Viable weed seed density and diversity in soil and crop productivity under conservation agriculture practices in rice-based cropping systems

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ABSTRACT

Viable weed seed density and diversity in soil were assessed in an experiment that comprised two types of crop rotation [rice-wheat and rice-maize], two crop residue management (without residue and with residue), and four tillage techniques: conventional tillage (CT) transplanted puddled rice (TPR) – CT wheat/maize (CTTPR-CT), unpuddled transplanted rice – zero tillage (ZT) wheat/maize (UPTPR-ZT), ZT transplanted rice (ZTTPR-ZT) – ZT wheat/maize (ZTTPR-ZT), and ZT dry seeded rice (ZTDSR-ZT) – ZT wheat/maize (ZTDZR-ZT). The aim was to evaluate the density and community composition of viable weed seed in soil in UPTPR-ZT, ZTTPR-ZT, and ZTDZR-ZT systems with and without crop residue, using the seedling germination method. The soil seed density was assessed in 2013-14 and 2014-15 after 4th and 5th year crop cycles established on a sandy loam soil of Patna, India. Total viable seed density was the highest for Cyperus iria L. irrespective of the treatment in both years. Rice-wheat system recorded 4% higher (mean of two years) seed density over the rice-maize system. Residue management practices did not differ for total viable seed density in both years. The ZTDZR-ZT, UPTPR-ZT, and ZTDZR-ZT systems resulted in significantly higher Shannon-Wiener and Simpson, and evenness indices compared to the CTTPR-CT system. Total viable seed density was the least for ZTDZR-ZT compared to the remaining tillage practices in both years. The sequence for Leptochloa chinensis (L.) Nees emergence was ZTTPR-ZT > ZTDZR-ZT > UPTPR-ZT > CTTPR-CT in 2014-15 (P < 0.05), signifying the more dominance of monocotyledons in ZT systems. The density of total aboveground weed density (no. m⁻²) was higher in ZTDZR-ZT in 2013-14 and lower in 2014-15 compared with remaining tillage techniques at 65 days after sowing. Thus, higher aboveground weed density in ZTDZR-ZT system minimized the soil seed density over time. Complete ZT-based practices (ZTDZR-ZT, ZTTPR-ZT) with crop residue significantly enhanced the grain yield of component crops over the CTTPR-CT. Thus, it implies that exhaustion of soil seedbank in ZTDZR-ZT system after 5 years can reduce the aboveground weed infestation and attain the higher grain yield compared to the CTTPR-CT system.

1. Introduction

Seedbank is the source of the above-ground weed community in most cropping systems. The seedbank comprises weeds seed recently shed and older seeds that originate from earlier years. In agronomic crop production systems, the soil seedbank (viable + 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). Ball (1992) reported that cropping sequence was the most dominant factor influencing the weed species composition in soil, partly due to herbicide use in each cropping sequence producing a shift in the weed species in favor of species less susceptible to applied herbicides. Further, Carter and Ivany (2006) from Canada revealed that weed seedbank size had a critical impact on major

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change in weed community, and found that diversity of weed species was slightly lower for mouldboard plough than under direct drilling. However, Conn (2006) from Alaska reported higher total seed density under no-till than under chisel plough. These findings indicate that the compositions of weed seed in agricultural lands vary greatly, and need to be studied in different agro-ecosystems.

It is obvious that changes in crop establishment practices and adoption of conservation agriculture can alter the periodicity of weed emergence, dominance, and diversity, because of ecological favor toward few weeds or hindrance to some other weeds (Swanton et al., 2000). The conventionally tilled (CT) transplanted puddled rice (Oryza sativa L.) (CTTPR) followed by CT wheat (Triticum aestivum L.) is a common practice in the South Asian countries including India. The transplanted puddled rice requires a high input of labor and water, and results in emission of greenhouse gases (Nath et al., 2017a). Henceforth, continuous adoption of this system resulted in over exploitation of ground water, yield stagnation, deterioration in soil and environment quality (Nath et al., 2017b). Untransplanted puddled rice (UPTPR), zero till (ZT) transplanted rice (ZTTPR), and ZT dry seeded rice (ZTDSR) are tillage techniques under the umbrella of conservation agriculture. The severe weed infestations in conservation agriculture jeopardize its sustainability (Ghersa and Martinez-Ghersa, 2006; Chauhan et al., 2006). The previous studies of Bilalis et al. (2003), Chauhan et al. (2006), Lal et al. (2016), and Ranalivoson et al. (2018) reported the shift in weed species with adoption of ZTDSR, with monocotyledons particularly increasing in density. Recent result of Nandan et al. (2018a) revealed the higher aboveground weed emergence under UPTPR, ZTTPR, and ZTDSR systems than under CTTPR. The conservation agriculture based technologies cannot be overly generalized across the ecosystems (Hobbs, 2007). Hence, assessment of viable weed seed density in soil will provide a prompt answer for what will be the dominant weed flora in specific production ecology and its subsequent management under conservation agriculture.

However, effect of UPTPR, ZTTPR, and ZTDSR with and without crop residue under different cropping systems on weed seed dominance and diversity in soil of rice-based systems is not yet studied. Hence, the objective of present study were to evaluate the density and diversity of viable weed seed in soil, using the seedling germination method, and to

### Table 1
Tillage practices followed in rice, wheat, and maize crops.

| Treatment notation | Details | Rice | Wheat/maize |
|--------------------|---------|-----|-------------|
| CTTPR-CT           | Conventional tillage transplanted puddled rice: 3 times harrowing, 2 times cultivator in standing water and finally 1 planking. |  |  |
| UPTPR-ZT           | Untransplanted rice: 3 times harrow operations and 1 time plowing. No tillage operations in standing water. |  |  |
| ZTTPR-ZT           | Zero tillage transplanted rice. One day flooding prior to seedlings transplant without any soil disturbance. |  |  |
| ZTDSR-ZT           | Zero tillage direct seeded rice. Direct drilling of seeds using zero-till seed cum fertilizer drill without any tillage operations at 20 cm distance. |  |  |

### Table 2
Effect of cropping systems, residue management, and tillage techniques on total seed density (no. m$^{-2}$) of individual weed in 2013-14.

| Weed species          | Cropping system* | Residue management | With residue | With residue |
|-----------------------|------------------|--------------------|--------------|--------------|
|                       | Rice-wheat       |                   |              |              |
| Echinochloa colona L. | 11.2 ± 1.5       | 7.9 ± 0.9          | 11.5 ± 1.0   | 7.7 ± 1.5    |
| Lepachoila chinensis L. | 0.71 ± 0.0       | 1.34 ± 0.6         | 1.34 ± 0.7   | 0.71 ± 0.0   |
| Cyperus iria L.       | 27.5 ± 1.3       | 24.6 ± 2.0         | 26.0 ± 2.1   | 26.1 ± 1.0   |
| Cyperus rotundus L.   | 4.21 ± 1.5       | 2.67 ± 0.9         | 4.07 ± 0.6   | 2.81 ± 0.3   |
| Croasilia assalari Roxb. | 9.6 ± 0.9        | 7.2 ± 1.4          | 7.9 ± 1.3    | 8.9 ± 0.3    |
| Alternanthera philoxoides Griesb. | 10.1 ± 1.1 | 15.6 ± 2.6 | 12.5 ± 2.9 | 13.1 ± 2.0 |
| Echinochloa colona L. | 4.6 ± 0.9        | 6.5 ± 0.8          | 6.0 ± 0.3    | 5.1 ± 1.9    |
| Physalis minima L.    | 22.2 ± 3.9       | 9.0 ± 2.3          | 14.8 ± 2.9   | 16.4 ± 3.2   |
| Amaranthus viridis L. | 3.16 ± 0.9       | 5.71 ± 1.6         | 5.55 ± 1.4   | 5.32 ± 0.9   |
| Zinnia afera L.       | 3.99 ± 0.3       | 2.78 ± 0.6         | 3.55 ± 0.9   | 3.16 ± 1.1   |
| Trianaichora portulacastrum L. | 3.99 ± 0.7 | 6.03 ± 1.8 | 4.45 ± 0.8  | 5.57 ± 1.6  |
| Cyamotis axillar L.   | 1.02 ± 0.3       | 1.48 ± 0.7         | 1.48 ± 0.7   | 1.02 ± 0.3   |
| Ageratum conyoides L. | 2.07 ± 0.6       | 2.42 ± 0.2         | 2.42 ± 0.8   | 2.07 ± 0.4   |
| Euphorbia rostrata L. | 4.49 ± 1.8       | 4.90 ± 2.2         | 3.39 ± 1.6   | 6.01 ± 2.3   |
| Amarena baccfera L.   | 4.47 ± 1.4       | 3.01 ± 1.3         | 4.01 ± 2.4   | 3.47 ± 1.3   |
| Ludwigia hyssopifolia G. Don | 6.49 ± 1.9 | 4.07 ± 2.4 | 3.98 ± 1.7  | 6.58 ± 2.1  |
| Corchorus olitorius L. | 1.73 ± 0.8       | 0.71 ± 0.0         | 1.16 ± 0.4   | 1.27 ± 0.5   |
| Oldclandia corymbosa L. | 9.8 ± 2.8        | 9.4 ± 2.3          | 9.3 ± 2.5    | 9.9 ± 2.6    |
| Phyllanthus niruri L. | 1.34 ± 0.3       | 0.71 ± 0.0         | 0.71 ± 0.0   | 1.34 ± 0.3   |
| Boerhavia diffusa L.  | 20.8 ± 2.6       | 14.1 ± 6.4         | 14.9 ± 0.7   | 20.0 ± 2.1   |
| Mellitope indica L.   | 5.01 ± 1.2       | 1.65 ± 0.5         | 2.28 ± 1.1   | 4.38 ± 0.4   |
| Acharynechus aspera L. | 2.95 ± 1.2       | 1.16 ± 0.4         | 2.32 ± 1.2   | 1.745 ± 0.5  |
| Rumex dentatus L.     | 9.4 ± 1.3        | 7.8 ± 2.0          | 9.7 ± 1.9    | 9.4 ± 2.6    |
| Sonchus oleracens L.  | 1.34 ± 0.6       | 0.71 ± 0.0         | 1.02 ± 0.3   | 1.02 ± 0.3   |
| Oxalis corniculata L. | 18.0 ± 2.5       | 15.9 ± 2.9         | 17.1 ± 2.2   | 16.7 ± 3.2   |
| Medicagia denticulata L. | 6.1 ± 2.1 | 7.0 ± 2.8 | 7.8 ± 2.7   | 5.3 ± 2.3   |
| Chenopodium album L.  | 14.1 ± 2.6       | 28.0 ± 1.9         | 22.9 ± 1.9   | 19.3 ± 3.2   |
| Coronopus didymus Zinn | 6.4 ± 2.7        | 6.2 ± 2.2          | 6.7 ± 2.4    | 5.9 ± 1.9    |
| Solanum nigrum L.     | 6.4 ± 2.0        | 9.6 ± 1.2          | 8.3 ± 1.0    | 7.9 ± 0.9    |
| Anagalis kavaani L.   | 1.27 ± 0.5       | 0.71 ± 0.0         | 1.27 ± 0.5   | 0.71 ± 0.0   |
| Cibicum arvene L.     | 1.02 ± 0.3       | 1.96 ± 0.4         | 1.65 ± 0.5   | 1.34 ± 0.3   |
| Vicia sativa L.       | 0.71 ± 0.0       | 0.71 ± 0.0         | 0.71 ± 0.0   | 0.71 ± 0.0   |

*Data were subjected to square square-root (√/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.*
Effect of cropping systems, residue management, and tillage techniques on total seed density (no. m$^{-2}$) of individual weed in 2014-15.

| Weed species                  | Cropping system* | Residue management | Tillage techniques |
|-------------------------------|------------------|--------------------|-------------------|
|                               | Rice-wheat       | No residue         | CTTPR-CT          |
| Echinochaia colona L.         | 17.1 ± 2.0       | 12.3 ± 1.3        | 15.0 ± 1.3        |
| Lepidochloa chitenss L.       | 2.91 ± 0.6       | 5.56 ± 0.8        | 4.59 ± 1.7        |
| Cyperus iria L.               | 27.6 ± 2.3       | 23.7 ± 2.2        | 26.0 ± 2.3        |
| Cyperus rotundus L.           | 3.72 ± 1.3       | 2.28 ± 0.8        | 2.60 ± 0.4        |
| Corisalia exilis Rottb.       | 7.9 ± 0.8        | 5.9 ± 0.1         | 7.3 ± 0.3         |
| Alternanthera philoxoides Griseb. | 12.0 ± 1.6   | 14.9 ± 2.2        | 15.2 ± 1.9        |
| Euphorbia hirta L.            | 4.3 ± 0.6        | 6.1 ± 0.5         | 4.8 ± 1.4         |
| Physalis minima L.            | 20.1 ± 2.3       | 8.0 ± 1.8         | 13.6 ± 2.3        |
| Amaranthus viridis L.         | 2.68 ± 0.7       | 6.53 ± 1.7        | 5.38 ± 1.2        |
| Portulaca oleracea L.         | 3.30 ± 1.8       | 3.20 ± 1.0        | 3.10 ± 1.2        |
| Triantietha portulacosa L.    | 3.99 ± 1.2       | 6.81 ± 1.4        | 6.86 ± 2.3        |
| Cynoectis aurel L.            | 2.20 ± 0.2       | 3.01 ± 0.8        | 2.61 ± 0.6        |
| Ageratum conyroides L.        | 1.81 ± 0.7       | 2.49 ± 0.9        | 2.08 ± 1.0        |
| Eclipta prostrata L.          | 3.75 ± 1.0       | 4.09 ± 0.8        | 2.86 ± 1.9        |
| Amaranthus baccifer L.        | 3.73 ± 1.5       | 2.56 ± 0.9        | 2.93 ± 1.7        |
| Ludwigia hyssopifolia G. Don. | 5.38 ± 1.2       | 3.41 ± 0.5        | 3.34 ± 0.9        |
| Corchorus olitorus L.         | 1.94 ± 1.2       | 1.30 ± 0.6        | 1.67 ± 0.9        |
| Oldenlandia corymbosa L.      | 8.1 ± 2.1        | 7.8 ± 1.9         | 8.2 ± 2.0         |
| Phyllanthus niruri L.         | 1.21 ± 0.2       | 0.71 ± 0.0        | 0.71 ± 0.1        |
| Boerhavia diffusa L.          | 17.0 ± 2.1       | 11.7 ± 2.8        | 16.4 ± 1.1        |
| Melilotus indicus L.          | 4.16 ± 1.0       | 1.46 ± 0.4        | 1.97 ± 0.9        |
| Achyranthes asper L.          | 2.51 ± 0.8       | 1.07 ± 0.3        | 2.01 ± 1.3        |
| Rumex dentatus L.             | 1.35 ± 2.0       | 12.4 ± 2.0        | 12.1 ± 1.8        |
| Sonchus oleraceus L.          | 1.62 ± 0.3       | 0.71 ± 0.0        | 0.96 ± 0.3        |
| Oxalis corniculata L.         | 23.4 ± 2.3       | 25.9 ± 1.2        | 25.8 ± 1.5        |
| Medicago denticulata L.       | 9.9 ± 1.1        | 10.9 ± 2.3        | 11.2 ± 0.7        |
| Chenopodium album L.          | 13.1 ± 2.1       | 23.3 ± 1.1        | 19.6 ± 2.1        |
| Coronopus didymus Zinn        | 6.5 ± 1.2        | 6.5 ± 0.6         | 6.8 ± 1.7         |
| Solanum nigrum L.             | 7.2 ± 1.1        | 10.8 ± 2.1        | 7.7 ± 0.1         |
| Anagallis arvensis L.         | 1.16 ± 0.5       | 0.71 ± 0.0        | 0.71 ± 0.0        |
| Cynara cardunculus L.         | 1.79 ± 0.7       | 1.71 ± 0.5        | 1.46 ± 0.5        |
| Vicia sativa L.               | 3.54 ± 1.4       | 6.20 ± 2.4        | 7.20 ± 2.0        |

2. Materials and methods

2.1. Site and soil characteristics

The field study was conducted at the Research Complex for Eastern
Effect of cropping systems, residue management, and tillage techniques on soil weed seed diversity in 2013-14 and 2014-15.

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Broadcasting for wheat and dibbling for maize (manual placement of transplanted in CTTPR-CT, UPTPR-ZT, and ZTTPR-ZT plots. Manual wheat (variety ‘HD 2967’) planting rate was 50 holes/row 30 cm apart and 30 holes/ft for maize (variety ‘Decalb 9120’) in ZT plots. While, 21 days old rice seedlings (variety ‘Arize Tex’) were transplanted in CTTPR-CT, UPTPR-ZT, and ZTTPR-ZT plots. Manual broadcasting for wheat and dibbling for maize (manual placement of seeds in a hole at specified distance of 20 cm seed to seed) were performed in CT plots. A recommended dose of 120:60:40, 120:60:40, and 150:75:50 kg ha⁻¹ of nitrogen:phosphorus:potassium was applied in rice, wheat, and maize crops, respectively. Urea for nitrogen, diammonium phosphate for phosphorus, and muriate of potash for potassium were used for fertilization. The 18% of required nitrogen with full phosphorus and potassium were applied as basal in rice. While, two split applications were performed for rest of the nitrogen. The 20% of required nitrogen, along with full phosphorus and potassium were applied as basal in wheat and maize crops. The rest of the nitrogen was applied in three equal splits. The grain yield from a net plot area of 3 m × 3 m was manually harvested leaving the border area and threshed and analyzed for the grain moisture content (in hot air oven) in each plot. The net plot grain yield was adjusted at 14% moisture and expressed as t ha⁻¹.

2.2. Treatment details and experimental design

The study was carried out in split-split plot design with three replications comprising two types crop rotation (rice - wheat and rice - winter maize (Zea mays L.)) in main plot, two crop residue management practices (without residue and with residue) in sub-plot, and four tillage techniques: CT transplanted puddled rice (CTTPR) - CT wheat/maize (CTTPR-CT), unpuddled transplanted rice – ZT wheat/maize (UPTPR-ZT), ZT transplanted rice - ZT wheat/maize (ZTTPR-ZT), and ZT dry seeded rice (ZTDSR) - ZT wheat/maize (ZTDSSR-ZT) in sub-subplot having a fixed plot in each year (Nandan et al., 2018a, 2018b). For field experimentation, each main plot (crop rotation) was divided into two sub-plots for residue management treatments, and each subplot was divided into four sub-subplots for accommodating tillage techniques (Supplementary Fig. S1). The treatment ZTDSSR-ZT delineates the conservation agriculture practice. The field was prepared as per tillage practices in sub-subplot (Table 1). In ZTTPR practice, plots were flooded one day prior to seedling transplant without any soil disturbance. Then, seedlings were transplanted with gentle pressure with thumb. In residue added treatments, crop residue was retained on soil surface in all ZT plots, and incorporated with cultivator in CT plots. In no residue plots, crop residue after harvest of rice, wheat, and maize crops were removed. The dimension of each main, sub, and sub-sub plot was 21 m × 32 m, 10.5 m × 32 m, and 10.5 m × 7.5 m, respectively.

2.3. Crop and weed management

Zero-till happy-seeder with inclined plate seed metering system (machine company ‘Damesh’; manufacturer: Dashmesh Group; Malerkotla, Punjab, India) was used for sowing of rice (variety ‘Arize Tex’), wheat (variety ‘HD 2967’), and maize (variety ‘Decalb 9120’) in ZT plots. While, 21 days old rice seedlings (variety ‘Arize Tex’) were transplanted in CTTPR-CT, UPTPR-ZT, and ZTTPR-ZT plots. Manual broadcasting for wheat and dibbling for maize (manual placement of seeds in a hole at specified distance of 20 cm seed to seed) were performed in CT plots. A recommended dose of 120:60:40, 120:60:40, and 150:75:50 kg ha⁻¹ of nitrogen:phosphorus:potassium was applied in rice, wheat, and maize crops, respectively. Urea for nitrogen, diammonium phosphate for phosphorus, and muriate of potash for potassium were used for fertilization. The 18% of required nitrogen with full phosphorus and potassium were applied as basal in rice. While, two split applications were performed for rest of the nitrogen. The 20% of required nitrogen, along with full phosphorus and potassium were applied as basal in wheat and maize crops. The rest of the nitrogen was applied in three equal splits. The grain yield from a net plot area of 3 m × 3 m was manually harvested leaving the border area and threshed and analyzed for the grain moisture content (in hot air oven) in each plot. The net plot grain yield was adjusted at 14% moisture and expressed as t ha⁻¹.

Pretilachlor 400 g a.i. ha⁻¹ (Rift 50 EC, Syngenta) as pre–emergence was used in CTTPR and UPTPR treatments without applying any post–emergence herbicide. While, pendimethalin 750 g a.i. ha⁻¹ (Stomp 330 EC, BASF) as pre–emergence and bispyribac sodium 20 g a.i. ha⁻¹ (Nominee Gold 10% SC, PI Industries Ltd.) at 25 days after sowing (DAS) were applied in ZTTPR and ZTDSSR treatments. One hand weeding was performed in rice irrespective of treatment at 65 DAS. Glyphosate 1.5 kg a.i. ha⁻¹ (Glucyl 41% SL, Excel Crop Care) was sprayed before wheat and maize sowing under ZT plots. However, no pre-sowing glyphosate was applied in CT plots. Sulfosulfuron (75% WG) + metolachlor 50% WG) 32 g a.i. ha⁻¹ (Ready-mix Total 80 WG, UPL Ltd.) was applied in wheat crop at 25 DAS. Atrazine 1.25 kg a.i. ha⁻¹ (Atratral 50 WP, Rallis India Ltd.) was applied at 25 DAS in maize. Herbicides were applied with 500 L ha⁻¹ water for pre-emergence herbicides and 400 L ha⁻¹ water for post-emergence herbicides using knapsack sprayer (200 kPa pressure) fitted with a flat fan nozzle.

2.4. Soil sampling and viable weed seed density estimation

The field experiment was initiated in 2009. For assessing the viable weed seed density in soil, sampling was performed in 7th May 2013 and 10th May 2014 (once in every year) at the end of 4th and 5th year cropping cycles i.e. after harvest of wheat in rice-wheat system and after maize in rice-winter maize system. The soil sampling and emergence study was performed in two years (2013-14 and 2014-15) for repetition and validation of the study. Soil samples were collected from five sites in each sub-sub plot (10.5 m × 7.5 m area) at 0–15 cm soil depth in a W shaped pattern with a post-hole auger (15 cm height and 7.5 cm diameter). The sampled soil from five sites was mixed thoroughly and passed through 4 mm sieve to remove large debris and soil clods, and air-dried. Finally, 4 kg soil for individual treatment of each replicate (sampling
area 10.5 m $\times$ 7.5 m) was kept in plastic trays (dimension: 375 mm $\times$ 300 mm $\times$ 75 mm) in a non-heated greenhouse. The relative humidity of 70–90% was experienced inside the greenhouse throughout the year. As the experiment was in split-split plot design, having two main plots, two subplots, and four sub-subplots, a total of 48 trays ($2 \times 2 \times 4 = 16$ treatment combinations $\times$ 3 replications) were kept for assessing the weed seed density. Occasional water was applied in trays to keep moist for germination. In this investigation, weed seedling germination method was used to assess the viable weed seed density and composition (Barberi and Cascio, 2001; Moonen and Barberi, 2004; Carter and Ivany, 2006; Lal et al., 2016). This method can underestimate the absolute weed seedbank (viable $+$ dormant) size, but provides a relative comparison to assess the viable weed seed density under different crop management practices (Lal et al., 2016). To break seed dormancy, application of water was suspended every 4 months for a period of 15 days. Two months prior to the termination of experiment in each year, soils were treated with 1000 mg L$^{-1}$ solution of potassium nitrate ($\text{KNO}_3$) to expedite the germination of remaining viable seeds (Barberi and Cascio, 2001). Weed seedling emergence study was performed for 2013-14 (May 7, 2013 to April 7, 2014) and 2014-15 (May 10, 2014 to April 10, 2015). During each year, six flushes of weed emergence were assessed. Emerged weed seedlings were identified, counted, and removed in each flush. After each count, soil was pulverized and sprinkled with water for further emergence. After completion of first year observations (May 7, 2013 to April 7, 2014), the soil was removed from trays and trays were refilled with soil from experimental field for

Fig. 2. Emergence pattern of major rainy season weeds (no. m$^{-2}$) in both years under cropping system, residue management, and tillage techniques (cumulative of three rainy season flushes in each year); Data were subjected to square square-root ($\sqrt{x+0.5}$) transformation. Error bars are standard error of mean; For details of tillage treatments see Table 1.
2013-15 observations for repetition (May 10, 2014 to April 10, 2015) of the study. The aboveground weed density in field was counted with two 1 m x 1 m quadrats/treatment at the centre of plot in 2013-14 and 2014-15 in each crop of rotations at 65 DAS. The identified weeds were divided into grasses, sedges, and broad-leaved. The diversity indices, viz. Shannon-Wiener index, Simpson index, evenness index, richness index, and ecological dominance were calculated using the formulae described in Nkoa et al. (2015) and Nandan et al. (2018a).

2.5. Data analysis

The viable weed seed density in soil was expressed as number of seedling emerged m\(^{-2}\) (no.m\(^{-2}\)) from the germination study. Data were analyzed using the general linear model (GLM) procedure (Supplementary Fig. S2) of SAS (SAS Institute Inc. version 9.2, 2014) for split-split plot design (Supplementary Tables S1 and S2). Analyses were performed on year wise raw data of viable weed seed density and aboveground weed density m\(^{-2}\) basis after converting through square root () transformations. Total seed density of individual weed for respective treatment combination was analyzed through principal component analysis using the PAST 3.11 window based software. Least significance difference test was applied to compare the treatment means at the 5% level of significance.

3. Results

3.1. Density of viable weed seed

Weed species belonging to different botanical families were emerged in two years (2013-14 and 2014-15) (Tables 2 and 3). Of the total 33 weed species, 15 species were present abundantly in all treatments. While, remaining 18 species were emerged lesser in number in few
treatments under study. 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 in both years (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).

### 3.2. Weed diversity indices

The tillage practices in rice ecology significantly influenced the weed seedbank diversity and dominance (Table 4) in both years. The UPTPR-ZT and ZTDSR-ZT systems recorded significantly higher Shannon, evenness, and richness indices over the CTTPR-CT system in 2013-14 and 2014-15. However, UPTPR-ZT and ZTDSR-ZT systems did not differ \((P > 0.05)\) for these indices. Whereas, CTTPR-CT system led to the higher ecological dominance than that of ZTDSR-ZT system \((P < 0.05)\).

### 3.3. Weed emergence pattern

#### 3.3.1. Rainy season weed emergence

The higher *C. iria* emergence was observed in rice-wheat system over rice-maize system (Fig. 2). In 2013, *C. iria* and *Echinochloa colona* (L.) Link were higher in without residue treatment, but it was reverse in 2014. In 2013, the emergence of *C. iria* and *E. colona* followed the sequence of CTTPR-CT > ZTDSR-ZT > ZTTPR-ZT > UPTPR-ZT \((P < 0.05)\). While in 2014, ZTTPR-ZT system recorded the significantly higher *C. iria* and *E. colona* density, compared to the remaining tillage practices. In both years, rice-wheat without crop residue recorded the

![Fig. 4. Category-wise total aboveground weed density (no. m\(^{-2}\)) under different treatments in 2013-14 and 2014-15. Cumulative of rainy and winter season weeds in each year were subjected to square square-root (\(\sqrt{x + 0.5}\)) transformation. Different letters (a–c) between columns are significant at \(P \leq 0.05\).](image-url)
higher Physalis minima L. emergence over rice-maize system with residue addition. While, P. minima emergence was higher under UPTPR-ZT, ZTDSR-ZT, and ZTTPR-ZT systems than under CTTPR-CT in 2013 and 2014 (Fig. 2).

3.3.2. Winter season weed emergence

Among the 5 dominant weed species of winter season, all belonged to the broad-leaved (Fig. 3). In 2014-15, 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 (P < 0.05). The UPTPR-ZT, ZTTPR-ZT, and ZTDSR-ZT systems recorded the lower O. corniculata seed density in 2013-14 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, in both years (Fig. 3). Solanum nigrum L. seed density was higher in rice-maize system without residue addition. Among tillage practices, ZTTPR-ZT and UPTPR-ZT recorded higher S. nigrum emergence over CTTPR-CT in both years.

3.4. Aboveground weed density and grain yield of crops

In 2014-15, narrow-leaved weed density was higher in without residue treatment than in residue addition at 65 DAS (P < 0.05) (Fig. 4). The sequence of aboveground narrow-leaved weed density for tillage practices was ZTDSR-ZT > CTTPR-CT > ZTTPR-ZT > UPTPR-ZT (P < 0.05) in 2013-14, while, in 2014-15 the sequence was ZTTPR-ZT > ZTDSR-ZT > CTTPR-CT = UPTPR-ZT.

Crop residues did not differ for rice grain yield during 2013-14 and 2014-15 (Table 5). Added crop residue enhanced the grain yield of maize, wheat, and rice by 7–10%, 5–11%, and 3–8%, respectively, over without residue in different years. The ZTDSR-ZT system recorded significantly higher rice grain yield over remaining tillage practices by 7–17% in 2013-14, and 13–25% in 2014-15. Wheat grain yield followed the sequence of ZTDSR-ZT > ZTTPR-ZT > UPTPR-ZT > CTTPR-CT in both years. These alternate tillage systems enhanced wheat yield by 16–23% in 2013-14, and 20–23% in 2014-15, compared to that in CTTPR-CT (Table 5). Similar trend was also noticed for maize grain yield.

3.5. Community structure of viable weed seed

Component I and II occupied 38.8 and 17.5% interventions for seedbank density, respectively (Fig. 5) in the principal component analysis. Importantly, rice-wheat system distinctly situated from rice-maize system in the coordinates. Also, weed community in CTTPR-CT and UPTPR-ZT systems considerably differed from ZTDSR-ZT and ZTTPR-ZT systems. Present study revealed that cropping systems, residue management, and tillage practices divided weed seedling emergence into different groups: (1) O. corniculata, R. dentatus (2) S. nigrum, A. philoxiroides, C. album, (3) B. diffusa, and C. iria (Fig. 5). Remaining weed species showed little similarity in emergence pattern, as they were present in a cluster in the principal component analysis.

4. Discussion

Present study revealed that shifting from 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 seedbank. 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 seedbank 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). Weed emergence pattern showed that C. iria population was higher in rice-wheat cropping system (Fig. 2). Generally, maize is a wider row crop, allowing more C. iria infestation in the field, whereas in wheat, less infestation of C. iria caused more emergences in natural germination study. The result is supported by aboveground weed density, which showed that narrow-leaved weed density was higher under rice-maize system than under rice-wheat in 2013-14 (Fig. 4). While, higher E. colona seed density was higher in rice-wheat system, might be due to the higher association of E. colona in rice-wheat ecology. In winter season, rice-maize system recorded higher R. dentatus and C. album seed density (Fig. 3). The wider spacing in winter maize crop caused dominance of broad-leaved weeds, which restored the soil seedbank with these weeds. Interestingly, added crop residue recorded higher weed seedbank
density compared to that of without residue. Surface-laden crop residue affected seed germination by shading and alteration in chemical properties in soil seed zone (Nath et al., 2017c). Further, inhibition and delaying in field weed emergence in residue added treatments maintained more viable weed seed in the soil profile, which emerged in natural seedling emergence study.

It is important to mention that adoption of ZTDSR-ZT reduced the weed seed density (Fig. 1). Basically, weed seedling emergence study was undertaken at the end of 4th and 5th years of crop rotation, therefore, surface laden weed seed under ZTDSR-ZT practice already germinated in 4 years in field (Nandan et al., 2018a; Susha et al., 2018). Many of the previous workers reported more weed infestation in field under ZT systems during initial years as weed seeds reside at top 2 cm soil profile (Chauhan and Johnson, 2009; Nath et al., 2017c). Hence, higher field weed emergence might have exhausted the weed seed in soil in ZTDSR-ZT system compared to that in CT system. Further, weed seed become more susceptible to predation in conservation agriculture (Crutchfield et al., 1986), leading to reduction in seed reservoir and seed viability. Field weed emergence result recorded lesser weed density during cropping season in CTTPR-CT system (Fig. 4). Therefore, this system recorded higher seedling emergence because of viable weed seed in the soil profile germinated in greenhouse study.

The ZTDSR-ZT and UPTPR-ZT systems recorded significantly higher Shannon, evenness, Simpson, and richness indices over CTTPR-CT system (Table 4). Tillage operations in CTTPR-CT system affected the vertical distribution of weed seed based on frequency and type of tillage implement used. The soil pulverization in CT system buried weed seed in deeper soil depth. These buried weed seed could not expose to sunlight and did not germinate. Hence, certain weed emerged at field scale, keeping the remaining seed in soil. Seed that could not germinate in field, germinated in natural emergence maintaining less uniformity in germination. On the contrary, ZTDSR-ZT, ZTTPR-ZT, and UPTPR-ZT systems provided equal chance to all weed seed to emerge because of unbiased seed deposition of all weeds on the soil surface. Principal component analysis also confirmed the distinct variation in weed community composition among CTTPR-CT and ZTDSR-ZT systems (Fig. 5), as they distantly situated in the ordinates. Further, significantly higher ecological dominance index in CTTPR-CT system further confirmed the severity of few weeds and non-uniformity in the weed flora.

Present study also suggested that narrow-leaved weeds have a tendency to dominate in ZT systems over time, as the seed density of E. colona and C. iria were high under ZTDSR-ZT and ZTTPR-ZT systems.
than under CTTPR-CT system. Adoption of different tillage techniques may suppress or encourage the emergence of weeds, as germination of few weeds is influenced by previously germinated weeds, because of inter-specific competition. The principal component study confirmed that emergence pattern of *O. corniculata*, *C. album*, and *C. iria* were mainly influenced by crop management practices. On the contrary, the preponderance of *E. colona*, *C. iria*, *P. minima*, and *A. philoxeroides* in the rainy season and *O. corniculata*, *C. album*, *R. dentatus*, *C. didymus*, and *S. nigrum* in winter season gives a direction of future weed management strategies. The CTPTR-CT system recorded higher seed density as compared to that of ZTTPR-ZT and ZTDSR-ZT systems (Fig. 1). The recommended herbicide schedule was adopted in different tillage systems in field study. It can be speculated that pre-sowing application of glyphosate 1.5 kg a.i. ha−1 in ZT systems did not allow weeds to recharge seedbank in between crop season. However, no application of glyphosate in CTPTR-CT system allowed seedbank to recharge with new seeds. It resulted in more seed density in CTPTR-CT system than that of ZTDSR-ZT in both years. Therefore, crop rotation with adequate pre-planting and post-emergence herbicides application might limit the weed seed density in ZTDSR-ZT system. Long-term adoption of conservation tillage/agriculture practices (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 seedbank. Hence, our hypothesis that total seed density and cumulative emergence is lower in ZTDSR-ZT system than in CTPTR system holds true, and accepted. Conservation agriculture practice (~ZTDSR-ZT) and new generation tillage practices (UPTPR-ZT and ZTTPR-ZT) attained higher grain yield of component crops over CTPTR-CT system (Table 5). Better crop management, added crop residue, and better soil microclimate in ZT-based practices resulted in the higher grain yield of component crops. Further, added crop residue suppressed weed density, and reduced crop-weed competition, resulted in higher crop growth, yield attributes, and finally yield. The findings recommend that conservation agriculture (~ZTDSR-ZT) and alternate tillage practices (UPTPR-ZT and ZTTPR-ZT) can suppress the weed density and attain higher yield than CTPTR-CT over time.

5. Conclusion

It is evident that weed emergence pattern is affected by tillage techniques, crop residue management, and crop rotations. *C. iria*, *C. rotundus*, *P. minor*, *P. minima*, *D. diffusa*, *A. philoxeroides*, *O. corniculata*, *C. album*, *R. dentatus*, *C. didymus*, and *S. nigrum* are the dominant weeds in this ecology and showed a variable emergence pattern. Present study emphasizes that ZTDSR-ZT, ZTTPR-ZT, and UPTPR-ZT could stimulate the emergence of some new weeds in the production ecology. Hence, weed community composition may vary from existing weed flora, as seedbank is recharged with newly emerged weeds. This information will help to develop strategic weed management for conservation agriculture and other tillage practices. Importantly, total weed seed density was lower under ZTDSR-ZT and ZTTPR-ZT systems than under CTPTR-CT system. It indicates that ZTDSR-ZT and ZTTPR-ZT systems can minimize weed infestation over time as long as there is a high standard of weed management that minimizes seed return. Hence, conservation agriculture (ZTDSR-ZT and crop residue retention) is a sustainable practice for weed management and higher productivity in rice-based cropping systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

**Rajiv Nandan**: Supervision. **Vikram Singh**: Supervision. **Virender Kumar**: Supervision. **S.S. Singh**: Supervision. **K.K. Hazra**: Supervision. **C.P. Nath**: Formal analysis, Writing - original draft. **R.K. Malik**: Writing - review & editing. **S.P. Poonia**: Writing - review & editing.

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Appendix A. Supplementary data

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