage and supplied with residues, the soils show natural improvement in overall quality, support many microorganisms and become 'mellow' to the point of being easily penetrated by roots and earthworms. This transition may take several years to accomplish but, given the opportunity, it invariably occurs.

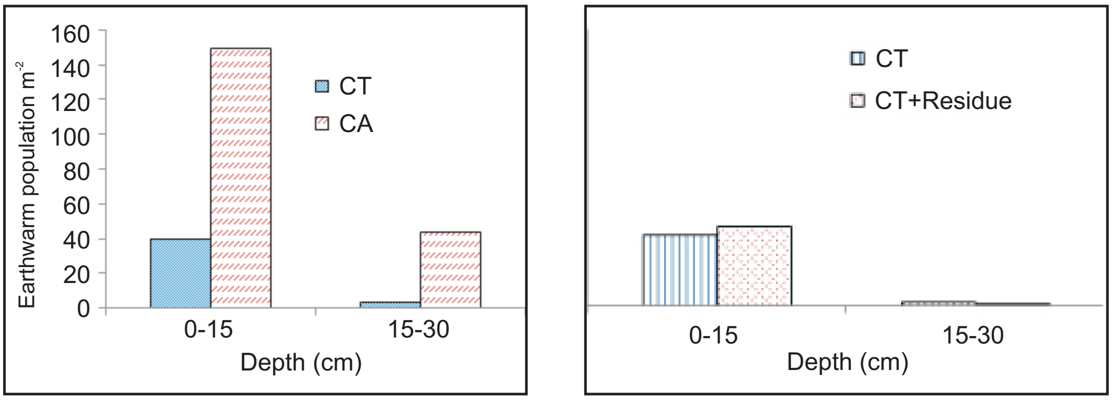

Figure 1. Earthworm abundance per depth layer and treatment. Treatments compared were: CT vs. CT+residue (right); and, CT vs. CA (left). Mean values followed by an asterisk are significantly different between the two treatments compared (*$P < 0.05$). (Castellanos-Navarrete *et al.* 2012)

8. Weeds in CA systems

Tillage affects weeds by uprooting, dismembering, and burying them deep enough to prevent emergence. Ploughing also moves weed seeds both vertically and horizontally, and changes the soil environment; thereby promoting or inhibiting weed seed germination and emergence. Reduction in tillage intensity and frequency, as practiced under CA, generally increases weed infestation. Compared to conventional tillage (CT), presence of weed seeds is more in the soil surface under ZT, which favours relatively higher weed germination. Increased weed infestation was recorded in aerobic direct-seeded rice than with conventionally puddled transplanted rice (Singh *et al.* 2008). Similarly, Mishra *et al.* (2012a) observed that over the course of time, a ZT–ZT sequence favoured relatively higher weed growth over a CT–CT sequence in a rice– wheat system. While weed growth in the initial year was not higher under the ZT–ZT sequence, in the third year of experimentation total weed dry weight was significantly higher under the ZT–ZT than CT–CT tillage sequence (Table 6).

Table 6. The effect of tillage sequence on total weed dry weight (g m^{-2}) at harvest in rice and wheat (Mishra *et al.* 2012a)

Tillage sequence	Rice	Wheat
ZT– ZT	154a*	130a
ZT– CT	177a	114a
CT– ZT	102b	131a
CT– CT	99b	96b

* Data within a column with same letter do not differ significantly (P= 0.05).

Infestation of *Phalaris minor* is a serious problem in wheat grown after rice in north-western India. This has increased due to continuous adoption of rice-wheat system and use of same or similar herbicides. New herbicides with a different mode of action are being advocated these are also sometimes proving ineffective for control of *Phalaris*. Modifying cultivation practices may help in reducing its infestation. Results from on-farm trials at several locations in Haryana, India revealed that population density of littleseed canary grass (*Phalaris minor*) was considerably lower and grain yield of wheat was comparatively higher under ZT than CT (Figure 2). Hence, weeds are a major constraint in CA systems.

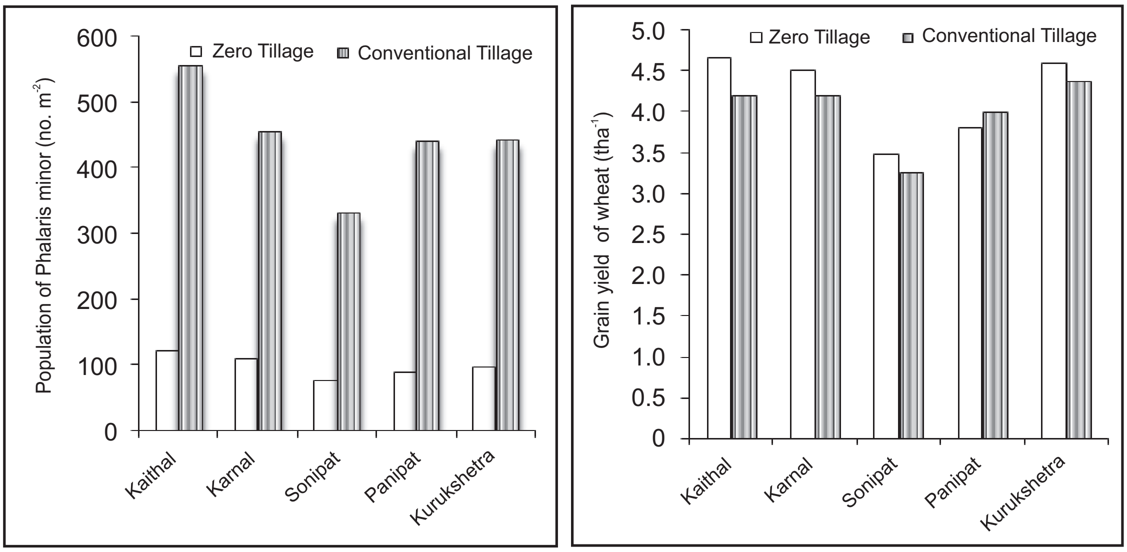

Figure 2. Effect of tillage on population of *Phalaris minor* and grain yield at different locations in Haryana (Gupta and Seth 2007)

Further, changes from conventional to conservation farming practices often lead to a weed flora shift in the crop field, which in turn dictate the requirements of new weed management technologies involving various approaches, viz. preventive measures, cultural practices (tillage, crop residues as mulches, intercropping, competitive crop cultivars, herbicide tolerant cultivars, planting dates, crop rotations etc.), and herbicides, is of paramount importance in diversified cropping systems. It may be noted that weed control in CA depends upon herbicides and agronomic practices. However, the recent development of post-emergence broad-spectrum herbicides provides an opportunity to control weeds in CA, and enabling to have uniform crop stands and yield levels similar to conventional tillage systems.

8.1. Weed ecology

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. The composition of weed species and their relative time of emergence differ between CA systems and soil-inverting CT systems. There is mounting evidence that retention of preceding crop residues suppresses the germination and development of weeds in minimum tillage systems, thus enhancing system productivity. The changes in the soil microenvironment that result from surface mulching can result in either suppression in germination of annual weeds or increased weed growth of some weed species. The composition of weed species and their relative time of emergence differ between CA systems and soil inverting CT systems. Brar and Walia (2007) reported that CT favoured the germination of grassy weeds in wheat compared with ZT in a rice-wheat system across different geographical locations of Punjab, while the reverse was true in respect to broad-leaved weeds (Figure 3).

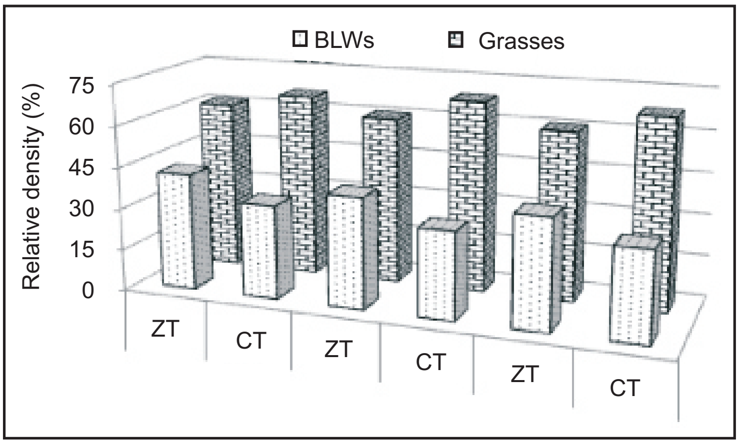

Figure 3. Effect of tillage on the relative density of grasses and broad-leaved weeds in wheat in different locations of Punjab (Brar and Walia 2007)

Some weed seeds require scarification and disturbance for germination and emergence, which may be enhanced by the types of equipment used in soil-inverting tillage systems than by conservation tillage equipment. The timing of weed emergence also seems to be species dependent. Bullied *et al.* (2003) found that species such as common lambsquarters (*Chenopodium album*), field penny cress (*Thlaspi arvense*), green foxtail (*Setaria viridis*), wild buckwheat (*Polygonum convolvulus*), and wild oat (*Avena fatua*) emerged earlier in a CA system than in a CT system. However, redroot pigweed (*Amaranthus retroflexus*) and wild mustard (*Sinapis arvensis*) emerged earlier in the CT system. Changes in weed flora make it necessary to study the composition of weed communities under different environmental and agricultural conditions.

8.2. Weed dynamics

Weed infestation show a drastic change due to continuous adoption of different cultivation practices such as sowing technique, tillage, method of weed control, residue management, cropping system, and application of inputs. Continuous adoption of a particular factor over the years may either increase or decrease the infestation of different weed species depending on several factors. Zero tillage brings about a paradigm shift in weed growth, requiring clear understanding and formulating a strategy for their management.

Certain weed species germinate and grow more profusely than others under a continuous ZT system. As a consequence, a weed shift occurs due to the change from a CT to a ZT system. For example, the infestation of awnless barnyardgrass (Mishra and Singh 2012a), rice flat sedge (Kumar and Ladha 2011), Indian Sorrel (Chhokar *et al*. 2007), nut sedge (Kumar and Ladha 2011), field bindweed (Shrestha *et al*. 2003), crabgrass (Chauhan and Johnson 2009), Burclover (Mishra and Singh 2012a), goatweed (Chauhan and Johnson 2009), crowfootgrass (Chauhan and Johnson 2009) has been found to increase; while others like little canary grass (Chhokar *et al*. 2009), wild oat and lambs quarters (Mishra and Singh 2012a), bermuda grass (Bhattacharya *et al*. 2009), Italian ryegrass and yellow starthistle (Scursoni *et al*. 2014) showed decline under ZT compared with CT.

Some weed spscies are not affected by tillage systems followed. For example, although emergence of awnless barnyard grass (*Echinochloa colona*) and rice flatsedge (*Cyperus iria*) was higher under continuous ZT than continuous CT or rotational tillage systems (ZT– CT and CT– ZT); no such tillage effect was noticed on pink node flower (*Caesulia axillaris*). Higher seedling emergence of awnless barnyard grass (*Echinochloa colona*) and rice flatsedge (*Cyperus iria*) under continuous ZT was attributed to their small seed size, which failed to germinate when buried deeply in CT (Mishra and Singh 2012a).

A shift in weed populations towards small-seeded annuals is generally observed under conservation tillage systems. Contrary to this, in spite of small seed size, little canary grass has shown a remarkable reduction in their population under ZT compared to CT system in the Indo-Gangetic Plains. This may be attributed to (i) higher soil strength in ZT because of crust development in the absence of tillage, which can mechanically impede seedling emergence (Chhokar *et al*. 2007), (ii) less soil temperature fluctuation under ZT

(Gathala *et al*. 2011b), or (iii) relatively lower levels of light stimuli, N mineralization and gas exchange under ZT, all of which are known to stimulate germination of many weed species under CT system (Franke *et al*. 2007).

Shifts in weed populations towards perennials have also been observed in conservation tillage systems. Perennial weeds thrive in reduced or no-tillage systems because the root system is not disturbed and herbicides used to control annual weeds are not effective on perennial weeds. Perennial monocots are considered a greater threat than perennial dicots in the adoption of reduced tillage systems. Unlike annuals, many perennial weeds can reproduce from several structural organs other than seeds. For example, purple nutsedge (*Cyperus rotundus*), tiger grass (*Saccharum spontaneum*) and johnson grass (*Sorghum halepense*) generally reproduce from underground plant storage structures, i.e. tubers or nuts and rhizomes. Conservation tillage may encourage these perennial reproductive structures by not burying them to depths that are unfavourable for 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.

8.3. Weed seed bank

A 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 several years. The seed bank 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. The success of the CA system depends largely on a good understanding of the dynamics of the weed seed bank in the soil. Under ZT, there is little opportunity for the freshly-rained weed seeds to move downwards in the soil and hence remains mostly on the surface, with the highest concentration in the 0–2 cm soil layer, and no fresh weed seed is observed below 5 cm soil depth (Figure 4). Under conventional and minimum tillage systems, weeds seeds are distributed throughout the tillage layer with the highest concentration of weed seeds in the 2–5 cm soil layer. Mouldboard ploughing buries most weed seeds in the tillage layer, whereas chisel ploughing leaves the weed seeds closer to the soil surface. Similarly, depending on the soil type, 60– 90% of 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 with suitable moisture and temperature than when buried deeper in conventional systems.

A small percentage of the fresh weed seeds that shattered in the crop field actually emerge as seedlings due to seed predation (Westerman *et al.* 2003). Therefore, unlike in

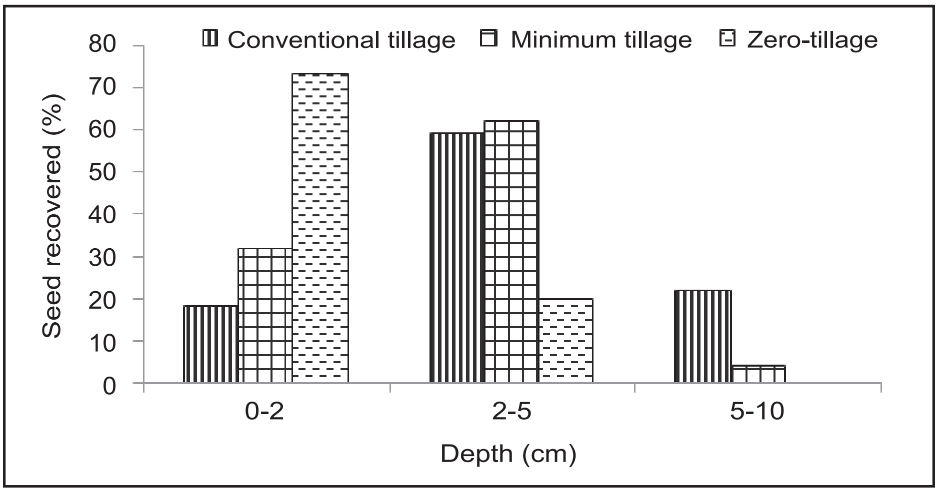

Figure 4. The effect of tillage systems on the vertical distribution of weed seeds (Chauhan and Johnson 2009).

conventional practice of burial that makes weed seeds largely unavailable, seed predation could be important in no-till systems where newly-produced weed seeds remain on the soil surface and are most vulnerable to surface-dwelling seed predators like mouse, ants and other insects (Baraibar *et al.* 2009; Chauhan *et al.* 2010). For example, reduced seed input from 2000 to 360 seeds m^{-2} as a result of post-dispersal predation of barnyard grass (*Echinochloa crusgalli*) was reported by Cromar *et al.* (1999). Further, CA systems may favour population growth of harvester ants by not damaging the nests, and may minimize the redistribution of weed seeds stored in superficial chambers (Baraibar *et al.* 2009). Weed seed predation can be encouraged to manage weeds in CA as it can substantially reduce the size of the weed seed bank. Such approaches are possible with no additional costs to growers. Predators prefer certain kinds of seeds, e.g. the ant species, tropical fire ant (*Solenopsis geminate*) prefers grass weed seeds over broadleaf weed seeds. Vertebrate and large invertebrate predators usually prefer larger seeds. Such selectivity in seed consumption may result in shifts in weed population. The seed size and ease of consumption are factors influencing the preference of granivores, particularly ants.

9. Weed management

Management of weeds is a major issue in agricultural production system, particularly under CA where the infestation is likely to be higher than conventional intensive–tillage. Understanding ecology, seed bank and dynamics of specific weed flora is essential for developing effective management strategies in divergent situations. Weed control in CA is a greater challenge than in conventional agriculture because there is no weed seed burial by tillage operations (Chauhan *et al.* 2012). The behaviour of weeds and their interaction with crops under CA is complex and not fully understood. The weed species that germinate in response to light are likely to be more problematic in CA. In addition, perennial weeds become more challenging in this system (Shrestha *et al.* 2006). In the past, attempts to implement CA have often resulted in 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. Crop yields can be similar for conventional and conservation tillage systems if weeds are controlled and crop stands are uniform (Mahajan *et al.* 2002). Various approaches employed to successfully manage weeds in CA systems includes preventive measures, cultural practices (tillage, crop residue as mulches, intercropping, cover cropping, competitive crop cultivars), use of herbicide-tolerant cultivars, and herbicides.

9.1. Preventive measures

Preventive weed control encompasses all measures taken to prevent or arrest the introduction and arrest of weeds. Weed seeds resembling the shape and size of crop seeds are often the major source of contamination in crop seeds. Contamination usually occurs at crop harvesting if the life cycle of crop and weeds is of similar duration. Preventive measures are the first and most important steps 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 the following:

- Use weed-free crop seed
- Prevent the dissemination of weed seeds/propagules from one area to another or from one crop to another by using clean machinery/implements, screens to filter irrigation water and restricting livestock movement
- Use well-decomposed manure/compost so that it does contain any viable weed seeds
- Remove weeds near irrigation ditches, fence rows, rights-of-way, etc. prior to seed setting
- Mechanically cut the reproductive part of weeds prior to seed rain
- Implement stringent weed quarantine laws to prevent the entry of alien invasive and obnoxious weed seeds/propagules into the country.

9.2. Cultural practices

A long-term goal of sustainable and successful weed management is not to merely control weeds in a crop field, but 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, mulching, inter-cultivation, intercropping, cover crops, crop rotation/diversification and other agro-techniques–once labeled as uneconomical or impractical–should be relooked and 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 a change in the timing of weed emergence. Shrestha *et al.* (2002) concluded that long-term changes in weed fiora are driven by an interaction of several factors, including tillage, environment, crop rotation, crop type, and timing and type of weed management practice.

9.2.1. Tillage

Tillage has long been an essential component of conventional agricultural systems and it is the most important among the traditional means of weed management in agriculture. The effect of primary tillage on weeds is mainly related to the type of implement used and to tillage depth. These factors impact the weed seed and propagule distribution over the soil profile; and therefore directly affect the number of weeds that can emerge in a field. Differential distribution of seeds in the soil profile subsequently leads to changes in weed population dynamics. Weed seeds buried deep germinate but fail to emerge due to the thick soil layer above it, resulting in death of the weed seedling. Tillage stimulates weed germination and emergence of many weed seeds through brief exposure to light. ZT wheat in a rice–wheat system reduces littile seed canary grass (*Phalaris minor* Retze) infestation, which is highly competitive and can cause drastic wheat yield reductions under heavy infestation (Figure 3), but it favours the infestation of toothed dock (*Rumex dentatus* L.) and cheeseweed mallow (*Malva parviflora* L.) (Chhokar *et al.* 2007) and wild oat (Mishra *et al.* 2005). Cheeseweed mallow is favoured by shallow seed burial and scarification (Chhokar *et al.* 2007) leading to more weed population under a ZT system.

A reduction in weed density occurs if the weed seed bank depletion is greater than weed seed shedding. However, this situation is rarely achieved with no-tillage. Therefore, weed densities in no-tillage systems are generally higher than in plough-based systems (Mishra *et al.* 2012a). The findings of a long-term experiment with four tillage systems (Figure 5) adopted for 12 consecutive years in a continuous winter wheat or a pigeon bean–winter wheat rotation showed that total weed seedling density in ZT, minimum tillage using rotary harrow (15 cm depth), and chisel ploughing (45 cm depth) was relatively higher in the 0–15, 15–30, and 30–45 cm soil layers, respectively (Barberi and Lo Cascio 2001). But ZT may affect seedling emergence of some weed species under a particular cropping system.

The impact of tillage on weed infestation varies depending upon the weed seed morphology *vis-a-vis* agro-climatic situations. For example, infestation of little seed canary grass in the crop sown with ZT was 21–33% less compared to the conventional method of

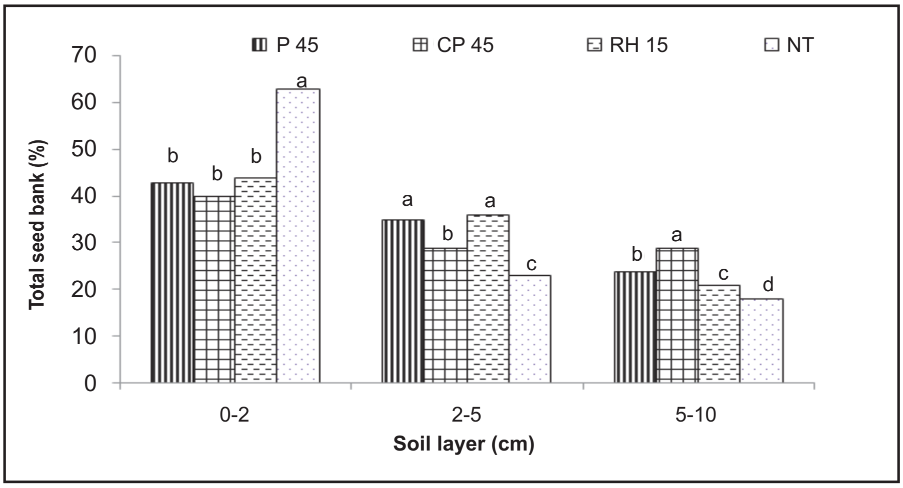

Figure 5. Percent weed seedling distribution over soil layers in mouldboard ploughing at 45 cm depth (P 45), chisel ploughing at 45 cm depth (CP 45), rotary harrowing at 15 cm depth (RH 15), and zero-tillage (ZT) after 12 consecutive years' application of the different tillage systems (Barberi and Lo Cascio 2001)

sowing (Singh 2007). However, the benefit of ZT in reducing the *P. minor* population was relatively lower under late-sown conditions (Lathwal and Malik 2005). In a black cotton soil, ZT planting reduced the infestation of little seed canary grass and lambs quarter but increased the problem of wild oat under transplanted rice–wheat system (Mishra *et al.* 2005). On the other hand, a DSR–wheat system with continuous ZT reduced the population of wild oat and lamb's quarter in wheat (Mishra and Singh 2012). Some authors observed a small difference in weed populations between conventional and ZT fields, while relatively less weeds were reported in ZT wheat from the Indo-Gangetic Plains (Hobbs and Gupta 2001; Singh *et al.* 2001; Malik *et al.* 2002). Variation in the composition of the soil seed bank and prevailing agro-climatic conditions among the site is responsible for such observations. Mulugeta and Stoltenberg (1997) noticed a several-fold increase in weed seedling emergence due to tillage. The impact of tillage *vis-à-vis* weed infestation in the crop field is influenced by the previous cropping systems. Continuous ZT increased the population density of awnless barnyard grass *and* rice flatsedge in rice, but rotational tillage systems significantly reduced the seed density of these weeds (Table 7). Continuous ZT with effective weed management using recommended herbicide + hand weeding was more remunerative and energy efficient (Mishra and Singh 2012a). Similarly, ZT with effective weed control was more remunerative in soybean–wheat system (Mishra and Singh 2009).

Table 7. Weed seed bank (no/ number per 500 g soil) in top 20 cm of soil as affected by tillage sequences in a DSR– wheat in a Vertisol of central India (Mishra and Singh 2012a)

Tillage sequence	*Echinochloa colona*			*Cyerus iria*			*Avena ludoviciana*			*Medicago hispida*		
	0–5 cm	5–10 cm	10–20 cm	0–5 cm	5– 10 cm	10–20 cm	0–5 cm	5–10 cm	10–20 cm	0–5 cm	5–10 cm	10–20 cm
ZT–ZT	15.40a*	9.56a	6.89a	3.52a	1.50a	0.62a	59.6a	13.0a	2.82a	35.6a	11.30a	4.89a
ZT–CT	9.70b	6.67b	3.17b	1.93b	1.17a	0.55a	16.0b	10.4b	1.85b	14.4b	4.06c	1.33b
CT–ZT	9.30b	4.50c	3.06b	1.60b	0.39b	0.58a	33.6c	13.8a	2.53a	10.2c	3.50c	1.83b
CT–CT	3.30c	2.72c	1.61c	3.44a	1.33a	0.62a	41.1b	14.6a	3.07a	16.1b	8.67b	4.00a

* Data within a column with same letter do not differ significantly (P=0.05).

Furrow Irrigated Raised-Bed System (FIRBS) and ridge tillage systems are the form of reduced and conservation tillage, respectively, that appear to overcome weed control problems associated with conventional and NT systems (e.g. Chopra and Angiras 2008a, 2008b; Mishra and Singh 2012a; Sharma *et al.* 2004). Besides improved weed management, FIRBS has been found improves input use-efficiency. Chauhan *et al.* (1998) obtained reasonably good control of little seed canary grass in wheat on raised beds but broad-leaved weeds in furrows were not controlled. The problem with little seed canary grass was less as the weed seeds lying on top of the raised beds failed to germinate as the top of bed dried quickly. This method also facilitated mechanical weeding as the area in the furrows could easily be cultivated and even manual weeding could be done. When crop plants are 40 cm tall, soil is excavated from the furrows and is moved back to the ridge crest, thereby affecting weeds, weed control and the crop–weed interaction (Forcella and Lindstorm 1998). However, changes in weed communities were influenced more by location and year than by tillage systems. For instance, FIRBS effectively reduced total weed density and weed biomass at Palampur, India, but was not superior to other tillage practices in Hisar, India (Table 8).

Table 8. Effect of tillage on total weed density, dry matter of weeds at 60 DAS in different locations in India

Location	Weed density (no.m^{-2})			Weed dry weight (g m^{-2})			Reference
	CT	ZT	FIRB	CT	ZT	FIRB	
Faizabad	-	-	-	14.40	20.2	-	Yadav *et al.* (2005)
Palampur	270.0	283.3	241.0	131.3	139.4	107.3	Chopra and Angiras (2008a)
Palampur	228.0	245.0	203.0	113.0	126.0	91.0	Chopra and Angiras (2008b)
Karnal	83.2	62.0	-	18.1	20.7	-	Chopra and Chopra (2010)
Delhi	137.9	168.5	-	15.6	19.1	-	Tuti and Das (2011)
Jabalpur	155.0	213.0	-	-	-	-	Mishra and Singh (2012b)
Hisar	89.3	87.4	96.1	30.1	26.5	32.4	Jat *et al.*(2013b)

9.2.2. Stale seedbed

Seedbed preparation can contribute to weed management by affecting weed seed dynamics and seedling densities at planting. In CT, disking or ploughing at intervals achieves control of initial weed populations before crop sowing. Cultivation for seedbed preparation affects the weeds in two ways: (i) it destroys the emerged vegetation after primary tillage, and (ii) it stimulates weed seed germination and consequent seedling emergence and reallocation of seeds towards the soil surface; this phenomenon could be exploited to manage weeds through application of the stale (false) seedbed technique.

No-till stale seedbed practice can help to reduce weed pressure in CA systems. In this technique, the field is irrigated 10–15 days prior to actual seeding to favour the germination of weed seeds lying on the soil surface. Emerged weeds are then destroyed by the application of non-selective herbicides like glyphosate, paraquat or ammonium glufosinate. It depletes the seed bank in the surface layer of the soil and reduces subsequent weed emergence. Where light rains occur for an extended period before the onset of the monsoon or irrigation is available, it may be possible to kill several flushes of weed growth before planting. To ensure success, cropping should be delayed until the main flush of emergence has passed. However, this practice may not be exploited where the season available for crop growth is short, which may reduce the yield potential of the crop. The main advantage of the stale seedbed practice is that the crop emerges in a weed-free environment, with a competitive advantage over late-emerging weed seedlings. The practice of false seed bed technique may decrease weed infestation in crops by 80% or more compared to standard seedbed preparation (Van der Weide *et al.* 2002).

The stale seedbed technique is widely used in many countries to manage weedy rice and awnless barnyard grass in rainfed rice. Stale seedbeds reduce weed populations in direct-seeded rice (Rao *et al.* 2007), and may be especially effective when combined with no-till practices (Chauhan *et al.* 2006). Pittelkow *et al.* (2012) reported that ZT stale seedbed practice was effective at reducing the population of sedges and grasses, but not for controlling redstem weeds. This practice is very effective in ZT wheat in the north-western Indo-Gangetic Plains (Mahajan *et al.* 1999).

9.2.3. Crop residues

Crop residues present on the soil surface can influence weed seed germination and seedling emergence by interfering with sunlight availability and creating physical impedance, as well as improving soil and moisture conservation and soil tilth. Residues on the soil surface can vary greatly in dimension, structure, distribution pattern and spatial heterogeneity. Weed biology, and the quantity, position (vertical or flat, and below- or above-weed seeds) and allelopathic potential of the crop residues may influence weed germination (Chauhan *et al.* 2006).

Soil cover using crop residues is a useful technique to manage weeds. Weed emergence generally declines with increasing residue amounts. However, the emergence of certain weed species is also favoured by some crop residue at low amounts. For example, germination and growth of wild oat and animated oat (*Avena sterilis* L.) may get stimulated with low levels of wheat residue. High amounts of crop residues have implications for weed management in CA through reduced and delayed weed emergence. The crop gets competitive advantage over weeds due to delayed weed emergence, which results in relatively less impact on crop yield loss. Further, late emerging weed plants produce less number of seeds than the early emerging ones (Chauhan and Johnson 2010). For example, the residue of Russian vetch (*Vicia villosa* Roth) and rye (*Secale cereal* L.) reduced total weed density by more than 75% compared with the treatments with no residue (Mohler and Teasdale 1993). The presence of rye mulch in corn significantly reduced the emergence of white lambs quarter, hairy crabgrass (*Digitaria sanguinalis* (L.) Scap.), and common purslane (*Portulaca oleracea* L.) and total weed biomass (Mohler and Calloway 1992). However, crop residues alone may not be able to fully control weeds, e.g. hairy-vetch residue suppressed weeds early in the growing season but herbicide was needed to achieve season-long weed control. The effectiveness of crop residue to reduce weed emergence also depends upon the nature of weed species to be controlled. Chauhan and Abugho (2012) reported that 6 t ha^{-1} crop residues reduced the emergence of jungle rice, crowfoot grass and rice flat sedge by 80–95% but only reduce the emergence of barnyard grass by up to 35% (Figure 6).

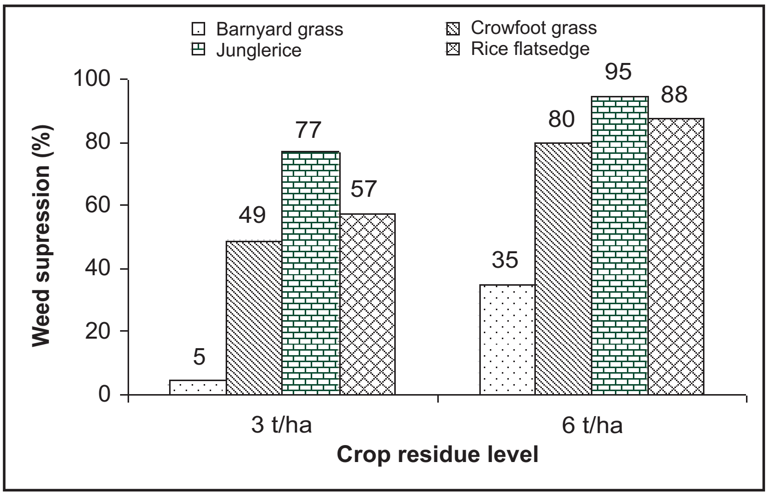

Figure 6. The effect of rice residues on weed germination (Chauhan and Abugho 2012)

The increased moisture content and decreased temperature of soil due to the presence of crop residue may increase the germination of some weed species. Compared with stubble burning, stubble retention in some cases resulted more significant weed problem, e.g. brome grass (*Bromus diandrus*), barley grass (*Hardeum leporinum*), *etc.* (Table 9). In dryland areas, the amount of available crop residue may be insufficient to substantially suppress weed germination and growth (Chauhan and Johnson 2010). Further, certain crops like oilseeds and pulses produce less biomass than cereals. Therefore, the effects of crop residue on the weed population depend on the region, crop and rainfall. There is a need to integrate herbicide use with residue retention to achieve season-long weed control. In high-residue situations, it is important that residue does not hinder crop emergence.

Table 9. Impact of crop residue management prior to sowing on weed seedling emergence

Weed species	Crop residue treatment	
	Burned	**Retained**
Wireweed (*Polygonum aviculare* L.)	No change	Decrease
Brome grass (*Bromus diandrus* Roth)	Decrease	Increase
Barley grass (*Hordeum leporinum* Link.)	Decrease	Increase
Annual ryegrass (*Lolium rigidum* Gaudin)	Decrease	Increase
Wild oats (*Avena ludoviciana* Durieu.)	Increase	Decrease

Source: CRC for Australian Weed Management (www.grdc.com.au/resources/Links-pages/~/media/A4C48127FF8A4B0CA7DFD67547A5B716.pdf)

9.2.4. Intercropping

Intercropping involves growing a smother crop between rows of the main crop such that the competition for water or nutrients does not occur. Intercrops help to effectively pre-empt resources used by weeds and suppress weed growth, and hence can be used as an effective weed control strategy in CA. for example, Alfalfa+barley, Alfalfa+oats, Fababean+red clover, Maize+Italian ryegrass/perennial ryegrass, Maize +redclover/hairy vetch, Maize/cassava+cowpea/peanut/sweet potato, Pigeonpea+urdbean /mungbean/soybean/cowpea/sorghum, Rice+*Azolla pinnata*, Sorghum+cowpea/mungbean/peanut/soybean, Chickpea+mustard, etc. are some successful weed suppressing intercropping systems.

Intercropping of short-duration, quick-growing, and early-maturing legume crops with long-duration and wide-spaced crops leads to quickly ground cover, with higher total weed suppressing ability than sole cropping. This technique enhances weed control by increasing shade and crop competition. Like cover crops, intercrops increase the ecological diversity in a field. In addition, they often compete better with weeds for light, water and nutrients. Success of intercropping relies on the best match between the requirements of the component species for light, water and nutrients, which increases resource use. Many short-duration pulses like cowpea, greengram and soybean effectively smother weeds without reducing the yield of the main crop. For instance, total weed growth reduced under intercropping combinations of chickpea+mustard over the sole chickpea crop without losing productivity of the main crop (Rathi *et al.* 2007). Similar observations were also recorded by Dubey (2008) under a maize+cowpea intercropping system (Table 10). Compared with the sole crop, increased canopy cover and decreased light availability for weeds in maize–legume intercropping was responsible for the reduction in weed density and dry matter (Kumar *et al.* 2010). However, intercropping cowpea in maize under CA had the greatest impact on weeding activities in the farmer's field, with labour hours increasing by 40% due to the additional precision required for weeding compared with maize-only fields (Lai *et al.* 2012).

Table 10. The effect of intercropping on weed growth (Dubey 2008)

Intercropping system	**Weed density (number m^{2})**				**Weed dry matter (g m^{-2})**	**Maize equivalent yield (t ha^{-1})**
	Echinochloa colona	***Phylanthus niruri***	***Commelina communis***	**Total**		
Sole maize	5.3* (27.9)	7.5 (56.1)	3.5 (11.7)	10.4 (107.5)	6.0 (35.4)	2.97
Maize + cowpea (grain)	3.6 (12.9)	6.1 (37.2)	2.9 (8.1)	8.3 (68.4)	4.8 (22.5)	4.07
Maize + cowpea (fodder)	4.1 (16.8)	6.4 (40.6)	3.5 (11.7)	8.6 (73.5)	5.3 (27.8)	3.27
LSD (P=0.05)	0.5	0.6	NS	0.6	0.5	-

* Square-root transformed values, original values are in parentheses.

One of the principles of CA is to include green manuring, with its bioherbicidal characteristics and weed smothering capabilities, along with an additional benefit of adding biomass to soil. *Sesbania* can be grown with rice as a co-culture to suppress weeds, and in addition to weed control it can also fix large amounts of N (Ladha *et al.* 2000). Sesbania intercropping for 25–30 days in a dry-seeded rice under CA followed by killing of *Sesbania* using 2,4-D or mechanical means was effective in controlling weeds, but the contribution from N fixation was small because of intercropping and short growth duration (Singh *et al.* 2007). This practice was also a highly beneficial resource conservation technology for soil and water conservation, weed control and nutrient supplementation in maize (Sharma *et al.* 2010). The *Sesbania* option also provides an alternative to crop residue.

9.2.5. Cover cropping

Ground cover with dead or live mulch, allowing less time for weeds to establish during fallow or turnaround period is an important component of CA technology. Inclusion of cover crops in a rotation between two main crops is a good preventive measure when developing a weed management strategy. Cover crops are fundamental and sustainable tools to manage weeds, optimize the use of natural resources, and reduce water runoff, nutrient leaching and soil erosion. Competition from a strong cover crop can virtually shut down the growth of many annual weeds emerging from seeds. Aggressive cover crops can even substantially reduce growth and reproduction of perennial weeds that emerge or regenerate from roots, rhizomes or tubers, and are more difficult to suppress.

Cover crop effects on weeds largely depend upon the species and weed community composition. Weed suppression is exerted partly through resource competition for light, nutrients and water during the cover crop growing cycle, and partly through physical and chemical effects that occur when cover crop residues are left on the soil surface as a dead mulch or ploughed down.

Weed pressure in CA can be reduced by including short-duration legume crops e.g. mungbean, cowpea, green gram, *Sesbania,* etc., during the fallow period between harvesting wheat and planting rice. This practice facilitates emergence of weeds during the legume period (stale seedbed effects) and reduces the population during the rice season (Kumar *et al.* 2012). The density of annual ryegrass plants in a wheat crop decreased to one-third after green manured lupins compared with the harvested lupin crop, and to <20% after green manured oats and mustard (Anderson 2005). In India, *Sesbania* grown as a cover crop produced green biomass up to 30 t ha^{-1} in 60 days, and controlled most of the weeds (Mahapatra *et al.* 2004).

Growing green manure or cover crops in the summer season or as a relay crop to efficiently suppress weed growth is a cost and labour efficient practice. Therefore, green manures are sometimes also called the herbicides of small farmers. Perennial grasses such as cogon grass (*Imperata cylindrical* (L.) *P. Beauv.) and bermuda grass (Cynodon dactylon* (L.) *Pers.),* and other problem weeds like *Striga* spp. and Siam weed (*Chromolaena odorata* (L.) King & H. E. Robins.) can be suppressed by one or two seasons of cover crops. In CA, a number of cover crops, including legumes (alfalfa, Sesbania, sunhemp, clover, soybean, lupin and cowpea) and non-legumes (sunflower, rapeseed, rye, buckwheat and sudan grass) could be exploited to suppress and smother various weeds.

9.2.6. Crop diversification

Crop rotation involves alternating different crops in a systematic sequence on the same land. It limits the build-up of weed populations and prevents weed shifts as the weed species tend to thrive in a crop with similar growth requirements. Different crops require different cultural practices, which help to disrupt the growing cycle of weeds, and prevent any weed species to dominate. For example, Johnson grass generally becomes a predominant weed in a continuous maize system but may be controlled by rotating with cotton. In monocropping systems, several weed species persist and expand rapidly. Cropping sequences provide varying patterns of resource competition, allelopathic interference, soil disturbance and mechanical damage, and thus provide an unstable environment that prevents the proliferation and dominance of a particular weed, and discourages growth and reproduction of troublesome weed species. The prolonged cultivation of the rice–wheat system in north-western India has resulted in increased population of sedges and grassy weeds. The diversification of the system even for a short period and intensification by including summer legumes/green manuring decreased the weed menace (Singh *et al.* 2008). The diversification of the system even for a short period and intensification by including summer legumes/green manuring decreased the weed menace (Table 11).

Certain crop-associated weed species e.g. barnyard grass in rice, wild oat and little seed canary grass in wheat, dodder (*Cuscuta* spp.) in alfalfa etc., may be discouraged by following a rotation of crops with contrasting growth and cultural requirements. Crop rotation is an effective practice for management of little seed canary grass because selection pressure is diversifled by changing patterns of disturbances (Chhokar and Malik 2002). Changing from rice–wheat to any other sequence not involving rice, reduces the population of little seed canary grass in wheat. In case, where sugarcane is taken followed by one ratoon, littleseed canary grass population goes down considerably. Replacing wheat with other crops like Egyptian clover (*Trifolium alexandrinum* L.), potato (*Solanum tuberosum* L.), sunflower (*Helianthus annuus* L.) and annual rape (*Brassica napus* L.) for 2–3 years in a rice–wheat cropping system significantly reduced the population of littleseed canary grass.

Table 11. Density of different weed species (no. m^{-2}) and weed dry matter production (g m^{-2}) in rice at 25 DAT under different crop sequences and grain yield (Singh *et al.* 2008)

Crop sequence	Grasses	Sedges	Broad-leaved weeds	Weed dry matter	Rice yield (t ha^{-1})
Rice–wheat	31.7	23.2	22.4	28.0	3.81
Rice–chickpea	32.3	20.3	13.5	25.3	3.88
Rice–wheat–greengram	9.9	7.3	3.3	9.9	4.09
Rice–wheat–Sesbania (GM)	17.4	13.0	15.1	19.4	4.21
Rice–mustard–greengram	16.2	9.9	7.2	15.9	4.05
Rice–lentil–cowpea (F)	15.7	8.4	4.7	13.3	4.13
Rice–pea	32.2	20.7	16.7	26.4	4.01
Rice–lentil+mustard (3:1)–cowpea (F)	17.2	11.5	6.5	15.1	4.15
Rice–maize+pea(1:1)–cowpea (F)	19.4	12.6	11.1	20.0	4.18
Rice–potato–green gram	12.5	10.4	7.6	14.5	4.19

A rice–wheat rotation suppressed the establishment and growth of wild oat in wheat, while a maize–wheat rotation resulted in a gradual build-up of wild oat. Integration of red clover in continuous maize resulted in a higher weed seed bank or emergence of several summer annual weeds compared to maize alone. In contrast, integration of red clover in the sweet corn–pea–wheat rotation led to a 96% reduction in the seed bank density of winter annuals (Brainard *et al.* 2008). The inclusion of sesame in several cropping sequences reduced the aerial growth of nutsedge (Varshney 2000). Parasitic weeds can be successfully managed by rotating the host crop with trap crops, as they induce germination of weed seeds but are themselves not parasitized. The added advantage of the crop rotation is that it also allows growers to use new herbicides that may control problematic weeds.

9.2.7. Cultivar competitiveness

Crop species and cultivars differ in their competitiveness with weeds. The expression of competitive advantage of crop genotypes against weeds is strongly influenced by environmental conditions. The competitive ability of a crop variety is reflected either by its ability to reduce weed growth and seed production or to tolerate weed interference and maintain higher levels of grain yield. Different genotypes of the same crop may differ in their competitive ability against weeds due to varying morphological traits (Table 12). Although there is conflicting evidence as to which crop characteristics contribute most to competitiveness, several studies have highlighted the role of rapid germination and emergence, vigorous seedling growth, rapid leaf expansion, rapid canopy development, extensive root systems, and also production of allelopathic compounds by the crop. However, mostly the crop competitiveness is enhanced by vigorous growth that reduces light quality and quantity beneath the crop canopy (Buhler 2002).

Table 12. Dominant crop characteristics for weed competitiveness

Crop	Weed competitive cultivar	Crop characteristics accounted for competitiveness	Weeds suppressed	References
Rice	PR 108	Leaf area index (LAI)	Mixed flora	Ghuman *et al.* (2008)
Rice	PI 312777	Allelopathic compound	Barnyardgrass	Gealy *et al.* (2014)
Wheat	Sonalika, Sujata, HD 2285, PBW 343	LAI; Biomass production	Wild oat	Mishra and Singh (2008)
Wheat	Saleem-2000 Ghaznavi-98	Biomass production	Wild oat	Khan *et al.* (2008)
Wheat	PBW 154, WH 435, PBW 343	LAI	Mixed flora	Chauhan *et al.* (2001); Walia (2002)
Corn	AG 1051	LAI; Shoot and root biomass	Mixed flora	Silva *et al.* (2011)
Oat	Blaze	Biomass production; Allopathic compound	Lambsquarters	Grimmer and Masiunas (2005)
Barley	Aura 6	Plant height	Field pansy, Chickweed	Auskalniene *et al.* (2010)
Canola and mustard	Yellow mustard	Quick emergence; Biomass accumulation; Plant height	Mixed flora	Beckie *et al.* (2008)
Canola	F1 hybrids	Plant height; Vigorous canopy growth	Wild oat	Zand and Beckie (2002)
Sugarcane	B41227	Sprawling type	Mix flora	Yirefu *et al.* (2012)

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A quick-growing and early canopy-producing crop is a better competitor against weeds than crops lacking these characters. Seed size within a species also influences competition through vigorous growth of plants from larger seeds. Use of weed suppressing genotypes may therefore reduce the need for direct weed control measures. However, not all traits that give a crop competitive advantage against weeds can be exploited. For example plant height is usually correlated with weed suppression but it is often negatively correlated with crop yield and positively correlated with sensitivity to lodging. Competitive ability can also be related to the production and release of allelochemicals. There is considerable allelopathic potential in some rice varieties against weeds, which indicates potential for using crop genotype choice as a cultural method for weed management.

Some wheat varieties, *viz*. 'PBW 154', 'WH 435' and 'PBW 343' are more competitive with little seed canary grass (*Phalaris minor* Retze) compared with durum varieties such as 'PBW 233' (Chauhan *et al.* 2001). This is probably due to more leaf area index (LAI) of the former varieties (Walia 2002). Similarly, rice variety 'PR 108' exhibited greater weed smothering ability over 'PR 114', 'PR 116' and 'PR 118' (Table 13) due to relatively higher LAI in 'PR 108' (Ghuman *et al.* 2008). Therefore, development of weed competitive cultivars without sacrificing yield potential is essential for integrated weed management. Future breeding and variety testing programs should take such factors of crop competitive ability with weeds into consideration. Negligible emphasis has been given on breeding cultivars for competitive ability with weeds. Major focus given so far on breeding for yield and quality may have inadvertently eliminated competitive traits in crops. Therefore, development of weed competitive cultivars without sacrificing yield potential is essential for integrated weed management. Future breeding and variety testing programs should take such factors of crop competitive ability with weeds into consideration.

Table 13. The effect of rice varieties on weed drymatter accumulation, photosynthetically active radiation (PAR) and grain yield (Ghuman *et al.* 2008)

Variety	Weed dry weight at harvest (kg ha^{-1})	Grain yield (t ha^{-1})
'PR 108'	64.8	4.04
'PR 114'	133.3	3.67
'PR 116'	104.8	4.16
'PR 118'	90.8	4.68
LSD (P=0.05)	18.6	0.43

9.2.8. Planting geometry

Planting density and pattern modify the crop canopy structure, and in turn influence weed smothering ability. Narrow row spacing brings variation in microclimate, viz. light intensity, evaporation and temperature at soil surface. The establishment of a crop with a more uniform and dense plant distribution results in better use of light and water, and leads to greater crop competitive ability. Crops grown in narrow rows start competing with weeds at an earlier stage than those in wide rows because of more rapid canopy closure and better root distribution. Narrow row widths and a higher seeding density will reduce the biomass of late-emerging weeds by reducing the amount of light available for weeds located below the crop canopy. Reduced growth of weeds was reported due to increased population and decreased spacing in rice (Ghuman *et al.* 2008). The LAI of closely-planted rice increased but PAR decreased, and grain yield was significantly higher than the widely-spaced crop (Table 14). Similarly, bi-directional sowing and closer row spacing (15 cm) are quite effective in suppressing the growth of littleseed canary grass in wheat.

Table 14. The effect of plant populations on weed dry matter, PAR and rice grain yield (Ghuman *et al.* 2008)

Plant population (no. m^{-2})	Weed dry weight at harvest (kg ha^{-1})	Grain yield (t ha^{-1})
50	59.8	4.62
33	94.9	4.02
25	140.6	3.77
LSD (P=0.05)	11.2	0.55

9.2.9. Allelopathy

There has long been observed an inhibitive response by plant species to certain neighboring plants. The Greek philosopher and botanist, Theophrastus, noted this effect from cabbage as early as 300 BC. In 1937, Austrian botanist, Hans Molisch, described this phenomenon as allelopathy, which he determined to be the result of biochemical interactions between plants. For instance, rapeseed, mustard and radish contain a number of compounds called glucosinolates that break down into powerful volatile allelochemicals called isothiocyanates during residue decomposition (Uremis *et al.* 2009). These chemical may suppress weed growth for several weeks or months. Several *Brassica* spp. could be useful allelopathic cover crops because these are winter-hardy and can be grown almost anywhere. Rye residue contains good amounts of allelopathic chemicals, viz. isothiocyanate benzyl and isothiocyanate allyl. When left undisturbed on the soil surface, these chemicals leach out and prevent germination of small-seeded weeds. The magnitude of allelopathic influence depends on allelopathic crops as well as on target weeds in a crop-weed environment.

Crop allelopathy against weeds may be exploited as a useful tool to manage weeds under CA. Several crops are able to strongly suppress weeds, such as alfalfa, barley, black mustard, buckwheat, rice, sorghum, sunflower and wheat; either by exuding allelochemical compounds from living plant parts or from decomposing residues. The growing need for sustainable agricultural systems has necessitated increased cover crop research to better utilize these covers for effective weed control. Thus it is necessary to understand the role of allelopathy for weed suppression within various cover crops (Price *et al.* 2008; Walters and Young 2008). Allelopathic interference on weeds is generally higher when grasses or crucifers are used as cover crops than when legumes are used. The use of allelopathic traits from crops or cultivars with important weed inhibition qualities, together with common weed control strategies, can play an important role in the establishment of sustainable CA systems. For instance, significant inhibitory effects of sunflower residues incorporated into field soil on the total number and biomass of weeds growing in a wheat field (Alsaadawi *et al.* 2012). Similarly, mulching of allelopathic plant residues, inclusion of certain allelopathic crops in cropping rotation or as intercrop or as cover crop may be practiced for weed management in CA (Table 15). These multiple approaches of allelopathic application have potential to act as natural weed controlling agents with varying degree of success depending upon environmental and managerial factors (Farooq *et al.* 2013). Allelopathy thus offers a viable option for weed management in CA.

9.2.10. Sowing time

Table 15. Weed control through allelopathic mulches, crop residues incorporation, cover crops and intercropping

Allelopathic source	Application mode	Crop	Weed species	Weed dry matter reduction (%)	Yield increase (%)	Reference
Sorghum	Soil incorporation	Wheat	Littleseed canary grass, Lamb's quarter	48–56	16–17	Cheema and Khaliq (2000)
	Surface mulch	Cotton	Desert horse purslane, Field bind weed, Bermudagrass	5–97	69–119	Cheema *et al.* (2000)
	Allelopathic extract	Cotton	Desert horse purslane	29	45	Cheema *et al.* (2000)
		Wheat	Littleseed canary grass, Indian Fumitory, Lamb's quarter, Toothed dock, Nutsedge	35–49	11–20	Cheema and Khaliq (2000)
Sunflower + Rice + Brassica	Soil incorporation	Maize	Desert horse purslane	60	41	Khaliq *et al.* (2010)
Cotton + Sorghum	Intercropping	-	Desert horse purslane, Field bind weed	92	24	Iqbal *et al.* (2007)
	Allelopathic extract	Wheat	Littleseed canary grass,Wild oat	2–16	2–6	Cheema *et al.* (2000
Rye	Cover crop	-	Common purslane, Pigweed	-	-	Nagabhushana *et al.* (2001)

Planting time influences the occurrence and manifestation of weed species. Thus, sowing time should be manipulated in such a way that ecological conditions for the germination of weed seeds are not met. In the north-western part of the Indo-Gangetic Plains, farmers advance wheat seeding by 2 weeks to get a head start over the noxious weed little seed canary grass and provide higher yield (Singh *et al.* 1999). Malik *et al.* (1988) reported more weed infestation in early/timely-sown chickpea than when sowing was delayed. Similarly, delayed sowing of lentil and chickpea reduced the infestation of *Orobanche* (Linke and Saxena 1989). However, this is not a viable approach in all cases as delayed sowing may also result in reduced yield. Sinha *et al.* (1988) reported that early sowing and closer row spacing reduced weed growth and increased dry matter accumulation, but also resulted in lower seed yield of pigeonpea. Lenssen (2008) reported that early planting of barley resulted in a small accumulation of weed biomass, and no weed seed production, while delayed planting resulted in decreased forage yield with high amounts of weed biomass and seed production, especially in ZT.

9.2.11. Nutrient and water management

Nutrients and water are te two major inputs influencing not only crop growth and productivity but also weed infestation. They often interact and influence each other's efficiency. Efficient management of nutrients and water is essential for managing weeds under CA systems. In fact, compared to conventional systems, a relatively different approach is required for nutrient and water management under CA. The level, amount and method of application of these inputs should be worked out to meet the crop requirement under no-till residue retained conditions.

The competitive interactions between crops and weeds get altered with increasing levels of soil fertility as both crops and weeds compete for the same nutrient pool. With added nutrients, resource use by weeds often increases more rapidly than by crops, resulting in a greater ability of weeds to compete for other resources. Nitrogen, the major nutrient for which the plants compete, should be banded close to the crop row, thus enhancing crop accessibility to the nutrient. Increasing rates of fertilizer application encourage more weed growth than crop growth if no weed control measure is followed (Sharma 1997). Under this situation, it is better to apply fertilizers at a lower rate than needed to maximize yields. Pre-sowing N fertilization can increase the competitive ability of the crop plant against weeds, particularly in crops with high growth rates at early stages. However, this effect is modulated by the type of weeds prevailing in a field. For example, in sunflower grown in Mediterranean conditions, a pre-sowing application of synthetic N fertilizer increased the suppression of late-emerging weeds such as lamb's quarter, black nightshade (*Solanum nigrum* L.) and common cocklebur (*Xanthium strumarium* L.) compared to a split application, i.e. 50% each at pre-sowing and top dressing (Paolini *et al.* 1998). In contrast, the same technique resulted in a competitive advantage for early-emerging weeds like wild mustard. Anticipation or delay of top-dressing N application in sugar beet increased crop competitive ability with dominance of late- or early-emerging weeds respectively (Paolini *et al.* 1999). Das and Yaduraju (2007) observed that an increasing N level decreased the infestation of little seed canary grass but had no effect on wild oat in wheat (Table 16). Inclusion of green manures not only adds nutrients and organic matter to the soil but also suppresses weed growth due to its dense foliage cover on the ground surface and the incorporation of existing weeds in the soil. In order to offset the likely initial setback to the ZT crop due to poor crop stand and vigour, it is advocated to use a 25% higher dose of nutrients, especially in crops like wheat (Sharma *et al.* 2012). Further, a greater proportion of N (up to 75%) can be applied as basal because top dressing of N may not be as beneficial especially under residue-retained and rainfed conditions.

In addition to fertilization, irrigation has a significant role in crop–weed competition. It offers selective stimulation to germination, growth and establishment of one plant over the others, and results in varying weed dynamics and competition in crops (Das and Yaduraju 1999). Dry weight of little seed canary grass was higher when wheat was irrigated at CRI and CRI+flowering stage than at other stages.

Table 16. Infestation of grassy weeds and yield performance of wheat as affected by irrigation and nitrogen (Das and Yaduraju 2007)

Treatment	**Population (no. m^{-2}) at 60 DAS**		**Dry weight (g m^{-2}) at 60 DAS**		**Grain yield (t ha^{-1})**
	Phalaris minor	***Avena ludoviciana***	***Phalaris minor***	***Avena ludoviciana***	
Irrigation regime					
CRI stage	14.4	3.3	21.8	6.3	3.15
CRI+tillering	19.3	3.0	18.4	5.4	3.53
CRI+ tillering + flowering	18.2	4.0	15.0	5.2	3.86
CRI + flowering	13.6	3.6	23.8	5.5	3.92
CRI+ tillering + flowering + dough	18.1	3.2	19.0	3.9	4.29
LSD (P=0.05)	NS	NS	6.66	1.41	0.38
N levels (kg ha^{-1})					
60	18.7	3.4	24.8	8.1	3.28
90	18.8	3.3	21.4	5.4	3.61
120	15.9	3.6	17.2	4.4	4.16
150	14.5	3.4	15.0	3.1	4.06
LSD (P=0.05)	3.34	NS	6.25	1.36	0.17

9.3. Mechanical measures

Farm mechanization plays a vital role for the success of CA in different agro-ecologies and socio-economic farming groups. It ensures timeliness, precision and quality of field operations; reduces production costs; saves labour; reduces weather risk under the changing climatic scenario; improves productivity, environmental quality and sustainability; and generates rural employment on on-farm and off-farm activities. Reduced labour and machinery costs are economic considerations that are frequently given as additional reasons to use CA practices. Compared to intensive tilled conventional rice–wheat system, ZT systems require much lesser energy and give higher energy output:input ratio as well as system productivity (Gangwar *et al.* 2006, Kumar *et al.* 2012). For example, Mishra and Singh (2012a) reported lower cost of cultivation, higher net returns and wider benefit:cost ratio in a ZT rice–wheat systems. Similarly in a ZT maize–wheat system, minimum energy usage, higher water productivity, higher net returns and enhanced energy input:output ratio were recorded by Ram *et al.* (2010).

9.3.1. Farm machinery

Conservation agriculture is essentially machine-driven and suitable farm machinery is required for land leveling, sowing, fertilization, weeding, irrigation, harvesting and other operations. Hence, the availability of suitable farm machineries is of paramount importance for adoption of this technology by farmers. For example, Farooq *et al.* (2007) noticed that access to ZT drills contributed towards the adoption pattern of the ZT wheat technology in Pakistan's Punjab province. `No-till' seed drill invented by Morton C. Swanson in 1975 was a great milestone in the history of modern day CA. It has allowed the farmers to sow seed without tilling the land. Direct drilling with ZT drill is a practice that addresses the issues of labour, energy, water, soil health, etc. However, this machine faces difficulties if crop stubbles are in high quantity, a situation that commonly occurs in CA systems. Harvesting of rice, wheat and many other crops like maize, sorghum, pegionpea, chickpea, greengram, blackgram, etc. is being done through combine harvester in many parts of India. In most regions, the crop residue lying on the soil surface is burnt so as to prepare the field for sowing of next crop. This is a very unscientific practice as it leads to environmental problem, loss of C and other essential nutrients. Despite some measures taken by different states and ban imposed by Supreme Court, burning is still the most common means of straw disposal.


Combine harvester

`Happy Seeder' technology—an improved version of the no-till seed drill and initially developed for direct drilling of wheat into rice residues (typically 5–9 t ha^{-1} of anchored and loose straw) in north-west India—is a recent novel approach which combines stubble mulching and seed-cum-fertilizer drilling functions. The stubble is cut and picked up in front of the sowing tynes, which engage almost bare soil, and deposited behind the seed drill as surface mulch. In addition to the benefits of direct drilling and retaining organic matter, the mulch also assists in moisture conservation and weed control. Observations from farmers' fields across Indian Punjab showed that the Happy Seeder (zero tillage) and rotavator (reduced tillage) are efficient methods for control of weeds as well as for *in situ* management of paddy straw (Kang 2013). The average reduction in the weed population in the happy seeder-sown wheat crop over the rotavator and farmer's practice was 26.5 and 47.7%, respectively. However, the reduction in weed population in the rotavator-sown crop was 29.3% over the farmer's practice (Singh *et al.* 2013). Advanced versions of the Happy Seeder, *viz.* turbo seeder, PCR planter and easy seeder are being developed for more efficient sowing and fertilizer placement. These machines could be used under CA systems both for seeding as well as managing weeds.

9.3.2. Land leveling

Happy seeder

Zero till drill

Laser land leveller with front loader

Laser land leveling, an integral component of CA, provides uniform moisture distribution to the entire field and ensures a proper crop stand and growth with reduced weed infestation. Unleveled fields frequently exhibit patchy crop growth with higher weed infestation. Compared to an unleveled field, weed management in a laser–leveled field is relatively easy, and requires less labour for manual weeding operations due to less weed infestation. Weed populations in wheat were recorded under precisely leveled fields (200 no. m^{-2}) compared to to traditional leveled fields (350 no. m^{-2}) (Jat *et al.* 2003). Precision land leveling may reduce up to 75% of the labour requirement needed for weeding operations (Rickman 2002).

9.4. Chemical weed management

The use of herbicides for managing weeds is becoming popular because they are cheaper than traditional weeding methods, require less labour, tackle difficult-to-control weeds, and allow flexibility in weed management. Herbicides are an integral part of weed management in CA. However, to sustain CA systems, herbicide rotation and/or integration of weed management practices is preferred as continuous use of a single herbicide over a long period of time may result in the development of resistant biotypes, shifts in weed flora and negative effects on the succeeding crop and environment. In CA, the diverse weed flora that emerges in the field after harvesting the preceding crop must be killed using non-selective herbicides like glyphosate, paraquat and 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 a conventional system, crop residues present at the time of herbicide application in CA systems may decrease the herbicide's effectiveness as the residues intercept herbicide droplets and reduce the amount of herbicide that reaches the soil surface. Proper selection of herbicide formulations for application under CA is necessary to increase their efficacy. For example, pre-emergence herbicides applied as granules may provide better weed control than liquid-forms 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, varies depending upon chemical properties and formulations. Herbicides with high vapour pressure, e.g. dinitroanilines are susceptible to volatilization from the soil surface. Climatic conditions and herbicide application methods significantly affect herbicide persistence under CA systems. Crop residues can intercept 15–80% of the applied herbicides which may result in reduced efficacy of herbicides in CA systems (Chauhan *et al.* 2012). Weed control by herbicide application was better in the CT system (80–96%) than in the ZT system (50–61%) (Chauhan and Opena 2012). Choosing an appropriate herbicide and timing of its application is critical in CA systems as weed control under no-till systems varies with weed species and herbicides used.

Pre-emergence herbicides may not be as efficient in controlling weeds in CA systems due to the presence of crop residues which can bind to soil-applied herbicides and favour the weed seedlings to escape the applied herbicides. For example, barnyard grass was fully controlled by pendimethalin and oxadiazon when applied on bare soil (without residue cover); however, some seedlings survived when these herbicides were applied in the presence of residue cover (Chauhan and Abugho 2012). For example, barnyard grass was fully controlled by pendimethalin and oxadiazon when applied on bare soil (without residue cover); however, some seedlings survived when these herbicides were applied in the presence of residue cover (Table 17).

Table 17. The effect of crop residue and herbicides on barnyard grass emergence (Chauhan and Abugho 2012)

Herbicide	**Residue amount (t ha^{1})**		
	0	**3**	**6**
Untreated	43.0	41.0	28.0
Oxadiazon 0.5 kg ha^{-1}	0.0	3.5	5.0
Oxadiazon 1.0 kg ha^{-1}	0.0	0.5	0.0
Pendimethalin 1.0 kg ha^{-1}	0.0	0.5	4.0
Pendimethalin 2.0 kg ha^{-1}	0.0	0.5	3.0

Several selective post-emergence herbicides, some of which are low dose and high-potency molecules, are now available to effectively manage weeds in major field crops like rice, wheat, soybean etc. under CA (Table 18). The effectiveness of post-emergence herbicides may be reduced by the presence of crop residues. Wolf *et al.* (2000) observed that the quantity of spray lodged on smooth pigweed (*Amaranthus hybridus* L.) was reduced by 38–52% by standing wheat stubble depending upon the spray travel speed. Post-emergence herbicides should be applied once the weeds become established, since the timing of weed emergence is less uniform in CA systems than in conventional-tilled systems.

10. Integrated weed management

Considering the diversity of weed problems in CA systems, no single method of weed control, viz. cultural, mechanical or chemical, provides the desired level of weed control. Therefore, a combination of different weed management strategies should be evaluated to widen the weed control spectrum and efficacy for sustainable crop production. The IWM system is not meant to replace 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 weed-free irrigation canals and bunds should be integrated for effective weed management. Weed control efficiency of applied herbicides and crop competitiveness against weeds could be improved by combining good agronomic practices, timeliness of operations, fertilizer and water management, and retaining crop residues on the soil surface. For example, effective ryegrass control (up to 97%) has been observed in a ZT stubble-retained system by using soluble herbicides and minimal disturbance seeders (Crabtree 1999). Similarly, integrating superior genotypes with a high seeding rate and early weed control lead to a 40% yield increase compared with the combination of weaker genotype, low seeding rate and delayed weed control (Harker *et al.* 2003). 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.

Table 18. Promising herbicides for weed control in different field crops under conservation agriculture

Herbicide	**Dose (g ha^{-1})**	**Time of application**	**Remarks**
a. Rice			
Pendimethalin	1000–250	6-7 DAS/DAT	Annual grasses and some broad-leaved weeds. Ensure sufficient moisture at the time of application.
Pyrazosulfuron	25–30	20–25 DAS/DAT	Annual grasses and some broad-leaved weeds
Azimsulfuron	35	20 DAS/DAT	Annual grasses and some broad-leaved weeds.
Bispyribac-sodium	25	15–25 DAS/DAT	Annual grasses and some broad-leaved weeds
Chlorimuron+metsulfuron	4	15–20 DAS/DAT	Annual broad-leaved weeds and sedges
2,4-D	500–750	20–25 DAS/DAT	Annual broad-leaved weeds and sedges
Fenoxaprop-p-ethyl	60–70	30–35 DAS/DAT	Annual grasses especially *Echinochloa* spp.
Fenoxaprop-p-ethyl+2, 4-D	60–70 + 500	20–25 DAS/DAT	Annual grasses and broad-leaved weeds
Fenoxaprop-p-ethyl+Almix	60–70 + 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
b. Wheat			
Pendimethalin	1000–1250	0–3 DAS	Annual grasses and some broad-leaved weeds. Ensure sufficient moisture at the time of application.
Clodinafop propargyl	60	25–30 DAS	Annual grasses specially wild oat
2,4-D	500–750	20–25 DAS	Annual broad-leaved weeds and sedges
Metribuzin	175–200	30–35 DAS	Annual grasses and broad-leaved weeds

Table continue...

Herbicide	Dose (g ha^{-1})	Time of application	Remarks
Sufosulfuron	25	25–30 DAS	Annual broad-leaved weeds and grasses
Sufosulfuron +metsulfuron	25 + 2	25–30 DAS	Annual grasses , broad-leaved weeds and sedges
Mesosulfuron+ idosulfuron	12 + 24	20–25 DAS	Annual grasses , broad-leaved weeds and sedges
Isoproturon +metsulfuron	1000 + 4	20–25 DAS	Annual grasses and broad-leaved weeds
c. Soybean			
Metribuzin	35–525	0–3 DAS	Annual grasses and broad-leaved weeds
Chlorimuron ethyl	6–9	15–20 DAS	Annual grasses, broad-leaved weeds and sedges
Fenoxaprop	80–100	20–25 DAS	Annual grasses
Fenoxaprop+Chlorimuron	80 + 6	20–25 DAS	Annual grasses and broad-leaved weeds
Imazethapyr	100	20–25 DAS	Annual grasses and broad-leaved weeds

Note: Non-selective herbicides like paraquat and glyphosate should be applied prior to sowing to kill existing weeds.

11. Herbicide-tolerant crops

Biotech crops have become the fastest adopted crop technology in the history of modern agriculture. Since commercialization in 1996, the biotech crop area has progressively grown for the last 17 years (Figure 7). However, compared to other biotech traits, herbicide-tolerance trait has contributed more towards the increased global biotech area. Weeds of different types emerge in the field; therefore farmers have to use several types of narrow-spectrum herbicides to control them. This weed control method can be very costly. 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.

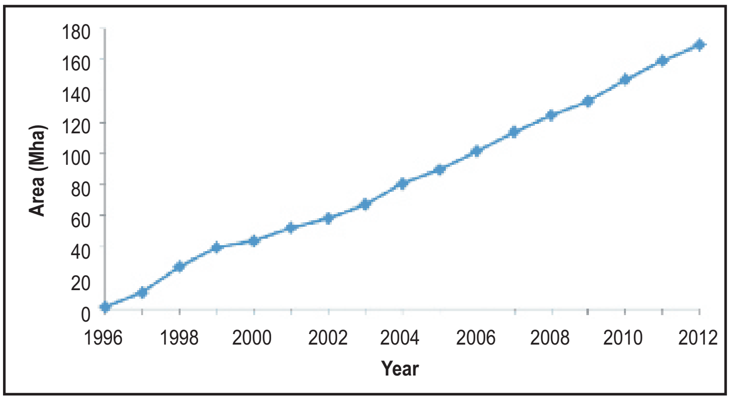

Figure 7. Global area of biotech crops (http://www.isaaa.org/resources/publications/briefs/44/executivesummary/pdf/Brief%2044%20-%20Executive%20 Summary%20-%20English.pdf dt.01.12.2014)

Several crops have been genetically modified for resistance to non-selective herbicides. These transgenic crops contain genes that enable them to degrade the active ingredient in an herbicide and render it harmless. 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 therefore easily control weeds during the entire growing season and have more flexibility in choosing times for spraying. Herbicide-tolerant crops (HTCs) offer farmers a vital tool in fighting weeds and are compatible with CA systems. HTCs of soybean, corn, canola and cotton are being grown on a large scale. In 2012, herbicide-tolerant soybean alone occupied 80.7 m ha, which is nearly half of the global biotech area (Table 19).

CA systems have been adopted on a large-scale worldwide; and the expansion in the area under CA was accelerated due to the introduction of HTCs. For instance, introduction of HT soybeans encouraged rapid adoption of CA practices in the United States (Ammann 2005). In fact, these two technologies have registered a double digit growth in area with one complementing the other. Weed management in ZT–sown HTCs is much easier and post-emergence application of non-selective herbicides like glyphosate provides a weed-free environment without harming the crop plant. This results in considerably less costs for different operations such as ploughing, sowing, fertilization as well as weed control. Farmers in developing countries can benefit from relatively higher yields with reduced costs by adopting such technologies. There is a need to address some of the technologies and apprehension about GM crops in general and HTCs in particular, for practicing CA-based technologies.

Table 19. Dominant herbicide-tolerant crops grown in the world (James 2012)

Herbicide-tolerant crops	Area (M ha^{-1})	% total biotech area
Soybean	80.7	47
Canola	9.2	5
Maize	7.8	5
Cotton	1.8	1
Sugarbeet	0.5	<1
Alfalfa	0.4	<1
Others	<0.1	<1
Total	100.5	61

Compared to selective herbicides, the use of non-selective herbicides in HTCs offers several potential advantages:

- Application of fewer herbicides to a crop
- Reduced number of sprays in a season

- Flexibility – possible to control weeds later in the plant's growth
- Saves labour and fuel because of less spraying
- Reduced soil compaction because of less spraying by tractors
- Ability to control weeds that previously could not be controlled in a particular crop because of the absence of a suitable selective herbicide
- Use of low toxicity compounds which do not remain active in the soil. This may help farmers to manage weeds without the need for environmentally-suspect herbicides
- Ability to use no-till or conservation-till systems, with consequent benefits to soil structure and organisms
- Excellent weed control and hence higher crop yields.

Glufosinate tolerant canola (*Brassica napus*) infested with wild oat

The potential for weed resistance to a specific herbicide is always a concern with herbicide programs, and this concern increases with HTCs in CA systems. For instance, many farmers in the USA have adopted CA with repeated use of glyphosate on glyphosate-resistant crops (Givens *et al.* 2009). Some HTCs are becoming volunteer weeds and causing segregation and introgression of herbicide-resistant traits in weed populations (Owen and Zelaya 2004). For example, oilseed rape transgenes can survive for several years even if all cultivars with the conferred trait are removed from the area (Beckie and Warwick (2010). There are also some other apprehensions that HTCs can lead to:

- Increased herbicide use
- Adverse effects on biodiversity
- Development of herbicide-resistant weeds due to over-reliance on a single herbicide or a group of closely-related herbicides. Horseweed (*Conyza Canadensis* (L.) Cronquist) has reportedly developed resistance to glyphosate in ZT roundup-ready corn–soybean rotations in the United States (Mueller *et al.* 2003)
- Gene-drift from HTCs to similar species may confer resistance to their wild relatives which can become a serious weed in the crop, constituting a new phenomenon of intensification, the 'transgenic treadmill' (Binimelis *et al.* 2009)

- Poor application of herbicides can cause serious damage to non-herbicide-tolerant crop cultivars in adjoining areas.

Therefore, HTCs 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.

12. Case studies

12.1. Feasibility of CA in black cotton soils

Farmers' of several northern Indian states have derived benefit of adopting CA components specially in wheat under rice-wheat system. While the central Indian farmers' are still practicing the conventional tillage to grow wheat under the same cropping system. Hence, a preliminary survey was conducted among the farmers of the adjoining localities of Jabalpur during 2012-13 to find out the reason of not practicing resource conservation technology to grow wheat. It was noted that very few farmers were adopting ZT for sowing of wheat after burning the stubbles of preceding rice crop. But, the farmers' were not even aware about conservation agriculture system retaining the standing crop residues in the field. They expressed serious doubt that it could be a feasible proposition of sowing and growing a good crop without removing the crop stubbles. With great difficulties four farmers' agreed to provide their lands for demonstrating the potential of CA technology only when they were assured that they will be compensated economically if the technology fails to perform. Accordingly wheat was sown using a `happy seeder', without tilling and removing the existing rice stubbles. Out of four, one farmer ploughed his land the next day out of his sheer disbelief and fear to conservation technology on the basis of the advice from his friends/other farmers'. However, the crop of the remaining three farmers' performed much better under CA than the conventional practice (Table 20). The herbicides used in these OFR trials, viz. 2,4-D, mesosulfuron + iodosulfuron, clodinofop + metsulfuron and mesosulfuron alone, were chosen on the basis of the weed flora prevailing in the concerned fields. Wheat crop had good emergence and stand establishment. Weed population in three conservation agriculture OFR trials were less compared to other field trials in which land was prepared by conventional cultivator and harrow. Major weeds were L*athyrus sativa, Vicia sativa, Chenopodium album, Medicago hispida* and *Melilotus alba* among broad leaved and A*vena* sp. (wild oat) and *Phalaris minor* among grasses. The herbicide controlled the weed flora effectively and increased yield of wheat as compared to the fields cultivated by conventional practice with no weed control measures. The post emergence application of herbicides controlled *rabi* weeds effectively and gave higher benefit:cost ratio. The result also showed higher grain yield and income, and lower production cost, resulting in sharp increase in benefit:cost ratio under CA system.

Table 20. Performance of wheat crop in farmers' field under conventional and conservation agriculture practices in Panagar (Jabalpur) locality

Weed control measure	Weed count (no. m^{-2})	Dry weight (g m^{-2})	Grain Yield (t ha^{-1})	Total income (₹ ha^{-1})	Cost of production (₹ ha^{-1})	B:C ratio
a. under conventional practice						
Chemical weed control	27.9	13.6	2.90	40963	19188	2.12
Farmer's Practice	69.9	54.8	1.80	26294	18000	1.46
b. under conservation agriculture						
Chemical weed control	33.3	20.1	3.17	45554	16906	2.70
Farmer's Practice	70.0	57.8	2.00	29000	15500	1.87

A field day was organized to show the above performance of wheat in the demonstrated fields. All the farmers' visiting the demonstration sites expressed their satisfaction and happily wanted to provide their lands if any more such demonstration is to be conducted in future. Subsequently, performance of moongbean under CA was demonstrated in 3 farmers' fields during summer season of 2013 to reinforce the confidence among the farmers' towards CA technology (Table 21). Result revealed that CA with chemical weed control measure was effective and gave a seed yield of 1.30 t/ha, as compared to 0.73 t/ha under conventional practice; and provided an additional net return of ` 28975/ha with higher B:C ratio over farmers practice. It is a matter of pleasure that many farmers' are now expressing their willingness to adopt the technology and enquiring about the availability and price of the `happy seeder.'

Table 21. Performance of moongbean crop in farmers' field under conventional and conservation agriculture practices in Panagar (Jabalpur) locality

Treatments	Weed count (no. m^{-2})	Weed dry weight (g m^{-2})	Grain yield (t ha^{-1})	Cost of production (₹)	Gross return (₹)	B:C ratio
Conservation agriculture	44.0	28.2	1.30	19850	58395	2.94
Conventional agriculture	100.6	65.6	0.73	23400	32970	1.41

Wheat Chickpea

Performance of crops in farmer's field under CA in Panagar Locality (Jabalpur, MP)

12.2. Weed dynamics and soil health

A long-term experiment was initiated during kharif 2012 to monitor weed dynamics, crop productivity, and soil health parameters in a rice-wheat-moongbean cropping system under conservation agriculture system. The treatments consist of five crop establishment methods in main plots, viz. (i) CT(DSR)-CT(wheat)-ZT(greengram) without crop residue recycling, (ii) CT(DSR)-CT(wheat)-ZT(greengram) with crop residue recycling, (iii) ZT(DSR)+S-ZT(wheat)-ZT(greengram) without crop residue recycling, (iv) ZT(DSR)-ZT(wheat)-ZT(greengram) with crop residue recycling, (v) Transplanted rice (TPR)-CT(wheat); and three weed control measures in sub plots, viz. repetitive use of herbicides, rotational use of herbicides, and unweeded. *Sesbania* seeds were broadcasted in all DSR plots for brown manuring at 25 DAS. All ZT plots received pre-sowing application of non-selective herbicides.

Different crop establishment techniques significantly influenced the emergence of different weed flora, except *E. colona* and *D. retroflexa,* as well as total weed population and dry matter accumulation at 60 days after sowing (DAS) (Table 22). Significantly lower density of *C. iria* was recorded under ZT (DSR)+*Sesbania* with or without retention of previous season crop residue compared to CT (DSR) or TPR. Whereas, ZT (DSR)+ *Sesbania* with or without crop residue recorded higher population of C. *axillaris.* CT (TPR) recorded lowest population of *P. minima* and *D. retroflexa* during rice. So far as the total weed population and weed dry matter accumulation is concerned, lowest total weed density was recorded with ZT (DSR)+ *Sesbania* without residue retention, but it was statistically at par with TPR. However, CT (DSR) being at par with ZT (DSR) without retention of residue of previous season crop recorded significantly lower weed dry matter production. Amongst the weed control measures, continuous use of bispyribac + pre-sowing non-selective herbicides in ZT recorded significantly lower weed population and weed dry matter compared to weedy check. Highest grain yield of rice was recorded with CT-TPR (3.42 t/ha) which was statistically similar to ZT-DSR with residue recycling (3.14 t/ha). Amongst weed control treatments, continuous use of bispyribac-sodium @ 25 g/ha at 25 DAS being at par with rotational use of herbicides, recorded significantly higher rice yield compared to weedy check.

Different crop establishment methods influenced significantly the distribution of weed flora in wheat. Significantly lower population of *P. minor* and *C. album* was noticed in ZT (DSR)-ZT (wheat), statistically it was at par with TPR-CT (wheat) over CT (DSR)-CT (wheat). On the other hand, there was lower population of *A. ludoviciana* in TPR-CT (wheat) and CT (DSR)-CT (wheat), respectively. However, CT (DSR)-CT (wheat) recorded significantly lower population of *M. denticulata*. Whereas significantly lower weed population and weed dry matter was recorded with CT (wheat) sown after CT (TPR/DSR). Amongst weed control measures, significantly lower population and weed dry biomass

Table 22. Weed density and weed dry matter production in rice as influenced by different tillage systems and weed management measures

	Treatments	Density (No. m^{-2})					Weed dry weight (g m^{-2})	Grain yield (t ha^{-1})
		E. colona	*C. iria*	*P. minima*	*C. axillaris*	Total weed		
	Tillage and crop establishment							
M$_1$	CT(DSR)+S– CT(wheat)– ZT (greengram)	1.1 (0.7)	3.8 (13.9)	1.5 (1.7)	1.3 (1.3)	5.0 (24.3)	3.4 (10.7)	2.34
M$_2$	CT(DSR)+R+S – CT(wheat) +R – ZT(greengram)+R	1.2 (0.9)	3.8 (13.9)	1.3 (1.1)	1.2 (0.7)	4.5 (19.7)	5.8 (31.9)	2.96
M$_3$	ZT(DSR)+S – ZT(wheat) – ZT (greengram)	1.1 (0.7)	2.6 (5.7)	0.9 (0.3)	1.6 (1.7)	3.3 (10.3)	4.3 (17.9)	3.08
M$_4$	ZT(DSR)+R+S – ZT(wheat) +R – ZT(greengram)+R	1.0 (0.5)	2.9 (7.9)	1.5 (1.7)	2.0 (3.1)	4.2 (17.1)	5.4 (28.6)	3.14
M$_5$	CT(TPR) – CT (wheat)	0.9 (0.3)	3.3 (10.3)	0.7 (0.4)	1.9 (3.1)	3.9 (14.7)	5.0 (24.5)	3.42
	LSD (P=0.05)	NS	0.56	0.43	0.64	0.90	0.10	0.39
	Weed management							
S$_1$	Weedy check	1.1 (0.7)	6.4 (40.4)	0.9 (0.1)	2.6 (5.7)	7.3 (52.7)	10.2 (103.5)	2.41
S$_2$	Repetitive use of herbicide	1.3 (0.9)	1.0 (0.5)	1.6 (2.0)	1.0 (0.4)	2.3 (4.7)	2.4 (5.2)	3.35
S$_3$	Herbicide rotation	0.8 (0.1)	2.5 (5.7)	1.1 (0.7)	1.2 (0.9)	3.0 (7.9)	3.5 (11.7)	3.20
	LSD (P=0.05)	0.37	0.43	0.29	0.53	0.21	0.47	0.19

M$_1$-M$_5$: Main Plot, S$_1$-S$_3$: Sub Plot, DSR – direct-seeded rice, TPR – transplanted rice, S – *Sesbania* brown manuring, CT – conventional tillage, ZT – zero tillage and R – residue. Data subjected to $\sqrt{x+0.5}$ transformations. Figures in parentheses are original values.

were recorded with recommended herbicide + pre-sowing non-selective herbicide in ZT (Table 23). The wheat grown after direct seeded rice combined with either crop residue incorporation or retention significantly produced higher grain yield of wheat in both CT/ ZT (wheat), and these were statistically higher than that recorded in the conventional treatment of TPR-CT (wheat). Amongst weed control treatments, application of recommended herbicides with and without manual weeding produced significantly higher grain yield over weedy check.

The crop establishment techniques showed significant effect on soil health parameters. In absence of crop residue recycling, the rate of soil respiration was significantly higher in ZT-ZT than in CT-CT and puddle-CT systems. Crop residue recycling increased soil respiration rate in both ZT-ZT and CT-CT systems; and the tillage systems did not differ significantly in terms of soil respiration rate when crop residues were recycled (Figure 8). There was no effect of weed control measures on rate of soil respiration.

Table 23. Weed density and weed dry matter production in wheat as influenced by different tillage systems and weed management measures (2012-13)

	Treatment	Weed density (No. m^{-2})					Weed dry weight (g m^{-2})	Grain yield (t ha^{-1})
		P. minor	*A. ludoviciana*	*M. denticulata*	*C. album*	Total		
	Tillage and crop establishment							
M_1	CT(DSR)+S – CT(wheat) – ZT (greengram)	6.4 (40.4)	1.7 (2.3)	9.3 (85.9)	3.9 (14.7)	12.4 (153.2)	8.2 (66.7)	3.86
M_2	CT(DSR)+R+S–CT(wheat) +R-ZT(greengram)+R	6.0 (35.5)	2.0 (3.5)	10.5 (109.7)	2.6 (6.2)	12.8 (163.3)	8.0 (63.5)	4.07
M_3	ZT(DSR)+S – ZT(wheat) – ZT (greengram)	2.5 (5.7)	2.8 (7.3)	21.1 (444.7)	1.2 (0.9)	24.6 (604.6)	8.6 (73.4)	3.51
M_4	ZT(DSR)+R+S – ZT(wheat) +R – ZT(greengram)+R	1.6 (2.0)	2.6 (6.2)	22.5 (505.7)	0.9 (0.3)	23.3 (542.3)	12.1 (145.9)	3.84
M_5	CT(TPR) – CT (wheat)	3.8 (13.9)	1.6 (2.0)	8.2 (66.7)	3.8 (13.9)	12.0 (143.5)	6.8 (45.7)	3.58
	LSD (P=0.05)	1.0	1.1	1.8	1.4	2.60	5.4	0.25
	Weed management							
S_1	Weedy check	4.5 (19.7)	2.0 (3.5)	19.41 (375.8)	3.0 (8.5)	21.1 (444.7)	14.7 (215.5)	3.14
S_2	Repetitive use of herbicide	3.9 (14.7)	2.3 (4.7)	10.59 (109.7)	2.8 (7.3)	13.2 (173.7)	4.2 (17.1)	4.44
S_3	Herbicide rotation	3.7 (13.1)	2.0 (3.5)	12.9 (165.9)	1.7 (2.3)	16.7 (278.3)	7.3 (52.7)	3.74
	LSD (P=0.05)	1.0	0.74	1.07	0.55	1.15	3.9	0.47

M_1-M_5 : Main Plot, S_1-S_3 : Sub Plot, DSR – direct-seeded rice, TPR – transplanted rice, S – *Sesbania* brown manuring, CT – conventional tillage, ZT – zero tillage and R – residue. Data subjected to $\sqrt{x+0.5}$ transformations. Figures in parentheses are original values.

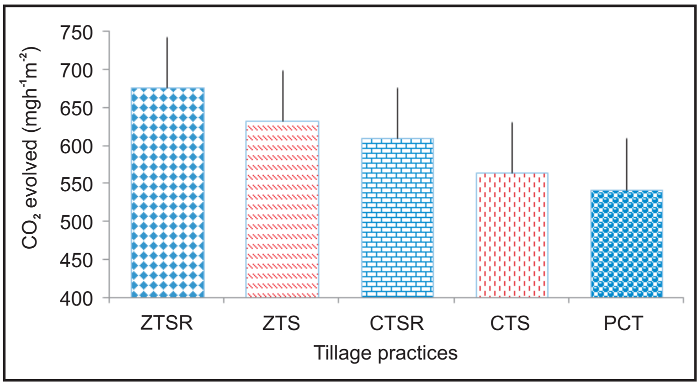

Figure 8. Effect of crop residues and tillage practices on soil respiration under wheat (CT: conventional tillage, ZT: zero tillage, S: *Sesbania* brown manuring, R: crop residue recycling and PCT: puddled/conventional tillage)

The tillage and crop residue management practices significantly affected the soil organic carbon (OC) content (Figure 9). The highest value of the mean OC content was 0.51% under ZTSR followed by 0.49, 0.48, 0.45 and 0.43% under ZTS, CTSR, CTS and PCT treatments, respectively. Although the magnitude of OC content increased with the addition of preceding crop residues, the differences between ZTSR and ZTS, and between CTSR and CTS were not significant. Similarly, no difference in this regard was noticed between CTSR and ZTSR treatments. However, there was significant difference between ZTSR and CTS treatments. This indicated that, compared to conventional practice, there was significant gain in soil organic carbon pool only when the complete conservation package of ZT along with crop residue recycling was adopted. Simply shifting the practice from CT to ZT, or mere recycling of crop residue under conventional tillage system may not provide the desired benefit in short term.

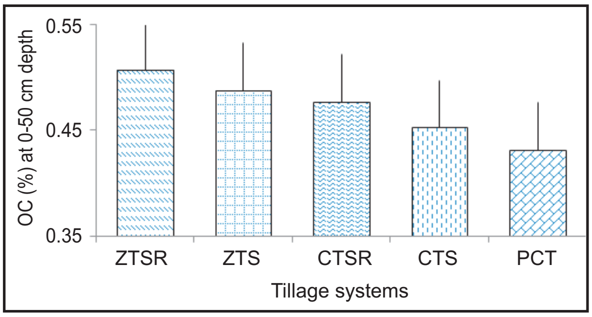

Figure 9. The organic carbon content in the soil as influenced by tillage and residue recycling practices (CT: conventional tillage, ZT: zero tillage, S: *Sesbania* brown manuring, R: crop residue recycling, PCT: puddled/ conventional tillage)


Performance of DSR under CA


Performance of DSR under CT

Performance of wheat under CA

Performance of DSR under CT

Performance of Mungbean under CA

Performance of Urdbean under CA

13. Constraints

Conservation agriculture is not a panacea to solve all agricultural production constraints but offers potential solutions to break productivity barriers, and sustain natural resources and environmental health. Despite several benefits, the adoption of CA systems by farmers in developing countries is still in its infancy as they require a total paradigm shift from conventional agriculture with regard to crop management (Table 24). CA technologies are essentially herbicide-driven, machine-driven and knowledge-driven, and therefore require vastly-improved expertise and resources for adoption in large areas. For wider adoption of CA, there is an urgent need for researchers and farmers to change their mindset and explore these opportunities in a site- and situation-specific manner for local adaptation.

Table 24. Two sides of the conservation agriculture system

Payoffs	Trade-offs
• Timeliness of operations • Reduced soil erosion • Water conservation • Improved soil health • Reduced fuel and labour costs • Reduced sediment and fertilizer pollution in lakes and streams • Carbon sequestration • Climate smart production practices	• Mindset: transition from conventional farming to no -till farming is difficult • Relatively knowledge intensive • CA equipment not available locally and adds to cost for transport • Reliance on herbicides and their efficacy • Prevalence of weeds, disease and other pests may shift in unexpected ways • Reduced crop yield in initial year if not properly practiced • Need to refine nutrient and water management practices

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

Several factors including bio-physical, socio-economic and cultural limit the adoption of CA by resource-poor farmers. The current major barriers to the spread of CA systems are (i) competing use of crop residues in rainfed areas, (ii) weed management strategies, particularly for perennial species, (iii) localized insect and disease infestation, and (iv) likelihood of lower crop productivity if site-specific component technologies are not adopted. In addition to these there are several other factors restricting the adoption of CA technologies in India (Table 25).

Table 25. The nature of constraints towards adoption of CA technologies in India.

Technical	• Non-availability of quality drill • Lack of regular monitoring of machines • Lack of training/ capacity building • Spare parts are not available locally • Lack of local manufacturers of machines
Extension	• Lack of extension support from state extension agencies • Lack of extension literature • Lack of attention by mass media • Lack of knowledge of extension agencies • Inadequate extension facility at disposal of input agencies • Lack of cooperation from fellow farmers
Financial	• Lack of credit facilities • Lack of money to buy new machines and inputs • No subsidy on machines • High cost of drill

Source: Meena and Singh (2013)

14. Conclusions

CA is a complex suite of resource-efficient technologies. It is possible to achieve the same or even higher yields with CA compared with CT. Altering tillage practices changes the depth of weed seeds in the soil, which play a role in weed species shifts and affect the efficacy of control practices. ZT systems cause a shift in weed flora, and may result in emergence of perennial weeds like purple nut sedge, bermudagrass and Johnson grass in most crops; and others like cheeseweed mallow and toothed dock in wheat. Restricting tillage also reduces weed control options and increases reliance on herbicides; consequently, evolvement of weed resistance to herbicides has become a serious and escalating problem for many CA farmers worldwide. The use of HT crops further aggravates the situation. ZT along with residue has beneficial effects on soil moisture, temperature moderation and weed control. 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 term.

15. Future outlook

The conventional agriculture-based crop management systems are gradually undergoing a paradigm shift from intensive tillage to reduced/zero-tillage operations as a result of the success and benefits of ZT wheat. The need of the hour now is to infuse new technologies for further enhancing and sustaining the productivity as well as to tap new sources of growth in agricultural productivity. The adoption of CA offers avenues for much needed diversification of agriculture, thus expanding the opportunities for cultivation of different crops during different seasons in a year. The prospects for introduction of sugarcane, pulses, vegetables etc. as intercrop with wheat and winter maize provide good avenues for further intensification and diversification of rice-wheat system.

Weed management research is lacking under conditions of CA. Therefore, development of integrated weed, disease or pest control strategies under CA systems is of paramount importance. Efforts are needed to understand weed, disease and insect responses to ZT soil and microclimate conditions on a long-term basis. Research should be conducted on soil biological aspects and the rhizosphere environment under contrasting soils and crops with particular emphasis on optimizing fertilizer management. Other areas of research includes machinery development for local farming systems, sowing into crop residues, understanding herbicide performance in crop residues with reduced tillage, changes in nutrient cycling and nitrogen demand, leaf and root diseases, etc. More focus is required on the influence of residue and weed management components.

Since herbicides cannot be eliminated from no-tillage, crop management, degradation pathways, adsorption–desorption and transport processes of herbicides are important research areas. Further, over-reliance on herbicides in a CA system is a concern from an environmental point-of-view. A major research effort in this area should be towards developing economically-viable strategies to prevent and manage herbicide resistance. Inclusion of allelopathic crop cultivars for managing weeds in the CA systems could be a strategy to avoid development of herbicide resistance. Crop cultivars differ significantly in their ability to inhibit the growth of certain weed species. To date, no progress has been made in understanding the genetics of crop allelopathic activity. However, more research is needed to thoroughly understand the genetic control of allelopathic activity. Several genes might be involved in regulating the production and exudation of allelochemicals. Concerted efforts using advances in plant biotechnology will help to unveil the genetics of this trait. A breeding program to transfer the allelopathic genes into modern cultivars to enhance their allelopathic activity for weed suppression may help to reduce over reliance on herbicides.

There is a need for analysis of factors affecting adoption and acceptance of no-tillage agriculture among farmers. A lack of information on the effects and interactions of minimal soil disturbance, permanent residue cover, planned crop rotations and integrated weed management, which are key CA components, can hinder CA adoption. This is because these interactions can have positive and negative effects depending on regional conditions. The positive impacts should be exploited through systems research to enhance CA crop yields. Information has mostly been generated on the basis of research trials, but more on-farm-level research and development is needed. For adoption of CA it is not enough to be aware with such technologies in view of their often non-compatibility with the existing practices. For example, some CA technologies like ZT, laser land-leveling, crop residues retention, prevention of residue burning practices prior to sowing, etc. are a radical departure from existing farming practices. Hence, farmers' involvement in participatory research and demonstration trials can accelerate adoption of CA, especially in areas where CA is a new technology.

About 57% of Indian rural households keep livestock as one component of their livelihood strategy. Traditionally crop residues are removed from the field for bedding and feed for those huge livestock population. In north-western India, one of the reasons of the success of ZT-wheat is that the additional residue requirements for this practice do not compete with livestock production, as the straw from rice, the crop widely grown before wheat, is not used as feed in this region and is generally burnt in the field itself. While the rice straw is preferred as livestock feed in the eastern part of Indo-Gangetic Plains, where ZT technologies have not yet been widely adopted. Hence, there is need to evolve strategies to harmonize competing uses of crop residues for adoption of CA.

Globally, 95% of the total CA area is under rainfed condition. In contrast to this, in spite of about 65% of its total arable land under rainfed/dry-land situation, in India adoption of CA so far took place mainly in irrigated farming systems. A comprehensive survey is needed to find out the issues resisting the adoption of resource conservation technologies under different agro-ecological regions of the country; and accordingly suitable strategies are to be formulated to address those bottlenecks by following the bottom-up approach for wider adoption of CA across the country.

16. References

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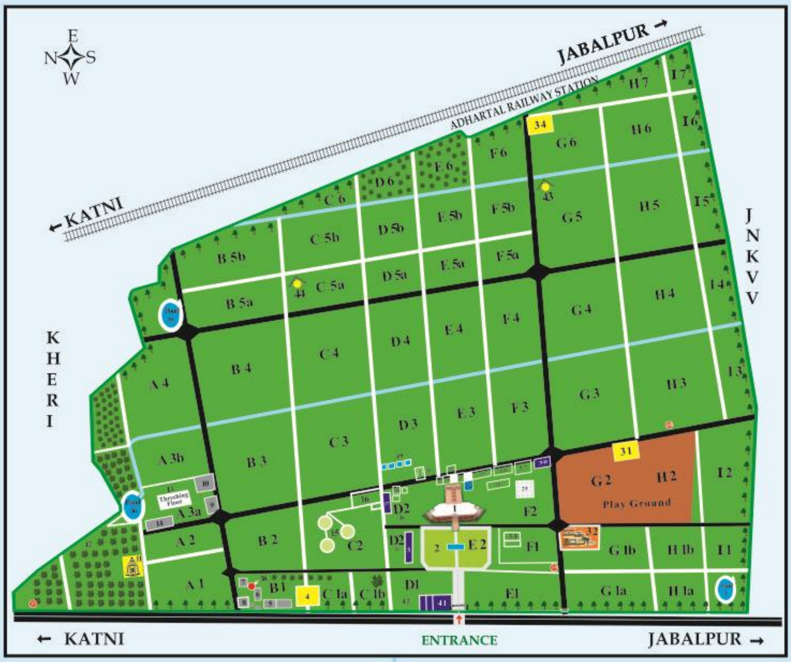
निदेशालय परिसर मानचित्र
DWR CAMPUS MAP



प्रशासनिक भवन	1	Administrative Building
फव्वारा एवं उद्यान	2	Fountain & Lawn
कार पार्किंग	3	Car Parking
प्रक्षेत्र भण्डार - 1	4	Farm Store-1
कार्यशाला	5	Workshop
ट्रैक्टर शेड	6	Tractor Shed
प्रक्षेत्र अनुभाग	7	Farm Section
मनोरंजन सदन	8	Recreation Club
प्रक्षेत्र भण्डार - 2	9	Farm Store-2
वर्मीकम्पोस्ट ईकाई	10	Vermicompost Unit
बागदाना बाबा मंदिर	11	Bagdana Baba Temple
बागान	12	Orchard
खलिहान	13	Threshing Floor
उपकरण शेड	14	Implement Shed
फेस सुविधा	15	FACE Facility
कंटेनमेंट सुविधा	16	Containment Facility
फील्ड प्रयोगशालायें	17	Field Laboratories
इनसेक्टरी	18	Insectory
मत्स्य संवर्धन कुण्ड	19	Fish Culture Pond
लाईसीमीटर	20	Lysimeter
रिप्रोग्राफिक यूनिट	21	Reprographic Unit
ओ.टी.सी. यूनिट	22	OTC Unit
कार्बन डाय ऑक्साइड चैम्बर	23	CO_2 Chamber
केन्द्रीय भण्डार	24	Central Store
पॉली हाउस	25	Poly House
नेट हाउस - 1	26	Net House-1
जलीय प्लेटफार्म	27	Aquatic Platform
नेट हाउस - 2	28	Net House-2
खरपतवार केफेटेरिया	29	Weed Cafeteria
विद्युत उपकेंद्र	30	Electric Substation
क्रीडांगन	31	Play Ground
निदेशक आवास	32	Director's Residence
जलीय खरपतवार हौज़	33	Aquatic Weed Tank
फायटोरेमेडियेशन इकाई	34	Phytoremediation Unit
तालाब - 1	35	Pond-1
तालाब- 2	36	Pond-2
ट्यूब वैल नं. 3	37	Tube Well No. 3
ट्यूब वैल नं. 2	38	Tube Well No. 2
ट्यूब वैल नं. 1	39	Tube Well No. 1
ट्यूब वैल नं. 4	40	Tube Well No. 4
सुरक्षा चौकी	41	Security Office
विक्रय केन्द्र एवं एस बी आई एटीएम	42	Sale Counter & SBI ATM
पर्यवेक्षण टॉवर- 1	43	Watch Tower-1
पर्यवेक्षण टॉवर - 2	44	Watch Tower-2
दुपहिया स्टैण्ड	45	Two Wheeler Stand
तालाब- 3	46	Pond-3

भा कृ अनु प - खरपतवार अनुसंधान निदेशालय

ICAR - Directorate of Weed Research