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Crop Establishment with Conservation Tillage on Viable Weed Seed Density and Diversity in Soil, Crop and Water Productivity under RWCS in North-West IGP: A Review

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ABSTRACT

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The rice–wheat cropping system in the North West IGP is the backbone of food security in India. In the 1990s, due to the scarcity of resources, the traditional Crop Establishment (CE) method shifted from Conventional Till Puddle Transplanted Rice (CTPTR) to CT Direct Seeded Rice (CTDSR) and Zero-Till DSR (ZTDSR) in paddy; and in wheat, from Conventional Till Wheat (CTW) to Zero Till Wheat (ZTW), with residue retention in rice (RRR) or in both rice and wheat (RRRW). Shift in CE methods led to change in Weed Seed Bank (WSB) dynamics and ultimately affected the weed management practices. Review study showed that CTPTR-CTW and ZTDSR-ZTW (RRRW) record the highest seed bank (SB) of grasses, sedges and BLWs as total weeds, in general; and predominant weeds i.e., *Echinochloa* spp., *Ammania baccifera*, *Commelina benghalensis* and *Digitaria sanguinalis*, in particular. It also showed the higher species richness (D_{Mg}) and Shannon–Weaver (H') indices. CTDSR-CTW and CTDSR-ZTW (RRR) show the lowest WSB and at par with Shannon–Weaver (H') index; further, lowest species richness (D_{Mg}) under CTDSR-CTW. The average yield losses caused by weeds in different wheat growing zones ranged from 20 to 32%. Uncontrolled weeds in wheat caused 60.5% reduction in wheat grain yield under CT and 70% in ZT conditions. Potential solutions include a shift from intensive tillage to no or reduced tillage and/or from transplanting to direct-seeding. Zero tillage ameliorates the problem of delayed sowing as well as reduces weeds like *Phalaris minor* in wheat. Adoption of conservation agricultural practices reduces the intensity of soil manipulation thereby creates an unfavorable condition for weed seed germination, reduces the organic matter depletion and soil degradation. Reducing tillage may shift weed communities from annual dicots to grassy annuals and perennials. Surface residues lower average soil temperatures and may delay emergence of both crops and weeds. Germination and growth of small-seeded annuals will suffer from restricted light availability, physical growth barriers and potential allelopathic effects from surface of irrigation water, but with an associated yield loss of 14 to 25%. Nevertheless, water use efficiency (WUE) in the residue. Compared with conventional puddled transplanting; direct seeding of rice on raised beds had a 13 to 23% savings rice wheat system was higher with direct seeded rice (0.45 g $L^{-1)}$ than with transplanted rice (0.37-0.43 g L^{-1}). Moreover, CT-TPR system, zero till direct-seeded rice (ZT-DSR) consumed 6%-10% less water with almost equal system productivity and demonstrated higher water pro-ductility.

Introduction

Seed bank is the source of the above-ground weed community in most cropping systems. The seed bank comprises weed seed recently shed and older seeds that originate from earlier years. In agronomic crop production systems, the soil seed bank (viable þ dormant seeds) is the primary source of new infestation of annual weeds in each year, and represents the majority of weed species. Buhler *et al.*, (1997) highlighted that understanding of soil weed seed dynamics is essential to develop improved weed management system. In fact, alteration in crop management practices such as crop rotation and tillage practices influence the viable weed seed density and dynamics by smothering and igniting the emergence of weeds (Dorado *et al.*, 1999).

Weeds are one of the key threats to crop productivity, input-use efficiency and profitability in rice-based cropping systems. Continuous cultivation of rice-wheat cropping sequence favored the intensification of grassy weeds (Bhatt *et al.*, 2016). Tillage systems, crop rotations, choice of crop and management practices affect weed infestation by altering weed seed banks and species composition. Cultivation of crops having similar management practices favors certain weed species to become dominant in the system (Chauhan *et al.*, 2012).

Weed biomass, density, composition and temporal variation are closely associated with management practices, especially tillage (Garcia de Leon *et al.*, 2014; Nichols *et al.*, 2015).

For example, conventional tillage practices may effectively control weeds by burial (Wall, 2008), or stimulate weed germination by raising soil temperature (Murphy *et al.*, 2006). Alternatively, minimal or reduced tillage can shift weed composition from broadleaf to grass species or perennial weeds or increase weed species diversity when specific habitats for certain weeds are created (Murphy *et al.*, 2006). Mulch or soil cover may reduce or inhibit weed germination through the release of allelopathic compounds or smothering of weeds (Thierfelder and Wall, 2010). Furthermore, weeds can be influenced by location, time, nitrogen management, timing of cultivation, rainfall, crop residue management, crop rotations, harvest procedures and other aspects of the production system (Wall, 2008).

Changes in tillage regime may cause floristic inversion due to changes in the seed-bank (Ball, 1992). Incorporating seeds deeper into the soil with tillage might favor conditions for an increase of seed-bank (Buhler *et al.*, 1997), but burying seeds might also avoid seed germination (Chauhan *et al.*, 2006) and favor seed deterioration (Gomez *et al.*, 2013). Under no-till and RTF, seeds are more likely to remain near the soil surface where they are susceptible to insect and bird predation in the summer periods (Baraibar *et al.*, 2017). Germination of some species is favored when seeds are near the soil surface and thus no-till and RTF will increase seedling emergence compared with conventional tillage. However, Mohler, (1993) observed that emergence increased in the first year followed by reduction in later years due to depletion of the seed surface fraction by the action of herbicides and shallow cultivation.

Moreover, crop residues associated with no-till and RTF may suppress weeds by blocking sunlight and reducing physical space for seedling emergence (Fernandez *et al.*, 2008). This paper reviews the crop establishment with tillage practices on weed seed density and diversity and productivity in rice-wheat rotation.

Crop Establishment Methods

Chauhan *et al.*, (2015) reported that grass weeds were higher in dry-seeded rice compared to puddled transplanted rice (PTR) and nonpuddled transplanted rice. The highest total weed density (225–256 plants m^{-2}) and total weed biomass (315–501 g m^{-2}) were recorded in dry-seeded rice, while the lowest (102–129 plants m^{-2} and 75–387 g m^{-2}) in PTR. Chhokar *et al.*, (2014) also found the highest yield and least weed abundance in the PTR. Compared to the transplanting rice, severe weed infestation was found in the dry and wet DSR and thus lesser yield was found in DSR compared to transplanting rice both in the presence and absence of weeds. The yield losses due to weeds in the DSR treatments ranged from 91.4 to 99.0 %, compared to 16.0 and 42.0 % in the transplanting treatments. Weeds, including *C.rotundus*, *D. aegyptium*, *Digera arvensis* Forsk., *Phyllanthus niruri* L., and *T. portulacastrum*, which were present in the unpuddled DSR treatments, were not found in the puddled plots, particularly the puddled transplanting treatments. When rice residues are kept on soil surface as mulch, reduced weed emergence of key weeds of wheat in the range of 45-99%, depending on species and mulch amount. Emergence of *P. minor*, *Chenopodium album*, and *R. dentatus* was inhibited by 45, 83 and 88%, respectively at 6 t/ha rice residue load com-pared to without residue mulch (Kumar *et al.*, 2013).

Sharma et al.(2020) also found that CTDSR-CTW recorded the lowest Shannon–Weaver (H) and Species richness (D_{Mg}) while the highest in CTPTR-CTW, statistically at par with CTDSR-ZTW (RRR) and ZTDSR-ZTW (RRRW). Conversely, the highest β_W was observed under the CTDSR-CTW and the lowest in CTPTR-CTW which is at par with CTDSR-ZTW (RRR) and ZTDSR-ZTW (RRRW). Change in the crop establishment methods alters the soil ecology, while affecting the soil nutrient, soil structure and temperature, as well as the depth of burial of weed seeds, which ultimately affects the germination of weed species and its composition (Plaza *et al.*, 2011). In fact, level of soil disturbance affects the weed species richness, abundance and density of weeds (Lal *et al.*, 2016). Species diversity within weed communities and the nature of their relationship are of agronomic importance. However, weed categories and their species, maximum WSB observed at the top 0–10 cm, which gradually reduced with depth. Likewise, weed diversity indices, except β_W, also record the similar trend. Higher species richness and Shannon–Weaver index in top 0–10 cm indicate more diverse number of weed species exists; further, higher Simpson index in 0–10 and 10–20 cm soil depth signifies the dominance of some of the species in the upper layer as compared to the lower depth.

Nandan *et al.*, (2020) observed that the extent of weed seed emergence differed (0.7–29 m^2 in 2013-14 and 0.7–27 in 2014-15) among treatments. Density was the lowest for *Sonchus oleraceous* L., *Anagalis arvensis* L., *Phyllathus niruri* L., and the highest for *Cyperus iria* L. The total weed seed emergence was higher in rice-wheat rotation over rice-maize system (Fig. 1).On average, treatment receiving crop residue had the higher seed density over no-residue application. The total weed seed density in ZTTPR-ZT, UPTPR-ZT, and CTTPR-CT did not differ, however, they significantly recorded 4.8, 4.1, and 3.4% higher emergence (mean of two years) over ZTDSR-ZT, respectively (Fig. 1).However, in rice-maize system recorded the significantly higher *Oxalis corniculata* L. emergence over rice-wheat system by 64%, whereas, with residue treatment recorded 32% higher *O. corniculata* emergence over without residue addition (**Fig.**

2). The UPTPR-ZT, ZTTPR-ZT, and ZTDSR-ZT systems recorded the lower O. *corniculata* seed density by 37, 62, and 61%, respectively, over the CTTPR-CT. However, CTTPR-CT system had higher *Chenopodium album* L. and *Rumex dentatus* L. emergence over the other practices (Fig. 2). Among tillage practices, ZTTPR-ZT and UPTPR-ZT recorded higher *S. nigrum* emergence over CTTPR-CT.

Viability of weed seeds

Tillage-induced changes in seed distribution will also have implications for seed viability. Burial increases seed survival while seeds on or close to the soil surface can lose viability due to desiccation and harsh weather (Anderson, 2005).Therefore, depending on the extremity of the environment, the accumulation of seeds on un-tilled soil surfaces may increase the proportion of un-viable weed seeds in the seed-bank. Seed dispersal and recruitment may be affected by tillage practice. Field traffic and machinery operations such as tillage provide opportunities to introduce or spread weed seeds (Buhler *et al.,* 1997). One study showed cultivation following harvest significantly increased weed seed dispersal (Heijting *et al.,* 2009), and another found the weed seeds travelled 2–3 m in the direction of tillage, while in un-tilled soils the distance was negligible (Barroso *et al.,* 2006). Reducing tillage can therefore reduce the spread of weed seed both within and across fields.

Chhokar *et al.,* (2007) reported that *Rumex dentatus* was significantly higher (12.1 plants/m^2) under zero tillage (ZT) compared to conventional tillage (CT) (1.9plants/m^2). CT favored *Phalaris minor*. The average P. *minor* dry weight under ZT and CT was 234.7 and 386.5 g/m^2, respectively. This differential response reflected was due to variation in seed distribution during puddling performed for rice transplanting. Swanepoe *et al.,* (2015) reported that a temporal variation can be expected; with an increase in weed biomass under RT practices, while under CT practices weed biomass was more stable over cultivation time. Similarly, we detected a temporal trend in weed species diversity, where species diversity increased under RT but decreased under CT. Following this trend we would expect a time effect on species composition, with higher diversity the longer the trial continues. Indeed species diversity suggests that RT had higher species diversity than CT. CT also had a low Evenness index (E), which suggests that CT is dominated by a few weed species, but that these species occurs in high abundance, while RT had a lower E value and hence higher diversity, but at lower abundances. Furthermore, the temporal variation in weed biomass under different tillage practices concurs with Swanton *et al.,* (1999) who reported that weed biomass varied between tillage practice and cultivation year.

In conventionally tilled soils, this can be explained by the increase in environmental variables, such as temperature and moisture, as a result of tillage. Increased environmental variables could lead to more favorable conditions in certain years, and this in turn could lead to a large year-to-year variation in weed density. Changing tillage regimes changes the disturbance frequency of the farm field, which results in a shift in weed species (Boscutti *et al.,* 2015). As NT can favor certain granivore species over others, the associated shift in preferred seed consumption may contribute to altered seed-bank composition (Brust and House, 1988). While there is consensus that the weed species composition will shift in response to changes in tillage, whether the diversity of the weed community increases is less clear. Ecologically, highly disturbed environments will tend to be simpler than more stable ones.

Compared to tilled soils, higher weed species diversity has been observed in NT seed-banks (Sosnoskie *et al.*, 2006) emerged weed communities or both (Murphy *et al.*, 2006). Studies that report no increase in diversity with NT all found either crop rotation or weather had a larger effect on weed species diversity. While tillage will contribute to community shifts, the weed species present will be an expression of both management and the environment, which in many cases may be simply the weather (Boscutti *et al.*, 2015).

Nandan *et al.*, (2020) also found that weed species belonging to different botanical families were emerged (Tables 1). Of the total 33 weed species, 15 species were present abundantly in all treatments.The extent of weed seed emergence differed (0.7–29 m^{-2}) among treatments. Density was the lowest for *Sonchus oleraceous* L., *Anagalis arvensis L*., *Phyllathus niruri* L., and the highest for *Cyperus iria* L. Furthermore, CTTPR-CT to UPTPR-ZT and ZTDSR-ZT systems in rice-maize and rice-wheat systems significantly influenced the weed seed density and diversity. Fifteen weed species were abundantly present, and 5 species were in high frequency in all the treatments out of total 33 weed species in the seed-bank.

It indicated that manipulation in crop management practices can alter the abundance of weed species. Moreover, *C. iria*, *P. minima*, *O. corniculata*, *C. album*, and *B. diffusa* were present in huge density in all the treatments. Hence, these weed species in seed-bank can be the most dominant weed flora in these ecologies in future. The soil micro climate was not favorable for their germination in the field or low sensitivity of these weeds to the cropping systems and tillage techniques kept these weeds dormant in field (Nandan *et al.*, 2018a).

Barberi and Lo Cascio, (2001) reported that the 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. Moreover, the findings of a long-term experiment with four tillage systems (Fig. 3a) 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. 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 awn-less barnyard grass *and* rice flats edge in rice, but rotational tillage systems significantly reduced the seed density of these weeds.

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% (Fig. 3b). The effectiveness of crop residue to reduce weed emergence also depends upon the nature of weed species to be controlled.

Weed flora and density

Weed flora of wheat differ from field to field, depending on environmental conditions, irrigation, fertilizer use, soil type, weed control practices and cropping sequences. The predominant weeds associated with conventional till wheat are *Phalaris minor*, *Poa annua, Polypogon monspeliensis, Avena ludoviciana, Rumex dentatus, R. spinosus,* *Anagallis arvensis, Convolvulus arvensis, Malva parviflora, Medicago denticulata, Chenopodium album, Vicia sativa, Lathyrus aphaca, Circium arvense, Melilotus alba, Coronopus didymus, Polygonum plebejum* and *Spergula arvensis*. Among grassy weeds, *P. minor* and among broad-leaved weeds, *Rumex dentatus* and *Medicago denticulata* are of major concern in irrigated wheat under rice-wheat system in India (Chhokar *et al.*, 2006). *Phalaris minor* is major problem in heavy soils, whereas, wild oat is more prevalent in light textured soil under non rice-wheat rotation. Both *P. minor* and *R. dentatus* are highly competitive weeds and can cause drastic yield reduction under heavy infestation. Evolution of resistance in *P. minor* (Chhokar and Sharma, 2008) against isoproturon has made it a single weed species limiting wheat productivity in the North-Western plains of India.

Tillage can influence the vertical weed seed distribution in the soil profile, soil moisture, diurnal temperature fluctuations, light availability, and activities of seed predators and microbes. All these factors can affect weed recruitment in the field by influencing seed dormancy, emergence, and seed mortality. Reduced tillage favoured the growth of *Cirsium arvense* and *Convolvulus arvensis* (Catizone *et al.*, 1990). ZT wheat lowers the *P. minor* infestation, which is the main threat to the sustainability of wheat production under rice-wheat system (Franke *et al.*, 2007). Yadav and Singh (2005) observed that maximum *P. minor* population emerged from 0-3 cm soil depth. In both CT and ZT wheat, after direct seeded unpuddled and puddled rice, there was no emergence of *P. minor* from 6-9 cm depth but still 5% population could emerge from this layer after transplanted rice. Under CT wheat, there was 16% increase in *P. minor* density during 15 to 20 days after sowing in the field before irrigation, but after first irrigation the density of this weed increased by 175% during 20 to 40 days after sowing. In ZT wheat, the density of this weeds increased by 61% before irrigation and after irrigation this increase was only 102%.

Radhey Shyam *et al.*, (2009) reported that wheat sown with CT led to significantly higher density of *P. minor, M. indica, M. denticulata* and *C. album* as compared to ZT sown crop. Contrary to this, weed seeds remained in sub-surface under zero till sown crop due to puddling carried out during paddy transplanting and failed to germinate because of unfavorable conditions (Sinha and Singh, 2005). Mishra and Singh (2012) showed a strong propensity to increase under all the tillage systems (ZT and CT in rice and wheat continuous and alternated) indicating its ability to persist under modern cropping systems. But in subsequent years, continuous zero tillage lowered its population. *Chenopodium album* seedling emergence declined significantly due to ZT wheat sowing during first year; in subsequent years, population of *C. album* was completely eliminated due the increased density of *A. ludoviciana* and *M. hispida* in all the tillage systems.

Weed seed bank and its dynamics in soil

Weed seed bank is the natural storage of various weed seeds at different depths in soil. The seed bank in the soil builds up through seed production and dispersal, while it depletes through germination, predation and decay. The distribution of weed seeds within the soil profile is mainly influenced by different types of tillage practices. Repeated tillage reduces the number of weed propagules in the plough layer. Weed seed burial by tillage is difficult or negligible in case of conservation tillage than in conventional tillage. No-tillage system leaves most of the weed seeds in the top one cm of soil profile, whereas mouldboard ploughing tends to uniformly distribute seeds throughout the profile, and chisel ploughing and other reduced tillage systems are intermediate in differential distribution of seeds in the soil profile. Redistribution of seeds in soil profile is stimulated by tillage practices which favor germination. In the ZT system, the weed seed bank remains on or close to the soil surface after cropplanting (Chauhan *et al.,* 2006). Better tilth and exposure of the weed seeds to upper soil may be responsible for higher weed infestation under conventional tillage than ZT. Seeds of some species like *R. dentatus* are sensitive to burial depth, which could not emerge at a burial depth of 4 cm (Dhawan, 2005). Weed species like *Digitaria ciliaris* does not emerge from a seed burial depth of 6 cm (Chauhan and Johnson, 2008). Though most of the weed seedlings emerge from top 0.5 to 2 cm depth of soil layer, some weeds species like *Mimosa invisa* and *E. crusgalli* can emerge from a burial depth of 8 cm (Chauhan and Johnson, 2010). ZT systems may reduce the emergence of seedlings of some weed species, as seeds at the soil surface are prone to rapid desiccation. Tillage has also been found to influence vertical seed distribution and seed bank dynamics, resulting in higher weed pressure in ZT systems due to presence of weeds in uppermost soil layer (Singh *et al.,* 2015). Differential vertical distribution of seeds in soil has the potential to affect seedling emergence and weed population dynamics, as soil depths differ in availability of moisture, diurnal temperature fluctuation, light exposure and activity of predators. For determination of seed depth and seed germination, seed burial and excavation by tillage is main factor. However, tillage is not solely responsible for seed burial at different depths, but natural processes also play significant role in partial burial. Seed densities of *P. minor, Melilotus indica* and *C. album* in soil were significantly lower under ZT as compared to conventional tillage from 0 to 5,5 to10 and 10 to 15cm soil depths, respectively, whereas, seed density of *Rumex acetosella* in soil was found higher in case of ZT than others, but differences were significant only at 5-10 cm of soil depth (Shyam *et al.,* 2014).

Arif *et al.,* (2007) in maize noted that the major were *Cyperus rotundus*, *Cynodon dactylon*,*Chenopodium album*, *Echinochloa crus-galli* and *Cucumis prophetarum* and were sorted into groups according to their life cycle. Annual weeds did not show dependable response to tillage system eccept *E. colonum* which decreased with increase in tillage intensity. These results agree with Bostrom and Fogelforsm (1999) who reported that soil disturbance has limited influence on the summer annual weeds. Among the perennial weeds, the density of *C. dactylon* decreased with increase in tillage intensity while *C. rotundus* showed inconsistent response to tillage intensity.

Brar and Walia, (2007) also found that infesting wheat fields and of theses, *Phalaris minor, polypogan monspeliensis, Poa annua, Rumex dentatus, Medicago denticulate, Anagallis arvensis and Malva nelgecta were most common.* Slightly higher population of broadleaf weeds was observed in zero tillage as compare to the conventional methods while adverse trend was seen in case of broadleaf weeds

Punia *et al.,* (2016) reported that in rice *E. colona*, L. *chinensis*, *E. crusgalli*, *C. difformis*, *A. baccifera* and *Dactyloctenium aegyptium* were the major weeds emerged from soil at different soil depths. Number of weed seeds emerged was more in ZT-ZT and MT-ZT treatments as compared to CT-CT. Weed density was maximum in upper 0-5 cm soil layer in all treatments. Moreover, from different soil depths under different treatments before wheat sowing revealed predominance of *P. minor*, *C. album* and *M. indica* in all treatments. Density of weeds was maximum in CT-CT treatment and it was distributed in all soil depths being more in 0-5 and 5- 10 cm soil depths. In ZT-ZT and CT-ZT (rice-wheat) treatments, density of weeds was minimum and that was mainly concentrated in 0-5 and 5-10 cm soil depth. *P. minor* population was very low in ZT-ZT or CT-ZT treatments as compared to CT-CT in 0-5 cm and 5-10 cm soil depth. Density of broad-leaf weeds particularly *C. album* was more in CT-ZT treatment followed by ZT-ZT and MT-ZT treatments at both soil depths.

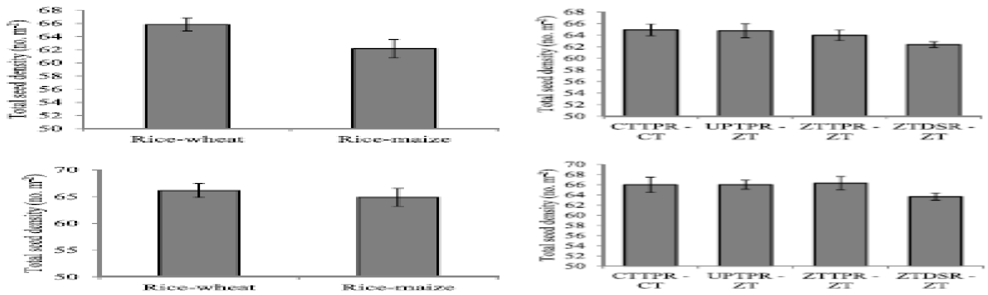
Sharma *et al.*, (2020) reported that the vertical distribution of SB of grasses, sedges, BLW, and total weeds had been affected by the different CE methods (Fig. 4a). In CTPTR-CTW, there was almost a uniform distribution of the grasses, BLWs, and total weeds, while the sedges SB observed significant reduction (14.29%) in the 20–30 cm layer. In CTDSR-CTW, the top layer (0–10 cm) contained about half of the total WSB (47–59%) and thereafter gradual decrease in the WSB with respect to the depth, except sedges in which there was an abrupt decrease in SB with depth i.e., from 73.33 per cent in 0–10 cm to 6.67 per cent in 20–30 cm. Furthermore, in CTDSR-ZTW (RRR) and ZTDSR-ZTW (RRRW) methods, SB of most of grasses (68–72%), BLWs (68–82%), and total weeds (65–76%) was confined to the upper layer of the soil profile (0–10 cm). The bottom layer (20–30 cm) consisted of the minimum grassy weeds (9–14%), BLWs density (5%) and total weeds (7–9%). Conversely, the top layer of soil profile (0–10 cm) consisted of about 54–59% sedges SB, while the subsequent layers, i.e., 10–20 cm and 20–30 cm consisted of 31–35% and 5–6% of sedges density in both the ZT systems (CTDSR-ZTW (RRR) and ZTDSR-ZTW (RRRW).

Table.1 Effect of cropping systems, residue management, and tillage techniques on total seed density (no. m^{-2}) of individual weed

Weed species	Cropping system*		Residue management		Tillage techniques			
	Rice-wheat	Rice-maize	Without residue	With residue	CTTPR-CT	UPTPR-ZT	ZTTPR-ZT	ZTDSR-ZT
Echinochloa colona L.	11.2 ± 1.5	7.9 ± 0.9	11.5 ± 1.0	7.7 ± 1.5	13.0 ± 0.8	8.5 ± 1.5	9.2 ± 2.5	7.6 ± 0.9
Leptochloa chinensis L.	0.71 ± 0.0	1.34 ± 0.6	1.34 ± 0.7	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0	1.34 ± 0.7	1.34 ± 0.7
Cyperus iria L.	27.5 ± 1.3	24.6 ± 2.0	26.0 ± 2.1	26.1 ± 1.0	29.2 ± 3.6	20.8 ± 0.8	25.6 ± 3.3	28.6 ± 2.8
Cyperus rotundus L.	4.21 ± 1.5	2.67 ± 0.9	4.07 ± 0.6	2.81 ± 0.3	2.81 ± 1.3	4.91 ± 0.4	1.96 ± 0.6	4.07 ± 1.1
Caesulia axillaris Roxb.	9.6 ± 0.9	7.2 ± 1.4	7.9 ± 1.3	8.9 ± 0.3	13.2 ± 2.1	8.1 ± 1.0	2.9 ± 1.1	9.4 ± 0.7
Alternanthera philoxiroides Griseb.	10.1 ± 1.1	15.6 ± 2.6	12.5 ± 2.9	13.1 ± 2.0	8.6 ± 1.6	13.5 ± 1.5	18.0 ± 3.2	11.2 ± 2.7
Euphorbia hirta L.	4.6 ± 0.9	6.5 ± 0.8	6.0 ± 0.3	5.1 ± 1.9	1.3 ± 0.6	8.6 ± 2.8	8.8 ± 0.6	3.4 ± 1.4
Physalis minima L.	22.2 ± 3.9	9.0 ± 2.3	14.8 ± 2.9	16.4 ± 3.2	13.1 ± 2.6	22.0 ± 5.4	16.1 ± 4.4	11.2 ± 1.5
Amaranthus viridis L.	3.16 ± 0.9	5.71 ± 1.6	3.55 ± 1.4	5.32 ± 0.9	4.85 ± 2.1	2.87 ± 1.3	6.50 ± 0.9	3.50 ± 1.6
Portulaca oleracea L.	3.93 ± 0.3	2.78 ± 0.6	3.55 ± 0.9	3.16 ± 1.1	3.09 ± 0.5	0.71 ± 0.0	6.74 ± 1.5	2.87 ± 1.3
Trianthema portulacastrum L.	3.99 ± 0.7	6.03 ± 1.8	4.45 ± 0.8	5.57 ± 1.6	5.61 ± 2.1	3.85 ± 0.6	6.17 ± 0.4	4.41 ± 0.9
Cyanotis axillaris L.	1.02 ± 0.3	1.48 ± 0.7	1.48 ± 0.7	1.02 ± 0.3	0.71 ± 0.0	0.71 ± 0.0	2.25 ± 0.8	1.34 ± 0.6
Ageratum conyzoides L.	2.07 ± 0.6	2.42 ± 0.2	2.42 ± 0.8	2.07 ± 0.4	1.34 ± 0.6	3.73 ± 1.0	2.59 ± 1.8	1.34 ± 0.6
Eclipta prostrata L.	4.49 ± 1.8	4.90 ± 2.2	3.39 ± 1.6	6.01 ± 2.3	5.94 ± 1.5	3.37 ± 1.3	6.38 ± 2.0	3.09 ± 1.5
Ammania baccifera L	4.47 ± 1.4	3.01 ± 1.3	4.01 ± 2.4	3.47 ± 1.3	4.80 ± 1.2	3.50 ± 1.4	3.22 ± 1.5	3.44 ± 1.7
Ludwigia hyssoypifolia G. Don	6.49 ± 1.9	4.07 ± 2.4	3.98 ± 1.7	6.58 ± 2.1	2.46 ± 1.7	3.72 ± 1.1	6.52 ± 2.1	8.42 ± 2.2
Corchorus olitorius L.	1.73 ± 0.8	0.71 ± 0.0	1.16 ± 0.4	1.27 ± 0.5	0.71 ± 0.0	1.62 ± 0.9	1.84 ± 1.1	0.71 ± 0.0
Oldenlandia corymbosa L.	9.8 ± 2.8	9.4 ± 2.3	9.3 ± 2.5	9.9 ± 2.6	10.1 ± 3.0	8.6 ± 2.9	9.2 ± 2.2	10.6 ± 3.6
Phyllanthus niruri L.	1.34 ± 0.3	0.71 ± 0.0	0.71 ± 0.0	1.34 ± 0.3	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0	1.96 ± 0.6
Boerhavia diffusa L.	20.8 ± 2.6	14.1 ± 6.4	14.9 ± 0.7	20.0 ± 2.1	14.7 ± 2.8	18.9 ± 1.9	16.1 ± 0.5	20.2 ± 1.3
Melilotus indicus L.	5.01 ± 1.2	1.65 ± 0.5	2.28 ± 1.1	4.38 ± 0.4	4.13 ± 1.5	3.09 ± 1.5	2.87 ± 2.1	3.22 ± 0.6
Achyanthes aspera L.	2.95 ± 1.2	1.16 ± 0.4	2.32 ± 1.2	1.79 ± 0.5	2.81 ± 1.1	2.75 ± 0.2	1.34 ± 0.6	1.34 ± 0.6
Rumex dentatus L.	9.4 ± 1.3	7.8 ± 2.0	7.9 ± 1.9	9.4 ± 2.6	8.5 ± 2.2	10.5 ± 1.3	10.0 ± 0.7	5.5 ± 1.1
Sonchus oleraceous L.	1.34 ± 0.6	0.71 ± 0.0	1.02 ± 0.3	1.02 ± 0.3	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0	1.96 ± 1.2
Oxalis corniculata L.	18.0 ± 2.5	15.9 ± 2.9	17.1 ± 2.2	16.7 ± 3.2	21.4 ± 3.1	18.4 ± 1.5	12.8 ± 1.3	15.1 ± 2.1
Medicago denticulata L.	6.1 ± 2.1	7.0 ± 2.8	7.8 ± 2.7	5.3 ± 2.3	6.1 ± 1.6	6.6 ± 2.1	7.8 ± 2.8	5.7 ± 1.5
Chenopodium album L.	14.1 ± 2.6	28.0 ± 1.9	22.9 ± 1.9	19.3 ± 3.2	24.5 ± 3.5	23.2 ± 2.0	19.0 ± 3.8	17.8 ± 3.4
Coronopus didymus Zinn	6.4 ± 2.7	6.2 ± 1.2	6.7 ± 2.4	5.9 ± 1.9	4.2 ± 1.6	7.6 ± 2.2	6.7 ± 2.7	6.7 ± 2.4
Solanum nigrum L.	6.4 ± 2.0	9.6 ± 1.2	8.3 ± 1.0	7.7 ± 0.9	5.8 ± 2.0	9.4 ± 1.2	7.1 ± 1.9	9.7 ± 2.6
Anagalis arvensis L.	1.27 ± 0.5	0.71 ± 0.0	1.27 ± 0.5	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0	1.84 ± 1.0
Circium arvense L.	1.02 ± 0.3	1.96 ± 0.4	1.65 ± 0.5	1.34 ± 0.3	2.59 ± 1.0	1.34 ± 0.6	0.71 ± 0.0	1.34 ± 0.6
Vicia sativa L.	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0	0.71 ± 0.0

Data were subjected to square square-root ($\sqrt{(x+0.5)}$) transformation. Mean values of cropping systems are averaged over residue and tillage treatments. Values are expressed as mean ± standard error of mean.

Fig.1 Effect of different management practices on total viable seed density (no. m^{-2}) in soil



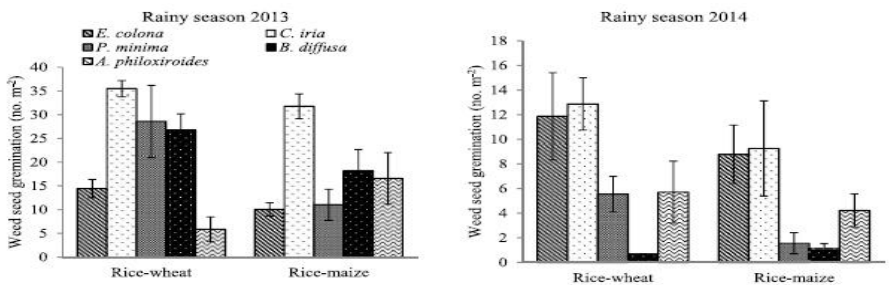


Fig.2 Emergence pattern of major rainy season weeds (no. m^{-2}) under cropping system and tillage techniques

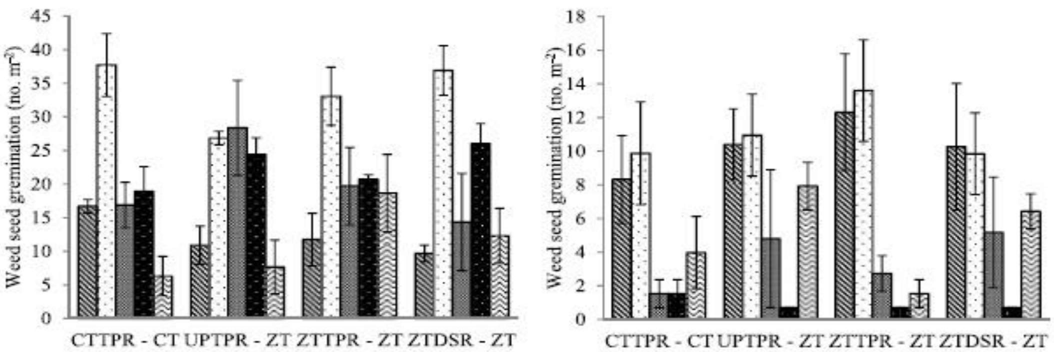


Fig.3a Percent weed seedling distribution over soil layers in mould board ploughing at 45 cm depth (P 45), chisel ploughing at 45 cm depth (CP 45), rotary harrowing at 15 cm depth (RH 15), and zero-tillage (ZT)

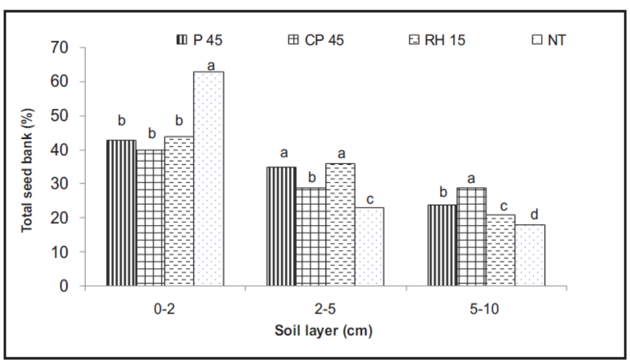


Fig.3b The effect of rice residues on weed germination (Chauhan and Abugho 2012)

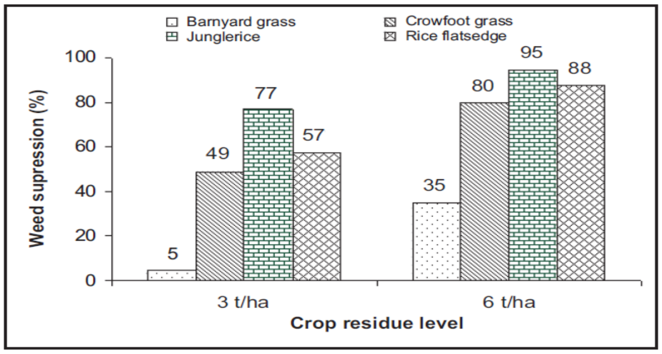


Fig.4a Vertical distribution of grasses, sedges and broadleaved weeds (BLWs) in different crop establishment methods of rice-wheat cropping system

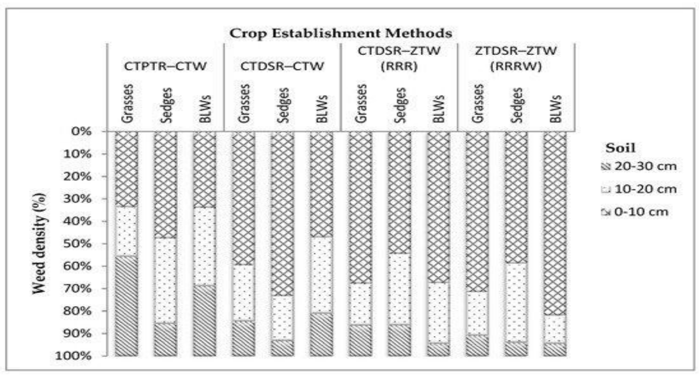
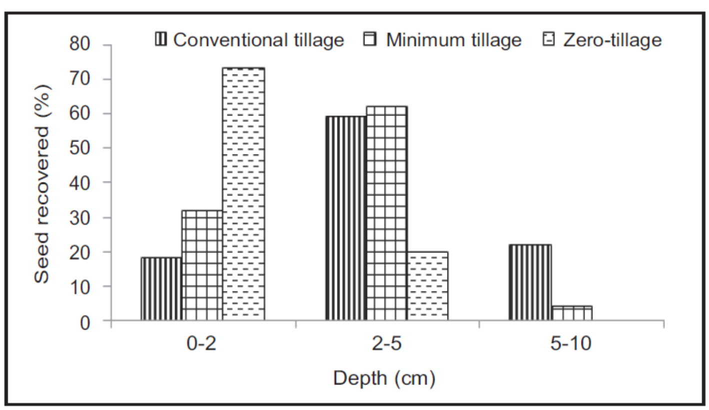


Fig.4b The effect of tillage systems on the vertical distribution of weed seeds



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 (Fig. 4b). 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 (Chauhan and Johnson, 2009).

Crop-Water Productivity

Weed-crop competition begins when crop plants and weeds grow in close proximity and their root or shoot system overlaps. In rice-wheat system, due to enough soil moisture after harvesting of rice, weeds emerge earlier than wheat or along with wheat crop. Losses in wheat yield are primarily due to reduction in tillering. The average yield losses caused by weeds in different wheat growing zones ranges from 20 to 32%. Water In irrigated environments, spatial and temporal variation of soil moisture offers opportunities for weed control. When the top layer of soil is dry, planting large-seeded crops into deep soil moisture can provide crops with an initial advantage over weeds. Another option under these conditions is to apply irrigation to germinate weeds, terminate them using herbicide, then plant the crop into the clean seed bed (Chauhan *et al.,* 2012; Mulvaney *et al.,* 2014).

Yield reductions due to weeds in wheat vary from 15-50%, depending upon the weed density and type of weed flora (Jat *et al.*, 2003). Uncontrolled weeds in wheat caused 60.5% reduction in wheat grain yield under conventional tillage (CT) and 70% in zero-till (ZT) conditions. In extreme cases the losses caused by weeds can be up to complete crop failure (Malik and Singh, 1995). 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 (Jat *et al.*, 2012). Compared to deep tillage, conservation tillage in maize-wheat cropping system involving minimum tillage (in wheat) with *Lantana camara* mulch 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 (Mishra and Singh, 2012). Direct-seeded rice required about 30-40% less water and had 3-times less global warming potential compared with the transplanted rice crop.

In conclusion the findings of the various studies clearly indicated the weed stress on the productivity of rice-wheat cropping system. Out of the various management practices tillage systems and crop establishment may have positive effect on the suppression of weeds in rice-wheat cropping systems. Crop establishment with zero tillage (ZTDSR-ZT and ZTTPR-ZT) had positive impact of crop performance over conventional CTTPR-CT. Avoiding wet tillage (puddling) in rice fallowed by zero till wheat (NPTPR-ZT) also had advantage over CTTPR-CT, but not to that level of complete ZT-based systems. The different TCE practices in rice season also influenced the post-rainy season crop performance. Moreover, total weed seed density was lower under ZTDSR-ZT and ZTTPR-ZT systems than under CTTPR-CT system. It indicates that ZTDSR-ZT and

ZTTPR-ZT systems can minimize weed infestation over time as long as there a high standard of weed management that minimizes seed return. Long-term adoption of conservation tillage (ZTTPR-ZT and ZTDSR-ZT) can minimize the weed severity and can be a sustainable crop management practice, as higher weed density in the initial years can exhaust the seed-bank. It is, therefore, concluded that conservation tillage-based crop establishment are sustainable strategies to upscale the crop productivity of rice-wheat rotation.

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