Vol. 21, No. 1, pp. 222-246 (2021)
Journal of Agricultural Physics
ISSN 0973-032X
http://www.agrophysics.in

Special Issue Article

Weed Dynamics and Management in Conservation Agriculture

R.S. CHHOKAR[1]*, T.K. DAS[2], V.K. CHOUDHARY[3], ANKUR CHAUDHARY[4], RISHI RAJ[2], A.K. VISHWAKARMA[5], A.K. BISWAS[5], G.P. SINGH[1] AND S.K. CHAUDHARI[6]

[1]*ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana*
[2]*ICAR-Indian Agricultural Research Institute, New Delhi*
[3]*ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh*
[4]*CCS Haryana Agricultural University, Hisar, Haryana*
[5]*ICAR-Indian Institute of Soil Science, Bhopal, Madhya Pradesh*
[6]*Krishi Anusandhan Bhawan II, Indian Council of Agricultural Research (ICAR), New Delhi*

ABSTRACT

The large-scale benefits of conservation agriculture (CA) have resulted in shift from conventional tillage to conservation tillage. This shift in tillage practice has also resulted in the shift in weed flora as well as weed management strategies for sustainable crop production. The weed shift in CA is being realized mainly due to adoption of no tillage, crop residue retention and crop rotation. Adoption of no-tillage practices increases the infestation of small seeded and perennial weeds and concentrates weed seeds in upper soil layers. The adoption of no-till wheat under rice-wheat system increases the infestation of broad-leaved weeds (*Rumex dentatus*, *Medicago denticulata, Sonchus oleraceous*) but decreases the infestation of *Phalaris minor*. Similarly, the adoption of no-till direct seeded or transplanted rice has shown abundance of water logging sensitive weeds such as *Trianthemaportul acastrum*, *Dactyloctenium aegyptium*, *Digitaria sanguinalis*, *Cyperus rotundus* and *Digera arvensis* and, which are virtually not observed in transplanted puddled rice. Weed management is really a challenge during the transition phase of CA in crops having restricted post-emergence herbicide options. The success of CA system depends on the efficient weed management with usage of herbicides as pre-planting (non-selective) and post-emergence (selective) options. The pre-plant non-selective herbicides such as glyphosate, glufosinate and paraquat will remain the key weed control tool in CA. The efficacy of pre-emergence herbicides in CA can be reduced due to their interception with crop residue mulch. Proper selection of herbicide, time and method of application as well as spray volume can improve the efficacy of pre-emergence herbicide in CA. However, the over reliance on herbicides alone is not desirable and will lead to shift in weed flora towards the tolerant and resistant ones, hence removal of escaped weeds has been advocated to avoid such situations. In CA system, the absence of tillage, which is otherwise utilized for weed control, presents challenges of designing suitable alternative weed management strategies involving crop plants competitiveness against weeds. Several cultural practices which can be useful are adjustment in crop row spacing, orientation, seeding density and sowing time, and use of competitive crop cultivars, residue mulching, diversified crop rotation, weed seed harvest, allelopathy and cover cropping. The integration of non-chemical and chemical weed management tools has to be utilized as the potential strategy for sustainable weed management in CA.

Key words: Conservation agriculture, herbicide, mulching, tillage, weed shift

*Corresponding author, Email: rs_chhokar@yahoo.co.in

Introduction

Weed infestation is a continuous problem in crop production and is highly influenced by the crop production practices followed (*i.e.*, crop rotation, tillage, fertilization, row spacing, herbicides, *etc*.), the soil characteristics and environmental conditions (Das, 2008). For long time tillage has been a major weed management tool in conventional agriculture system. However, intensive tillage in long run is not a sustainable practice as it degrades the soil resource as well as increase the cost of production. The advent of effective herbicides eliminated the need for tillage or mechanical weed control and made the way for adoption of no-tillage or conservation agriculture (CA) systems. The adoption of CA systems is globally increasing due to many advantages, such as conservation of the soil and water resources, improvement in soil fertility and crop productivity, as well as the saving in labour, energy and cost expenditure (Giller *et al.*, 2009; Govaetrs *et al.*, 2009; Powlson *et al.*, 2014; Bhattacharyya *et al.*, 2015; Das *et al.*, 2014, 2020a). The three components of CA system, i.e. minimum soil disturbance/tillage, soil surface cover with retention of crop residue and implementation of diversified crop rotations, have led to wide variations in germination, emergence, growth and type of weeds (Nichols *et al.*, 2015; Ball, 1992). The differential weed ecology and management in CA than in conventional agriculture may result in a shift in weed dynamics.

Weed composition is dynamic and changes with place, time and management practices. There are numerous factors such as climate, soil, nature of cropping system and management practices that influence the infestation of particular weed flora (Fried *et al.*, 2008; Fried *et al.*, 2012; Gaba *et al.*, 2014; Susha *et al.*, 2018). The reduction in the abundance of a particular weed species due to management practice will lead to increased infestation of other type of weed flora. Agronomic practices recognized as integral part of agro-ecosystem and acts as "filter" that either allow or constrain the growth and infestation of specific weed flora present in weed species pool in a niche (Cardina *et al.*, 2002; Navas, 2012). Despite a number of advantages of CA, weeds are a major threat to large scale adoption of CA (Derksen *et al.*, 2002; Farooq *et al.*, 2011; Baghel *et al.*, 2018, 2020). In general, weed diversity is increased under CA, due to adoption of crop rotation, as specific type of weed flora selectively invades a particular type of crop (Clements *et al.*, 1994; Buhler *et al.*, 1997). Further, more accumulation of weed seed in upper soil under CA relative to mould board plow or deep inversion system also allow/favour more infestation of weeds. The weed ecology and management under CA and conventional agriculture are considerably different. In CA systems, presence of crop residues on the soil surface may influence soil temperature and moisture regimes that affect weed seed germination and emergence patterns over the growing seasons. In CA, weeds emergence, seed bank composition, distribution, dispersal mechanisms, diversification, growing patterns, dry biomass accumulation and competition trends are complex and differ from conventional systems. Therefore, alternate, feasible and efficient weed management is necessary to minimize the weed severity. The CA system changes the pattern of tillage, planting system and other management practices, and also alters the environment resulting in a shift in weed flora. Long-term adoption of CA alters the weed flora from seasonal/annual to perennial weeds especially grasses. The initial adoption of CA changes the weed flora composition and increases their abundance and subsequent adoption of weed management practices may reduce the weed infestation (Choudhary *et al.*, 2015). Mtambanengwe *et al.* (2015) reported that long-term adoption of CA with appropriate weed management minimized the weed density by 6-51% in CA over conventional tillage (CT).

As the CA provides favourable micro-climate for germination and the emergence of weeds associated with high moisture and thermo moderating regime due to presence of residue, it results in increased weed severity, which is a major hurdle in the adoption of CA. Adoption of non-traditional weed management *i.e.* weed seed harvest and weed seed predation have been potential options in reducing weed seed bank and emergence. Likewise, allelopathy and thermal weed control are a new technique in modern weed management under CA. This paper updates the current emerging weeds under CA based cropping systems in India along with management perspectives.

Weed Dynamics in CA and CT system

Conservation agriculture favors more diverse weed flora with greater volume of weed seeds in upper soil horizon or close to the surface relative to conventional system, where rotation of crops is not generally followed and residue is burnt/ removed or incorporated with intensive tillage operation. However, weeds remain a problem in CA only during the initial years, as with passage of time loss of seed bank occurs due to more seed predation and unrestricted germination. So, agronomic practices should be adopted strategically to reduce heavy infestation or high weed pressure during initial years. However, conservation tillage may encourage establishment of perennial weed by not burying/destroying perennial reproductive structures i.e. tubers or nut and rhizomes to deeper depth. Continuous adoption of CA based cropping system is likely to influence weed dynamics and may result in greater emergence of perennial weeds like *Cyperus rotundus*,*Cyperus esculentus*,*Cynodon dactylon* and *Sorghum halepense.* Further, it also restricts tillage/interculture based options for weed control and likely to increase reliance on herbicides (Sharma and Singh, 2014). Further, the composition and relative time of emergence of weed species differ between CA systems and soil inversion based CT systems. Temperature and light incidence, varying on soil surface due to residue retention could also influence weed species dormancy and emergence.

Thus, crop production based on adoption of three principles of CA can alter the soil environment and lead to a major change in weed flora as well as weed management practices. The effect of three components of CA on weeds is being presented in the following sections.

Effect of tillage on weed dynamics and diversity

In conventional agriculture system among various field operations, tillage is the most energy consuming operation employed to prepare fine seed bed, residue incorporation, planting, and herbicide incorporation. Tillage works as primary cause of the vertical distribution of weeds by uprooting, destruction of food storage organs, burying deep and mixing in the soil (Sherestha *et al.*, 2002). Repeated inversions of soil destroy the establishment of weed propagules in the plow zone, while reduction in an inversion of soil shifts weed communities from annual dicots to small-seeded annual and perennial grasses (Choudhary *et al.*, 2015), and minimizes the weed seed bank. Minimum tillage curtailed 40% of weed seeds of *Ipomoea* sp. over CT (Mashavakure *et al.*, 2019). Non-inversion of soil possibly allowed the weed seeds to accumulate and remain dormant. This becomes active when comes across favourable condition, and weed complexity of the matrix formed (Santín-Montanyá *et al.*, 2016). In no-till systems, seeds of weeds and volunteer crops are frequently deposited in the first few centimeters of top soil. Continuous ZT in rice-wheat and maize-wheat systems had resulted in the lowest viable seed density as compared to CT system (Nandan *et al.*, 2020). The reduction in tillage intensity resulted in more weed diversity (Nandan *et al.*, 2018). Further, contribution from broad-leaved and narrow-leaved weeds toward total weed biomass was more pronounced in ZT conditions compared to the CT rice-wheat system (Nandan *et al.*, 2018). Increased weed diversity implies more competitive niche with diverse weed life histories and consequently reduced the opportunities favouring presence of difficult to control weeds or incidence of herbicide resistance (Miyazawa *et al.*, 2004; Gaba *et al.*, 2014).

Vertical distribution of weed seed

Tillage type influences the weed seed distribution in the soil profile. Intensive tillage alter the weed community by modifying vertical distribution of weed seed (Cardina *et al.*, 2002; Murphy *et al.*, 2006), providing light rich environment with fluctuating temperature and makes seed more vulnerable to germination (Streit *et al.*, 2002). In contrast of intensive tillage, seeding of crop under no till locate much of weed seed bank very close to soil surface and number of weed seed in unit kg of soil declined logarithmically with increase in soil depth (Yenish *et al.*, 1992). Weed seed bank enriched by three times in ZT over plowed soil, the majority of weed seeds accumulated in 0-5 cm, while with tilling most of the seeds occurred in deeper soil (5-10 and 10-20 cm) and uniformly distributed vertically in the plow zone in CT.

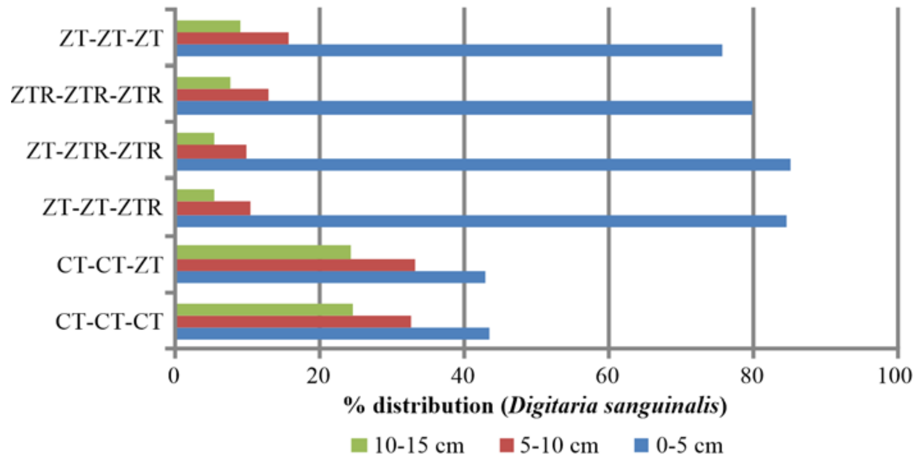
A study from Jabalpur showed that during the rainy season, the seed bank of *Digitaria sanguinalis* was 76-85% under ZT in 0-5 cm soil depth, whereas it was 10-16% in 5-10 cm and 5-9% at 10-15 cm soil profile depth. Contrarily, seeds were more or less uniformly distributed in CT system having 43% in 0-5 cm, 33% in 5-10 cm and 24% in 10-15 cm soil depths (Fig. 1a). During winter, the seed bank of *Medicago polymorpha* was 68-73% under ZT in 0-5 cm soil depth, whereas it was 21-24% in 5-10 cm and 6-8% at 10-15 cm soil profile depth. While, in CT system, seeds were uniformly distributed with 39, 34 and 27% at depth ranging 0-5,5-10 and 10-15 cm, respectively (Fig. 1b). Likewise, during summer, *Dinebra retroflexa* was 66-75% under ZT in 0-5 cm soil depth, whereas it was 14-19% in 5-10 cm and 10-15% at 10-15 cm soil profile depth. In contrast, seeds were uniformly distributed in CT system having 40-44% in 0-5 cm, 32-34% in 5-10 cm and 24-26% in 10-15 cm depths (Fig. 1c).

Rusu *et al*. (2015) from another study indicated that the adoption of minimum tillage (MT) increased the *Convolvulus arvensis* population by 11.2-39.1% in soybeans, 0.9-4.2% in wheat, and 11.9-24.4% in maize. Around 77% of *C. arvensis* seeds were located in 0-10 cm depth. However, tillage practices had no significant influence on yield, but CT considerably reduced the occurrence of perennial weeds. The crop establishment techniques with different combinations of CT, ZT and MT) *viz*. CT-CT, ZT-CT, CT-ZT, ZT-ZT and MT-ZT significantly influenced total weed population with more distribution of weed seeds to a greater depth under CT-CT, CT-ZT followed by MT-ZT compared to ZT-CT and ZT-ZT in rice-wheat cropping sequence (Punia *et al.*, 2016).

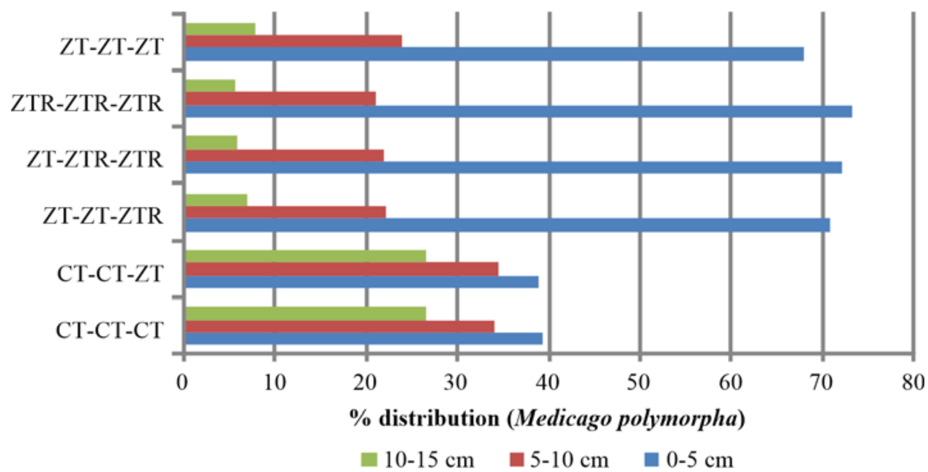
Shifting of weed flora

A shift from intensive tillage system to reduced or ZT leads to major change in weed population dynamics by altered patterns of soil disturbance and weed seed depth in soil (Ball, 1992; Yenish *et al.*, 1992; Chhokar *et al.*, 2007). Tillage intensity could lead to shift in weed flora comprising selective invasion of perennial weeds due to undisturbed root system under zero-till and small seeded annual in frequent tillage system (Blackshaw *et al.*, 1994). However, along with perennial weeds, ZT acts as effective niche for small seeded weed species also, as small seed that are sensitive to depth remains near to soil surface. Weed species, whose germination is stimulated by light, are likely to be more problematic in CA. Moreover, in the absence of tillage, perennial weeds may also become more challenging in this system (Choudhary *et al.*, 2016). It has been reported that 67.1-164.8% more weed seeds germinate which are present on the surface than in the sub-surface soil, though it largely depended on weed species, whereas weed seeds were evenly distributed in the CT. Thus weed density and diversity may increase under no-till cultivation but for the initial years due to accumulation of diverse weed flora seed near to surface. Adoption of cultural practices also exerts selection pressure on individual weed species, which may change the weed species composition in the soil seed bank (Mashavakure *et al.*, 2020).

Rice-wheat cropping system is the most predominant cropping system in the Indo-Gangetic Plains (IGP) of India (Das *et al.*, 2014; Bhattacharyya *et al.*, 2015; Das *et al.*, 2020a). In this system, CA is partially accepted by the farmers where mostly wheat is sown under ZT conditions in the presence of partial (anchored) or full (anchored + loose) residue using ZT machine or Turbo Happy Seeder, respectively. Rice is mostly grown as transplanted puddled rice (TPR) *a) Digitaria sanguinalis*



b) Medicago polymorpha



c) Dinebra retroflexa

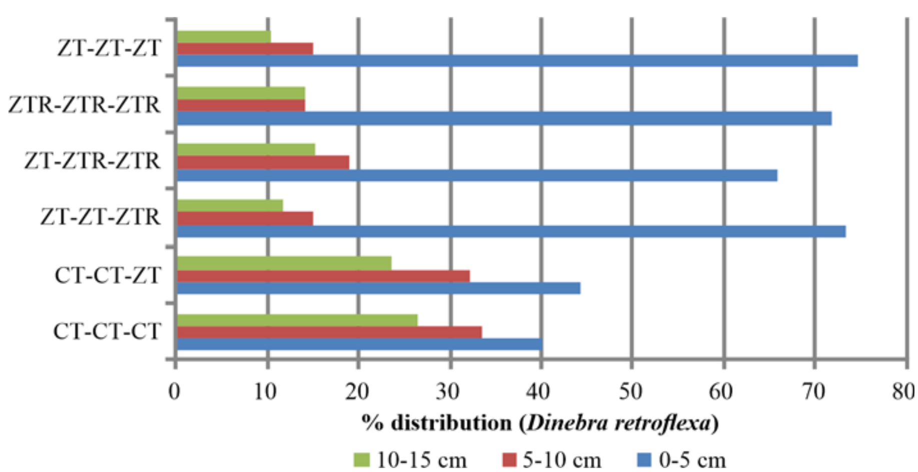


Fig. 1. Effect of tillage on weed seed bank in a) *Digitaria sanguinalis* during rainy b) *Medicago polymorpha* during winter; and c) *Dinebra retroflexa* during summer

with problems such as labour shortage and deterioration of soil physical conditions. The alternative to TPR system is direct seeded rice (DSR). However, DSR faces the severe problem of weed infestation compared to TPR along with yield penalty in some situations (Chhokar *et al.*, 2014).

In rice-based cropping system, ZT (DSR) + Sesbania brown manuring had the lowest total weed density. It was also observed that ZT had fewer *Cyperus iria*, but more *Caesulia axillaris* than that of TPR; while TPR had fewer *Physalis minima* and *Dinebra retroflexa*. Likewise in wheat, ZT had considerably less density of *Phalaris minor* and *Chenopodium album* over CT (Singh *et al.*, 2017). Under ZT rice, the density of *Echinochloa colona* increased, but *Physalis minima* decreased (Karunakaran and Behera, 2015). In rice-wheat system, study showed that ZT DSR with and without residue retention, ZT DSR after the cover crops of *Sesbania aculeata* or *Vigna unguiculata* and ZT transplanted rice showed greater weed density and dry matter accumulation than TPR. During initial year, ZT DSR had higher density of broadleaf weeds, sedges by 60 and 70.6%, respectively compared to TPR and 93% more sedges density compared to puddled wet DSR. ZT DSR without residue, ZT DSR with residue, ZT DSR with *S. aculeata* and ZT DSR with *V. unguiculata* as cover crop reduced weed dry matter accumulation by 14.3, 33.3, 23.1 and 60.0%, respectively compared to TPR (Jat *et al.*, 2019). In another study Mishra and Singh (2012) reported that adoption of continuous ZT increased the population of awnless barnyard grass (*E. colona*) and rice flat sedge (*C. iria*) in rice associated with surface accumulation of these small seed size weeds in ZT which failed to germinate when buried deep in TPR. Punia *et al.* (2016) after four years of study reported that, rice transplanted under ZT favoured *Ammania baccifera, Eclipta alba, Echinochloa crus-galli, E.colona, and Leptochloa chinensis*, while broad-leaved weeds particularly *Rumex dentatus* and *C. album* in wheat. In upland DSR, higher weed infestation was observed in CT with residue incorporation system compared to ZT with full residue retention (Yadav *et al.*, 2018).

The changing tillage and crop establishment methods in rice causes significant weed flora shift. The dry DSR exhibits greater diversity in weed flora than the TPR. Some of the weeds, including *Dactyloctenium aegyptium*, *C. rotundus*, *Phyllanthus niruri*, *Digera arvensis*, and *Trianthemaportu lacastrum* which infest the un-puddled DSR did not infest the TPR (Chhokar *et al.*, 2014). The differential weed flora is due to water stagnation conditions in TPR. Most of the weeds except aquatic weeds fail to germinate under submerged conditions and the efficacy of pre-emergence herbicides also improves (Janiya and Johnson, 2005; Kent and Johnson, 2001). Thus water management is an important cultural practice for weed control in rice. Hach *et al.* (2000) also confirmed that wet tillage compared to dry tillage significantly decreased the weed density, but absence of tillage increased the infestation of *E. crus-galli* and *Paspalum distichum* L. This stresses that there is need to have better understanding of biology and ecology of weeds for effective control measures. In rice, if we move to CA, we have to exclude the wet tillage practice and will make a major shift in weed dynamics as well as weed management practices. However, in the long run it may not be a sustainable practice as many research workers have reported a yield decline with long term aerobic rice adoption (Peng *et al.*, 2006; Kreye *et al.*, 2009) as well as emergence of some of the problematic weeds such as weedy rice/ red rice (*O. sativa* f. spontanea) and herbicide resistant weeds (Kumar and Ladha 2011). The emergence of weedy rice in Malaysia has forced some farmers to switch back to transplanting to overcome it. Chhokar *et al.* (2014) reported that tillage and weed control exhibited large scale variation in rice grain yield and weed flora. In weed free conditions (Fig. 2), amongst the various crop establishment options, TPR had the highest yield (6.61 t/ha) followed by NT transplanting (5.34 t/ha). The direct seeding under CT and NT had lower yields compared to transplanting. The better yield under TPR conditions was due to submergence conditions, which also provided better weed control (Kumar and Ladha, 2011).The yield reduction due to weeds was higher in the DSR treatments (94-97%) and lower (24-33%) in

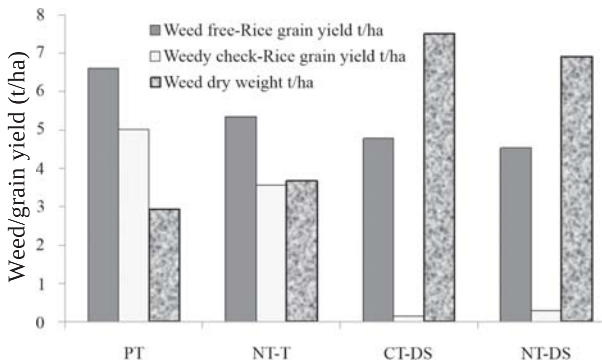


Fig. 2. Effect of crop establishment methods on weeds and grain yield of rice in rice-wheat system (Chhokar *et al*., 2014). The abbreviations denote, PT= puddle transplanting; NT-T= no till transplanting; CT-DS conventional tillage direct seeding; NT-DS= no till direct seeding

the transplanted rice due to severe weed competition, as weeds emerge along with the crop in abundance and compete with crop at an early stage, as compared to transplanting, where the weed seedling emergence was reduced and delayed, and competitive edge remain in favour of the crop.

Similarly, various researchers have reported lesser yield reductions in TPR compared to DSR (Kim and Pyon, 1998; Rao *et al*., 2007; Kumar and Ladha, 2011). The reduced weed infestation in the transplanting treatments either in puddled or ZT conditions is due to early crop coverage along with the feasibility of maintaining water stagnation immediately after the transplanting. Therefore, instead of DSR, if more focus is given on evolving some of the systems, such as machine transplanting preferably under no-till conditions, this will help in improving rice productivity, profitability and weed management. Further, to realize the potential benefits of CA under rice-wheat system, there is a need to develop rice cultivars that can perform equally under aerobic situation as in puddled conditions.

In wheat after rice, continuous ZT reduced the population of wild oats [*Avena ludoviciana* (L.) Dur.] and *C. album* L. Weed seed population was significantly greater under continuous ZT and CT as compared to rotational tillage with values 165, 101 and 71-85 weeds in 500 g soil, respectively within 0-20 cm depth. Rotational tillage systems significantly reduced the seed density of *A. ludoviciana* and *M. hispida* compared to continuous ZT or CT (Mishra and Singh, 2012). Zero tillage in wheat favored broad-leaved weed such as *Rumex dentatus* (12.1 plant m^{-2}) more compared to CT (1.9 plants m^{-2}), while higher proliferation of *P. minor* in CT (386.5 g m^{-2}) as compared to ZT (234.7 g m^{-2}). This differential response and shift in weed flora could be associated with distribution of wheat associated weed seeds during tillage and puddling operation in the preceding rice crop (Chhokar *et al*., 2007). Similarly, Shyam *et al.* (2014) showed significantly lower *P. minor*, *Melilotus indica* and *C. album* seed densities in soil under ZT as compared to CT.

In a study under rice-wheat-green gram system, tillage practices considerable influenced the nature and growth of weed species. Adoption of transplanted rice reduced the weed density by 72.2% and weed dry biomass by 79.7% than the CT. Likewise, ZT had 20 and 27.7% more weed density and dry biomass, respectively than CT, whereas it was reduced by 11.1 and 14.4%, respectively in ZT with crop residues (R) and 18.9 and 26.5%, respectively in CT with crop residues (Fig. 3). In wheat, weed density and dry biomass were 31.1 and 27.3%, respectively lower under ZTR, followed by CTR and ZT. In green gram, adoption of ZTR in system recorded 51.4 and 46.4% lower density and dry biomass of weeds, followed by 20.2 and 24.5%, respectively in CTR system over CT-CT-ZT system (Fig. 3).

In soybean-wheat system, under different establishment techniques (CT and ZT with either raised or flat bed) showed that during initial year highest weed density and weed biomass were observed from ZT flat bed followed by ZT raised bed, while after three years the highest weed density and weed biomass was recorded in CT flat and the lowest in ZT under raised bed. Over the years, higher proliferation of *D. aegyptium*, *Eleusine indica*, *L. chinensis*, and *Phyllanthus niruri* in ZT conditions is a matter of concern. Further, irrespective of crop establishment

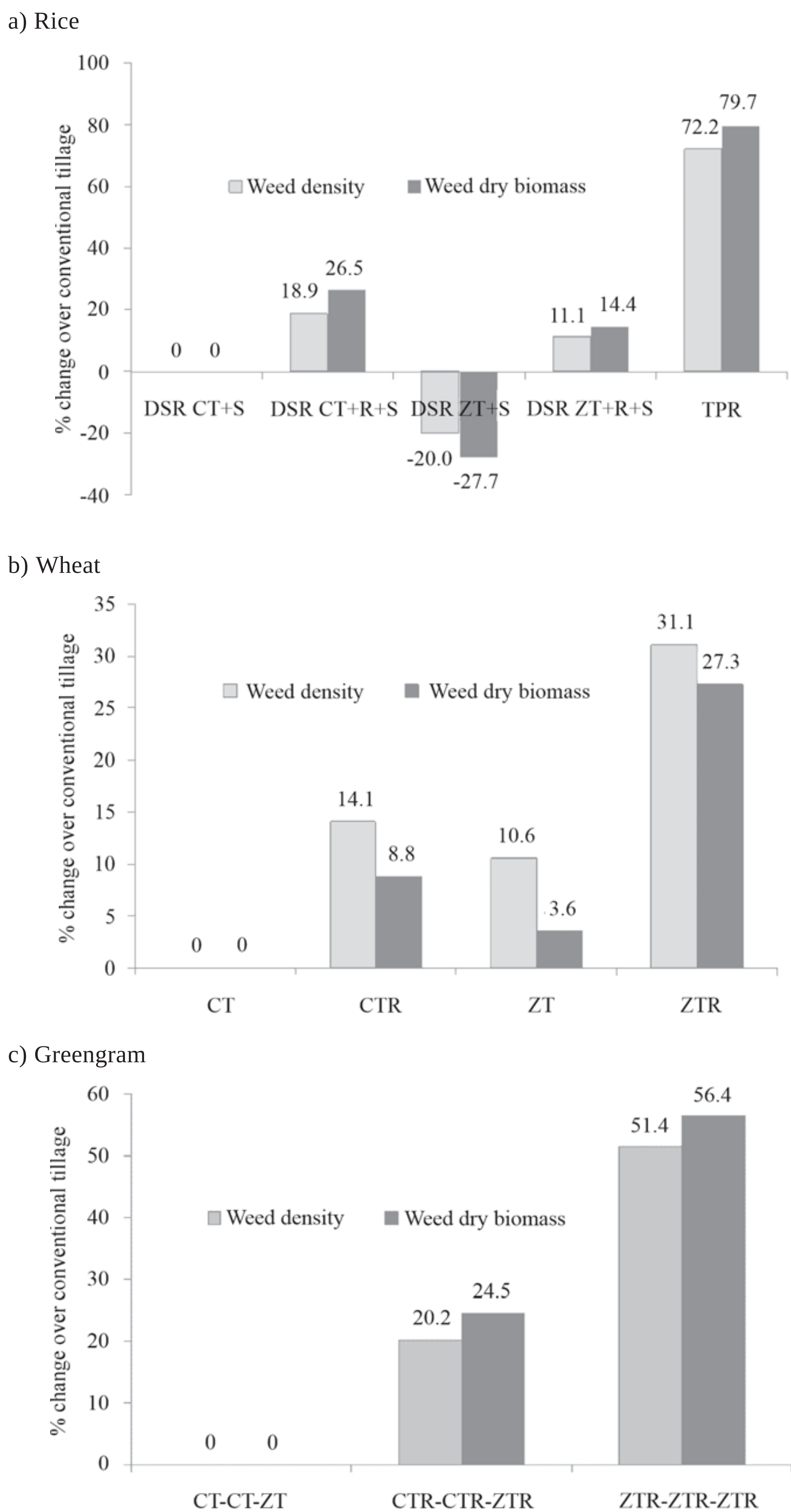


Fig. 3. Effect of tillage on weed density and dry biomass under rice-wheat-greengram

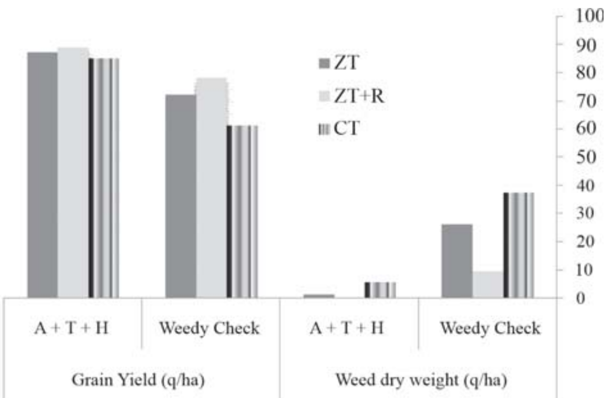


Fig. 4. Effect of tillage and herbicide mixture on weeds in maize. The post- emergence tank mixture consisted of atrazine + tembotrione + halosulfuron (A+T+H) at 900+90+67.5 g/ha

techniques application of pendimethalin (pre-emergence) followed by imazethapyr (post-emergence) provided effective control of weeds (Sepat *et al.*, 2017).

In maize-wheat system, tank mix application of herbicides in maize followed by ZT with 100% maize residue retention in wheat resulted in better weed suppression, more seed bank depletion, delaying in weed resistance, and higher productivity and profitability in maize-wheat system. Zero tillage with full residue retention of maize resulted in 14.0% greater reductions in weed dry weight and 6.9% higher wheat yields than CT (Susha *et al.*, 2018). Higher seed bank of *M. denticulate* was recorded in continuous ZT in maize-wheat cropping system and similar to it was ZT (maize)-CT (wheat), while the lowest was in CT-CT system. Conversely, *P. minor* and *C. album* seed bank was higher in continuous CT, which was at par with CT-ZT, and the lowest was in continuous ZT maize-wheat (Stanzen *et al.*, 2016).

Another experiment in maize having different crop establishment methods (ZT, ZT+R and CT) and herbicide treatments was conducted at Karnal. Among three tillage options, CT had more abundance of weeds (373.8 g m^{-2}) compared to ZT (260 g m^{-2}) and ZT+R (94.5 gm^{-2}) treatments at 45 days after sowing. Between two conservation tillage treatments, CA (ZT+R), had lower weed infestation. Also, ZT with and without residue retention had better yield compared to CT system both under herbicide treated as well as untreated control conditions. The yield gain was more in absence of post- emergence herbicide application. The pre-planting application of glyphosate helped in reducing the weed abundance. The post-emergence tank mixture consisting of atrazine + tembotrione + halosulfuron at 900+90+67.5 g ha^{-1} provided effective control of diverse weed flora in maize (Fig. 4). The earlier results also showed effectiveness of atrazine in combinations with HPPD (*p*-hydroxy phenyl pyruvate dioxygenase) inhibiting herbicides (mesotrione, tembotrione and topramezone) for control of diverse weed flora in maize (Chhokar *et al.*, 2019, 2020). The CA treatment, ZT+R was the top yielder due to the congenial micro-climate leading to better crop growth and consequently yield. However, the yield difference between ZT and ZT+R was non-significant. Similarly, the improved maize yield with conservation tillage practices have been reported by various workers (Memon *et al.*, 2007; Memon *et al.*, 2013; Thierfelder *et al.*, 2015). The tank-mix application of herbicides is a better option for farmers in terms of diverse weed flora control and better grain yield of maize (Chhokar *et al.*, 2020). Moreover, there is a need to integrate the different weed management strategies to achieve the effective and sustainable weed control in maize.

In a long-term maize-wheat-green gram system at Karnal, ZT and CA plots had lesser infestation of *C. rotundus*, compared to CT (Fig. 5). The significantly lower infestations of *C. rotundus* in conservation tillage options (ZT and ZT+R) was due to the pre-planting application of glyphosate before seeding of each crop. Pre-planting application of glyphosate and no-tillage act synergistically as the former destroyed below ground reproductive structures, while the latter prevents tillage induced dispersion of viable propagule from lower to upper layers.

Continuous adoption of CA-based cotton-wheat system led to weed flora shift in the form of dominance of sedges at IARI, New Delhi. Initially for five years, *C. rotundus* was major

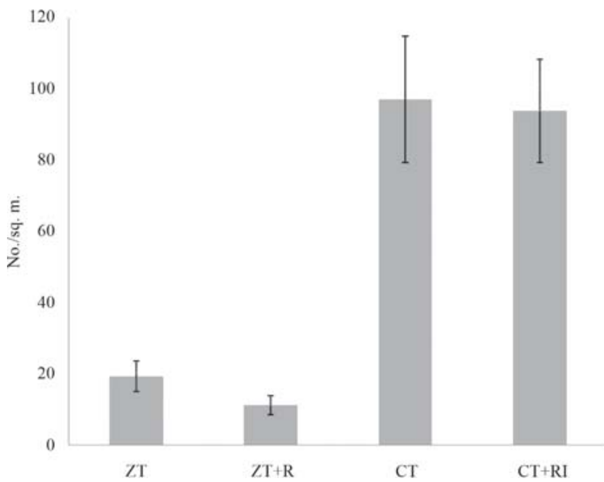


Fig. 5. Effect of tillage and residue on mean *Cyperus rotundus*density after 4th and 5th year of experimentation in maize under maize-wheat-greengram system. The error bar represents ± SEM. The abbreviations, R and RI denote residue retention and residue incorporation, respectively

weed among the sedges, but after six years, the population of *C. esculentus* increased significantly. The population of *C. esculentus* was significantly higher in cotton planted under the ZT narrow bed and CT systems compared to other systems. The ZT narrow bed with residue (ZT NB +R), ZT broad bed with (ZT BB +R) and without residue (ZT BB), and ZT flat bed with (ZT FB + R) and without residue (ZT FB) resulted in significantly lower density of *C. esculentus*. The continuous dominance of this weed in cotton has led to gradual reduction in the population of *C. rotundus*, which has been almost negligible in number or phased out (T.K. Das personal communication). *C. esculentus* showed complete tolerance to even non-selective glyphosate. It has very fast tuber-formation capability and produces more number of tubers than *C. rotundus*.

Accelerated weed seed predation

Adoption of ZT system encourage more seed losses *via* predation and germination by locating more seed bank on or close to the surface. Undisturbed conditions minimize tillage induced mortality and provide congenial habitat to the seed predators and pathogens (Shearin *et al.*, 2014). Further, biological activity of seed predators is increased in long term ZT condition associated with accumulation of food substrate in the form of organic and inorganic compounds near to soil surface (Trichard *et al.*, 2014).

Crop residue on weed dynamics

Retention of previous crop residues regulates/ modulates the soil temperature, and it delays the germination and emergence of weeds. Crop residues act as mulch which prevents light availability, provides a physical barrier and also releases allelochemicals. Thus, small-seeded annual weeds may not germinate and grow (Choudhary and Kumar, 2019). Placement of crop residues as mulch reduced 20-40.5% weed dry biomass over no residues. Retention of crop residue influences the weed dynamics and herbicide efficacy. Crop residues as mulch reduced the weed density by 70%, thus it reduces the concern of the use of herbicides in the CA system (Mtambanengwe *et al.*, 2015). Although weed management relies on the type of crop residues, thickness, evenness, etc., thick and uniform application of crop residues under CA suppress weed seedling emergence. Along with delayed emergence, it provides the favourable condition to the crop resulting in early vigor over weeds (Chauhan *et al.*, 2012).

Crop residue on weed emergence

Rice straw as mulch (6 t/ha) reduced emergence of *P. minor*, *C. album* and *Rumex dentatus* by 45, 83 and 88%, respectively and further increased the values to 65% and more than 90% for *P. minor* and *R. dentatus*, respectively with 8 t/ha compared to non-mulch (Kumar *et al.*, 2013). Moreover, inhibitory effect of rice straw on weeds was more pronounced with early seeding of wheat (25th October) compared to mid or late November. The highest dry weight of *P. minor* was recorded under CT (113.7 g m^{-2}) as compared to ZT without stubbles (102 g m^{-2}), ZT after partial burning (72.5 g m^{-2}) and ZT in standing stubble (65 g m^{-2}) in wheat (Brar and Walia 2008). Chhokar *et al.* (2009) observed that 2.5 t/ha rice residue mulch was not effective in suppressing weeds, but 5.0 and 7.5 t/ha paddy

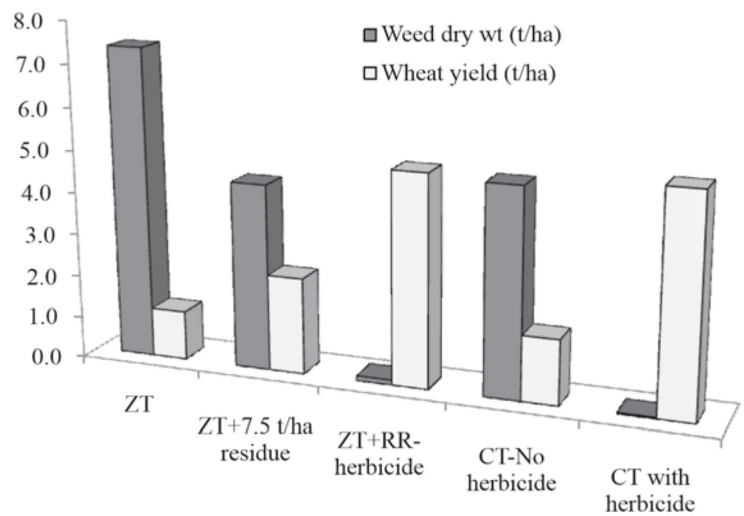


Fig. 6. Influence of tillage, residue and herbicides on weeds and wheat yield under rice-wheat system (Mean of two year data, Chhokar *et al.*, 2009). The abbreviation RR denotes residue retention

straw as mulch reduced weed biomass by 17-55% of *R. dentatus as* compared with ZT without residue (Fig. 6).

Wheat residue as mulch (5 t/ha) in ZT DSR reduced emergence of sedges, broad-leaved and grassy weeds by 22-70, 65-67 and 73-76%, respectively as compared to no residue in ZT DSR (Kumar *et al.*, 2013). Similarly, Singh *et al.* (2007) observed that wheat residue (4 t/ha) reduced the emergence of broad-leaved and grass weed species by 56-72 and 44-47%, respectively. However, wheat straw has more competitive uses as feed for milch animals compared to rice straw in N-W India. Chauhan and Abugho (2012) reported that 6 t/ha crop residues reduced the emergence of jungle rice (*Echinochloa colona* L.) crowfoot grass (*Dactyloctenium aegyptium*) and rice flat sedge (*Cyperus iria* L.) by 80–95%, but reduced the emergence of barnyard grass by up to 35% only. It was also reported that TPR and DSR with crop residue retention recorded lower weed dry biomass than DSR without residue by 51.6 and 44.5%, respectively, (Bana *et al.*, 2020).

ZT with retention of 7.5 t/ha rice residue in wheat under rice-wheat system reduced the weed dry weight by 40.2% compared to ZT without residue conditions. In ZT plots, *R. dentatus* and *M. denticulata* dominated, whereas *P. minor* was dominant in CT conditions (Chhokar *et al.*, 2007). The tank mix application of sulfosulfuron + metsulfuron 25 + 3 g/ha produced the minimum weed dry weight as this mixture is effective against diverse weed flora (Chhokar *et al.*, 2007). Also in ZT fields, strategy consisting of non-selective herbicides like glyphosate and paraquat if mixed with pre-emergence herbicides such as pendimethalin and trifluralin will reduce the subsequent weed emergence due to residual effects of pre emergence herbicides.

Adoption of modern seeding machine, e.g. ‘Turbo Happy Seeder’ helps in managing weeds through retention of crop residues as mulches, besides providing efficient seeding and fertilizer placement. With the usage of this machine, CA has been successfully used in the irrigated rice-wheat cropping systems of the IGP.

Crop residues on herbicide efficacy

The crop residues besides suppressing weeds also influence the herbicide efficacy depending on the residue load and its position. The success of CA based crop production is dependent on the availability of effective herbicides and their efficient usage. The efficacy of pre-emergence herbicides could be reduced due to interception of spray droplets by presence of previous crop residues (Chauhan *et al.*, 2012; Chaudhary *et al.*, 2019). Also, under ZT, due to non-burial of weed seeds and non-incorporation of soil-active pre-plant herbicides, the efficacy of herbicide is reduced. The majority of weed seeds remain on the soil surface under CA. Once weeds are established especially perennial weeds, it is difficult to control them due to the absence of soil inversion. Further, limited herbicide options due to accelerated development of herbicide resistance in *P. minor* against best herbicide chemistries call for the use of pre-emergence herbicides to sustain the potential wheat productivity. Under this situation, herbicide-based weed management plays a crucial role, however, the presence of crop residues on the soil surface often reduces their efficacy as a result these herbicides fails to provide adequate control. The higher efficacy of herbicides in surface retained scenarios could also be realized by increasing the spray volume along with modifying the application time, placement of herbicides and use of nozzles based on size of water droplet (Chaudhary *et al.*, 2019). Although residue retention decreases the efficacy of pre-emergence herbicide, it is better option than the straw burning being practiced by the farmers. The rice crop residue burning also decreases the efficacy of soil-active herbicides like isoproturon and pendimethalin (Chhokar *et al.*, 2009) and also increases the emergence of *P. minor* in wheat.

Crop residue and weed seed predation

Presence of crop residues not only inhibit emergence of weeds but also contribute to weed seed bank depletion. Weed seeds present on the soil surface are more prone to desiccation and greater predation activity of insects, especially ants. A study showed that post dispersal seed predation of *P. minor* was about 50-60% during one week period under ZT with presence of crop residues in between wheat harvest and rice planting compared with 10% under CT (Kumar *et al.*, 2013). However, potential impact of such studies is lacking under Indian conditions, as most of the rice area under rice-wheat system is under TPR. Tillage induced disturbance along with extensive burning of rice straw limits the success of this aspect under rice-wheat system.

Effect of crop rotation on weed dynamics

Rotation of crops acts as a key to improve crop yields, soil quality and pest management system. Monoculture leads to less diverse and difficult to control weed flora. Variation in weed species could be either due to the direct result of crop rotation or agronomic and weed management practices associated with cultivation of crop. Cropping system diversity is recognized as the proactive weed resistance management strategy (Beckie, 2009). Diverse cropping system leads to diverse weed community with less dominant weed species as generally observed in simple rotation or monoculture (Cardina *et al.*, 2002). Limited diversity in weed flora under monotonous cropping is associated with similar selection pressure of management practices and favouring the species with phenotypes and phenology similar to the crop (Koocheki *et al.*, 2009).

Shifting of weed flora

Cropping sequence acts as the most dominating factor in defining weed composition in a region. Continuous cultivation of single crop (monoculture) or crops having similar management system allows specific weeds to proliferate due to specific resource availability over the time in a niche (Liebman *et al.*, 2001). Regardless of diverse herbicide use, crop rotation is an important measure for diversifying weed communities and reducing selection pressure (Radosevich *et al.*, 1997). The diverse mechanisms, such as, diversifying spatial and temporal resource availability, niche disruption, dissimilar planting and harvesting dates, growth habit, competitive ability of the crops and soil disturbance, by which crop rotation reduces weed seed bank (Liebman and Dyck, 1993; Buhler, 2002). Different cropping systems, viz., cotton-wheat, maize-wheat, maize-wheat-summer green gram, maize-potato-summer green gram , maize-potato-onion, as compared to rice-wheat, cotton-African sarson (*Brassica carinata* A. Braun), cotton-gobhi sarson transplanted (*Brassica napus*sub sp. *Oleifera*var. *annua*), summer groundnut-toria (*Brassica rapa* var.*toria*) + gobhi sarson and summer groundnut-potato-pearl millet

(*Pennisetum glaucum* L.) reduced *P. minor* population by about 67, 80, 86, 89, 89, 89, 89, 92 and 97%, respectively as compared to rice-wheat system (Walia *et al.*, 2011). However, this study relies on crop rotation principle only; full adoption of CA under these cropping systems could be more encouraging in modulating weed infestation to greater values.

Long-term (10 years) CA studies in rice-wheat and rice-mustard system at IARI, New Delhi showed that there was gradual reduction in weed population in CA-based DSR, wheat and mustard crops (Baghel *et al.*, 2018, 2020; Das *et al.*, 2020a), but weed species dynamics/shift was observed over the years. The application of non-selective herbicide glyphosate/ paraquat in CA-based plots twice/thrice in a year (after rice, wheat and/or mung bean as applicable to treatments) was mainly responsible for this shift. Besides, selective herbicides (pre-emergence or post-emergence) as recommended for these crops were also applied to control existing annual weeds in these crops. This also led to dominance of perennial sedges due to lack of natural competition from the annual weeds. The triple ZT system with residue [~ mung bean residue (MBR) + ZTDSR – rice residue (RR) + ZT wheat (ZTW) – wheat residue (WR) + ZT summer mung bean (ZTSMB)], and without residue (~ZTDSR – ZTW–ZTSMB) resulted in higher population of *C. rotundus*than that of *C. esculentus*, whereas the other CA based - double ZT systems encountered higher infestations of *C. esculentus* than that of *C. rotundus* in rice under the rice-wheat system (Table 1). Under the rice-mustard system, *C. rotundus* population was considerably higher compared to *C. esculentus* in all the CA-based double or triple ZT systems (Table 2). The CT systems (*i.e.*, TPR-CTW/ZTW), in general, did not encounter infestations of *C rotundus* or *C. esculentus*. Population of *Euphorbia heterophylla* was on the increase in rice in rice-wheat system under ZT DSR-based CA systems except the ZTDSR-ZTW (Fig. 3). *C. rotundus* population was highest in the triple ZT system without residue, but was reduced due to the ZTDSR + brown manuring (BM) + residue system (~WR/ MR+ZT DSR+BM-RR+ZTW/ZTM*)* (Fig. 7; Table 1). The potential of brown manure *Sesbania* crop to reduce *C. rotundus* infestation has also been reported in maize (Susha *et al.*, 2018; Das *et al.*, 2020b). *Dinebra retroflexa* was on the increase, whereas *Alternanthera philoxeroides was* on the decrease in triple ZT DSR with or without residue (Fig. 1). In TPR the *C. rotundus*, *T. portulacastrum*, *A .philoxeroides, D. retroflexa*, *Euphorbia microphylla* were not observed in TPR system (Fig. 1). Chhokar *et al.* 2014 also observed that in TPR, water stagnation is responsible for elimination of the infestation of *T. portulacastrum*, *C. rotundus*, *D. aegypetium* and *D. sanguinalis.*

The density of *Sonchus oleraceous* and *M. denticulata* were significantly influenced with tillage and crop establishment methods in mustard under rice-mustard system (Table 3). The density of *S. oleraceous* was the highest in TPR-CT mustard (CTM) system closely followed by TPR-

Table 1. Weed dynamics in cotton - wheat cropping system

Treatment	*Cyperus rotundus* population (no./m^2) in 2015 (after 5 years)	*Cyperus esculentus* population (no./m^2) in 2016 (after 6 years)
CT	1.0†(0)‡	21.3(451)
ZT NB (Narrow bed)	5.7(32)	24.7(608)
ZT NB + Residue (R)	4.6(20)	10.7(113)
ZT BB (Broad bed)	6.9(47)	12.1(145)
ZT BB + R	5.1(25)	11.2(124)
ZT FB (Flat bed)	5.8(33)	11.3(127)
ZT FB + R	4.4(19)	7.7(58)
LSD (P≤0.05)	1.7	4.7

† Transformed population through √(x+1); ‡Original field population in the parentheses

Table 2. *Cyperus* spp. dynamics in rice under rice-wheat and rice- mustard cropping systems (after six years)

Treatments	Rice-wheat		Rice-Mustard	
	Cyperus esculentus population (no./m^2)	*Cyperus rotundus* population (no./m^2)	*Cyperus esculentus* population (no./m^2)	*Cyperus rotundus* population (no./m^2)
ZT DSR - ZTW/ZTM	88.1	21.3	1.3	70.7
ZT DSR+BM - ZTW/ZTM	24.0	21.3	6.7	114.7
WR/MR+ZT DSR - RR+ZTW/ZTM	44.0	17.3	0.0	73.3
WR/MR+ZT DSR+BM-RR+ZTW/ZTM	18.7	9.3	10.1	34.7
ZT DSR - ZTW/ZTM – ZTSMB	20.0	72.0	10.3	61.3
MBR+ZT DSR - RR+ZTW/ZTM -WR/MR+ZTSMB	12.0	69.3	6.1	101.3
TPR-ZTW/ZTM	0	0	0	0
TPR-CTW/CTM	0	0	0	0
LSD (P≤0.05)	7.8	3.7	2.1	11.5

Note: ZTDSR= zero tillage direct seeded rice; ZTW= zero tillage wheat; ZTM= zero tillage mustard; BM= brown manuring; WR= wheat residue; MR= mustard residue; RR= rice residue; SMB=summer mungbean

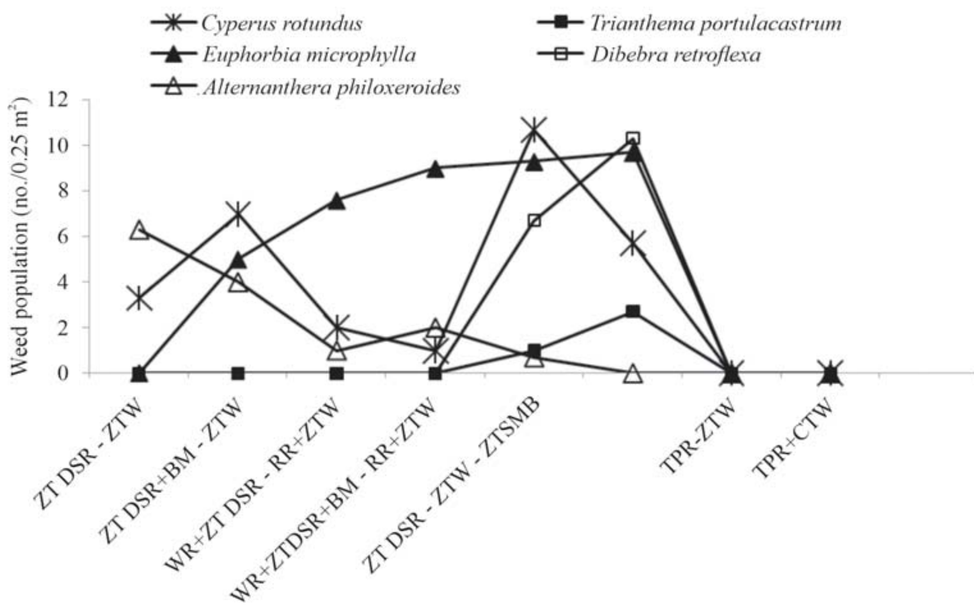


Fig. 7. Weed flora shift in rice under CA-based rice-wheat cropping system (after five years)

Abbreviations: ZTDSR= zero tillage direct seeded rice; ZTW= zero tillage wheat; BM= brown manuring; WR= wheat residue; MR= mustard residue; RR= rice residue; SMB=summer mungbean; CTW= conventional tillage wheat; TPR= transplanted puddled rice

ZTM and lowest in the triple ZT system (MBR+ZT DSR - RR+ZTM -MR+ ZTSMB). The occurrence of *M. denticulata* was observed in CA-based (double ZT) system having brown manure or residue or without residue after three years of experimentation under rice-mustard system. No soil disturbance (~ZT), crop or brown manure residue retention in all double ZT systems might play roles for the preponderance of *M. denticulata*. On the contrary, triple ZT systems and CT system were almost free from *M. denticulata*. Soil disturbance through repeated tillage across seasons under the CT system, and mung bean crop residue (shoots & roots biomass)

Table 3. *Sonchus oleraceous* and *Medicago denticulata* dynamics in mustard under the rice- mustard (R-M) cropping system

Treatment	*Sonchus oleraceous* (after 2 years of R-M system)	*Medicago denticulata* (after 3 years of R-M system)
ZT DSR – ZTM	4.4†(18)‡	19.8 (393)
ZT DSR+BM – ZTM	4.7(21)	19.4 (384)
MR+ZT DSR - RR+ZTM	3.8(13)	21.5 (473)
MR+ZTDSR+BM - RR+ZTM	5.0(24)	19.9 (398)
ZT DSR – ZTM – ZTSMB	5.3(27)	1.0 (0)
MBR+ZT DSR - RR+ZTM -MR+ SMB	3.2(9)	1.0 (0)
TPR-ZTM	6.1(36)	1.0 (0)
TPR-CTM	7.3(52)	1.0 (0)
LSD ($P \leq 0.05$)	1.1	1.2

† Transformed population through $\sqrt{(x+1)}$; ‡Original field population in the parentheses

Abbreviation: ZTDSR= zero tillage direct seeded rice; ZTM= zero tillage mustard; BM= brown manuring; WR= wheat residue; MR= mustard residue; RR= rice residue; SMB=summer mungbean; MBR= mungbean residue; TPR= transplanted puddle rice; CTM= conventional tillage mustard

under the triple ZT systems might be responsible for disappearance of *M. denticulata* from these plots. Thus, this study shows that mung bean crop may have an apparent role on the reduction of these two weeds.

Accelerated weed seed predation

Diverse crop in rotation diversify the weed flora, and also favour different types of predators which consume wide range of weed species seed (Heggenstaller *et al.*, 2006). Inclusion of green manuring may help in decaying of the weed seeds, whereas cover crop favours the build-up of predators (Shearin *et al.*, 2014). Furthermore, under CA, cover crop species and termination duration would be potential weed management strategies (Alonso-Ayuso *et al.*, 2018). Moreover, seed predation should be integrated with other management practices to reduce the weed emergence and their competitive ability.

Weed Management Approaches in CA

Preventive measures

The importance of preventive measures becomes more important under CA, as even a small quantity of weed seeds could cause a serious infestation in the forthcoming seasons under no-till conditions. Weed seeds similar in the shape and size of crop seeds are the important major source of contamination in crop seeds. Preventive measures such as use of weed-free crop seed, clean machinery/implements, well-decomposed manure/compost, removal of weeds near irrigation ditches, fence rows prior to seed setting, mechanical harvesting of reproductive parts of weeds prior to seed rain could be integrated for effective weed control under CA.

Stale seedbed (only with herbicides)

In CA systems potential yield can be realized if weeds are effectively managed during initial 2-3 years. The initial effective weed management through limiting the weed seed entry to the soil will ultimately deplete the seed bank. A comparative study on stale seed bed with glyphosate (1 kg ha^{-1}), stale seed bed with shallow tillage (5 cm) showed that prior to sowing, stale seed bed increased weed seedling emergence by 1.9–2.2-fold and decreased the viable seed bank of *E. colona* and *D. aegyptium*to by 25–30% of that without a stale seed bed. Densities of *C. rotundus* and grassy weeds reduced by 22-51% and 42-67%, respectively under stale seed bed compared to normal seed bed at 20 days after sowing. Both these methods lower weed seed bank by 13–33% after rice harvest with more pronounced effect with shallow tillage as compared to chemical based glyphosate. Further, sequential application of pendimethalin and bispyribac resulted in a significantly lower seed bank of both these grass weed species at harvest (Singh *et al.*, 2018).

Crop competition

Enhancing the ability of a crop to compete with weeds can be accomplished by providing the best possible environment for crop growth combined with practices that reduce the density and vigor of weeds. Multiple tactics as competitive crop cultivars, higher seed rates, altered row orientation and narrow row spacing can be integrated to enhance crop competition against weeds. Crops grown in narrow rows compete with weeds more as compared to wider rows due to quick and more canopy formation. Narrow spacing with higher seed rate provides lesser space to late emerging weeds by reducing the amount and quality of light available for weeds located below the crop canopy. Slightly higher seed rate under CA helps in better crop establishment and weed control. Decreasing row spacing and increasing crop plant density has been shown to increase competitiveness of many crops (Blackshaw *et al.*, 2000b ; Yenish and Young, 2004; Lemerle *et al.*, 2006; Mansoori, 2019). Teasdale (1995) found that growing corn in 38-cm-wide rows with increased density (compared to 76-cm rows) improved weed control. Moreover, increased seeding rate also reduces the herbicide requirement (Lemerle *et al.*, 2013).

Crop cultivars vary in their competitiveness against weeds (Zerner *et al.*, 2016; Marin and Weiner, 2014; Worthington *et al.*, 2015a, b; Lazzaro *et al.*, 2019). Screening and identification of competitive crop cultivars under CA system are also of prime importance to provide crop competitiveness. Further, breeding competitive cultivars with allelopathic effects improve their weed-competitive ability.

The main plant characteristics associated with crop competitiveness with weeds include faster emergence and root development, rapid early vegetative growth and vigor, early canopy closure and high leaf area index, profuse tillering or branching, increased leaf duration, greater plant height, rapid biomass accumulation during early stage and allelopathy (Ni *et al.*, 2000; Mason *et al.*, 2007; Saito *et al.*, 2010; Jha *et al.*, 2017).

In case of wider sown crops (cotton and maize), intercrops can be grown to reduce weed infestation by smothering effects as well as release of allelochemicals from the roots/crop residues. Different intercrops (bitter cumin, carom seed, coriander, fennel, fenugreek, oat, pearl millet, sorghum, marigold, sesame and sunnhemp) in cotton reduced weed emergence and biomass by 43-71% and 91-96%, respectively as compared to conventional farmer practices (Blaise *et al.*, 2020). Over the years, consistent weed suppression is observed where sunnhemp was used as intercrop that reduced weed biomass by 43% compared to control. Allelopathic effect associated with high total phenolics and terpenoid content in the above ground parts of sunnhemp could be the possible mechanism involved in the inhibition of weed seed germination and growth. Similarly, blackgram intercropped with maize reduces weed abundance. Since, resource availability is key to weed occurrence and intercropping increases resource utilization ultimately suppresses weeds. Brown manuring of *sesbania* can also be utilized for weed suppression in co-culture of rice/maize with *sesbania*. Also, the adoption of crop competitive practice helps in reducing the herbicide doses.

Cover crops

Inclusion of cover crops in a rotation between two main crops is a good preventive measure when developing a weed management strategy. Cover crop provides numerous short- and long-term benefits in terms of weed management, optimize acquisition of natural resources, reduce water runoff, nutrient leaching and soil erosion. Competition from a strong cover crop can virtually shut down the growth of many annual weeds. 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 inclusion under CA systems increase invertebrate seed predators as it provides desirable habitat for invertebrate predators (Gallandt *et al.*, 2005). Cover crops with high biomass deliver high amount of weed suppressive conditions (Teasdale, 2003), whereas lower biomass producing cover crops could stimulate germination of selected weed species due to insufficient in surface cover and inhibition of weeds, providing more uniform moisture conditions by retarding evaporation compared to the bare soil and release of nitrogen in case of legumes (Teasdale, 2003; Teasdale and Mohler, 2000). The cover crops also releases allelochemicals, which may create the conditions unfavourable for weed germination and growth. Besides off season cover crops (*Sesbania*), smother crops can be included in the cropping system to check the weeds through resource competition. CA in India requires through investigation on such aspects as non-availability of previous crop residues or lower availability of surface cover could nullify or diminish the role of surface retained residue in weed inhibition.

Adoption of proper crop rotation is a key component of weed management (Liebman and Gallandt, 1997). It provides multiple effects helping in weed management through variation in planting time and growth durations, crop establishment practices, competitive characteristics, and weed control practices to prevent the build-up of crop associated weeds in monoculture. Inclusion of fodder/forage crops in crop rotations also helps in suppressing weeds through competition, cutting, and grazing (Gill and Holmes, 1997; Liebman and Davis, 2000). Moreover, crop rotation having perennial forage species, may reduce the seed bank of annual species because of the decline in seed production due to crop competition as well as by predation, and decay of weed seeds.

Weed management through herbicides

In absence of tillage and interculture operations, chemical weed control is the main tool of weed management in CA system. Consequently, weeds become overwhelming problems, especially in the early years of the CA adoption and require special attention during the initial period (Eslami, 2014).

The three important pre-plant non-selective and non-residual herbicides are glyphosate, glufosinate and paraquat. Among these, glyphosate had an edge particularly in controlling the perennial weeds. The perennial weeds become problematic particularly under continuous adoption of CA system. Thus, the feasibility of pre-plant application of glyphosate as well as its post-emergence application in glyphosate resistant/tolerant crop cultivars (corn, cotton and soybean) had made it possible to effectively control perennial as well as other diverse weeds. The development of herbicide tolerant crop cultivars can give more options of chemical weed control and this herbicide resistant technology will promote the adoption of CA system. Moreover, pre-planting application of tank mixes of glyphosate with some pre-emergence herbicides such as pendimethalin etc. can be the most effective and economically viable weed control strategy and need to be explored in CA system. However, over-reliance or exclusive use of herbicides may change the weed population from easily controlled weeds to difficult to control weeds; furthermore, it becomes herbicide resistant biotypes. Under such situation best approach is to adopt integrated weed management.

In CA, application of pre-emergence herbicides or early post-emergence herbicides followed by one hand weeding controlled the wide range of weeds, thus recorded the highest weed control efficiency (Choudhary *et al.*, 2016; Sepat *et al.*, 2017).

The application of herbicides minimizes the weed seed bank and number of weeds over time. Therefore, under CA, herbicides must be included as potential tools to reduce weed density, species richness and species diversity and these would be economical and profitable as well (Muoni *et al.*, 2014). The potential herbicides for different crops under CA are given in Table 4.

Integrated weed management (IWM)

Despite continuous efforts to control weeds, their infestation is a continuous threat to the

Table 4. Herbicides for crop grown under conservation agriculture (Choudhury *et al*., 2016; Chhokar *et al*. 2012; Rao *et al*., 2007; Chhokar *et al*., 2020; Sprague and Burns, 2018)

Crop	Pre planting	Pre-emergence	Post-emergence
Wheat	Glyphosate Paraquat	Pendimethalin Pyroxasulfone Sulfentrazone Carfentrazone, Metsulfuron +	Clodinafop, Pinoxaden, Sulfosulfuron, Meso+iodosulfuron, Metsulfuron, 2,4-D, carfentrazone, Sulfosulfuron+ metsulfuron
Rice	Glyphosate Paraquat	Pendimethalin Pretilachlor	Bispyribac-Na, Penoxsulam, Pretilachlor, Triafamone 20% + Ethoxysulfuron 10% (Council active), Pyrozasulfuron, Flucetosulfuron, Azimsulfuron, Rice star (fenoxaprop+safener), Almix (metsulfuron+chlorimuron), Cyhalofop, Metamifop, Halosulfuron
Maize	Glyphosate Paraquat	Alachlor Diuron	Atrazine, Tembotrione, Mesotrione, Topramezone, Atrazine + mesotrione/ topramezone/ tembotrione, Halosulfuron, 2,4-D
Bajra	Glyphosate Paraquat		Atrazine, 2,4-D
Sorghum	Glyphosate Paraquat		Atrazine, 2,4-D
Barley	Glyphosate Paraquat	Pendimethalin	Pinoxaden, Isoproturon, Metsulfuron, 2,4-D, Carfentrazone, Metsulfuron+ carfentrazone
Mustard	Glyphosate Paraquat	Pendimethalin Oxadiargyl	Isoproturon, Quizalofop, Clodinafop, Pinoxaden
Soybean	Glyphosate Paraquat	Sulfentrazone Pendimethalin Alachlor Metlochlor	Chlorimuron, Imezathypyr, Flauzifop, Clodinafop, Quizalofop-ethyl, Fomesafen, Fomesafen 13.4%+ Fluazfop-p-butyl 11.1%, Propaquizafop 2.5% + Imazethapyr 3.75%, Imazethapyr 35% + Imazamox 35%, Acifluorfen 16.5%+ clodinafop 8%
Greengram	Glyphosate Paraquat	Pendimethalin Alachlor	Acifluorfen 16.5% + clodinafop 8%, Flauzifop, Clodinafop, Quizalofop-ethyl, Propaquizafop,
Chickpea/ Gram	Glyphosate Paraquat	Pendimethalin,Oxyfluorfen + Glyphosate; pyroxasulfone Sulfentrazone	Oxyfluorfen, Quizalofop-ethyl
Cotton	Glyphosate Paraquat	Pendimethalin Diuron Alachlor	Quizalofop-ethyl, Pyrithiobacs sodium, Fenoxaprop-p-ethyl

Contd...

Lentil	Glyphosate Paraquat	pyroxasulfone	Quizalofop-ethyl, Fenoxaprop-p-ethyl
Linseed	Glyphosate Paraquat; pyroxasulfone	Sulfentrazone	Clodinafop; Fluazifop-P-butyl; Sethoxydim; Bromoxynil; isoproturon; clopyralid; MCPA; imazethapyr; chlorsulfuron + linuron; topramezone, and fluthiacet-methyl
Pea	Glyphosate Paraquat	Pendimethalin Sulfentrazone	Bentazone,imazethapyr, Imazamox; Quizalofop-ethyl
Onion and Garlic	Glyphosate Paraquat	Pendimethalin	Oxyfluorfen; Quizalofop-ethyl

sustainable crop production particularly when a single method or practice of weed control is practiced. The evolution of herbicide-resistant weeds is one of the major issues being encountered due to sole dependence on herbicide as weed control option. Besides herbicide resistance, shift in weed population is another major challenge for the growers. To tackle these problems, IWM approaches may be quite helpful and is the best way to control the weeds. Integrated weed management involves the integration of the best practices providing the favorable conditions to crop but not to weeds and also minimize the impact of escaping weeds on the crop productivity. So, various diversified practices should be integrated to achieve effective weed management, which is environmentally and economically viable.

Approaches such as stale seed bed practice, modifying row spacing and orientation to provide uniform and dense crop stand, sowing time adjustment, and use of competitive cultivars, mulching and cover cropping, intercrops having allelopathic potential, crop diversification along with efficient nutrient and water management, should be integrated with chemical weed control for sustainable weed management in CA. Herbicides in sequence (pre- followed by post-emergence) or in mixtures should be targeted for diverse weed flora control. Also, modified or strategic tillage is another aspect which can be explored for management of some emerged problematic weeds difficult to control with herbicides in CA systems. Potential non-conventional weed management strategy, such as, harvest weed seed control to reduce weed seed bank is a new aspect under Indian conditions to be explored in future. This strategy is quite useful in present situations of diminishing availability of effective herbicides due to resistance evolution as well as restricted new chemical group introduction and can be targeted to reduce weed populations substantially and ultimately the potential for weed adaptation and resistance evolution.

Various agricultural practices should be adopted and integrated to reduce competitiveness of weeds or enhanced crop competitiveness. Further, practices for enhanced crop competive-ness with a combination of pre- and post-emergence herbicides could be integrated to develop sustainable and effective weed management strategies under CA systems.

Conclusions

Intensive agriculture has not only increased food grains production but also caused degradation of natural resources (soil and water), increased the cost of cultivation and aggravated environmental pollution. Conservation agriculture can be a remedy for these, but weeds are major constraint in the CA during initial phase of its adoption. The three principles of CA can influence weed emergence, persistence and dynamics and herbicide efficacy.

In the absence of tillage, a large proportion of weed seed bank remains generally on or close to the soil surface under CA and can lead to higher weed infestation of those weed species, whose germination is stimulated by light, On the other hand, weed seeds present on the soil surface are also more prone to desiccation and greater predation activity. So, in the absence of tillage, perennial and small seeded weeds may become more challenging in CA system. However, the feasibility of pre-plant application of glyphosate as well as its post-emergence application in glyphosate resistant/tolerant crop cultivars (corn, cotton and soybean) has made it possible to effectively control perennial as well as other diverse weeds. However, a recent restriction on the use of glyphosate can have implication on CA production systems unless a better alternative herbicide to glyphosate is not made available to farmers. The other principle of CA introduces crop diversity through crop rotation and/or intercropping resulting in significant influences on weeds, both spatially and temporally, that may have an edge against weeds. Moreover, the mulching and cover crops in CA can bring extra-benefits for weed management.

The efficacy of pre-plant and pre-emergence soil-applied herbicides may be reduced due to lack of herbicide incorporation by tillage and interception of herbicides by the crop residue, respectively. Therefore, there is need to alter herbicide application technique towards achieving higher weed control efficiency. Besides, the increasing reliance on herbicides and usage of herbicide-resistant crops in CA can also lead to changes in weed population dynamics and occurrence of herbicide-resistant weed biotypes. So, greater efforts are needed towards the optimization and integration of various non-chemical and chemical weed control options for effective weed management in CA under various cropping systems.

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Received: April 05, 2021; Accepted: June 19, 2021