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Effects of weed control strategy on weed dynamics, soybean productivity and profitability under conservation agriculture in India

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ABSTRACT

Weed management in conservation agriculture is very important for attaining sustainable crop yields. The effect of tillage, crop establishment techniques and weed management practices was evaluated on weed population of *Echinochloa colona* (L.) Link and *Digera arvensis* (Forssk) as well as the productivity of soybean in the soybean-wheat system during 2009–2012. The four main treatments, *viz.* conventional-tillage with raised bed (CT-B), conventional tillage with flat bed (CT-F), zero-tillage with raised bed (ZT-B), and zero-tillage with flat bed (ZT-F), and four sub-treatments, *viz.* unweeded control, pendimethalin 0.75 kg ha^{-1} as pre-emergence (PE) followed by one hand weeding at 30 days after sowing (DAS); pendimethalin 0.75 kg ha^{-1} as PE followed by imazethapyr 0.075 kg ha^{-1} as post-emergence (POE), and imazethapyr 0.075 kg ha^{-1} as POE were evaluated in split-plot design with three replications. Results indicated that total weed density and biomass was maximum in the first year, and declined gradually in third and fourth years. In 2009, ZT-F recorded the highest weed density and weed biomass followed by ZT-B. However in 2012, the highest weed density and weed biomass was observed in CT-F, while the lowest weed biomass was found in ZT-B followed by CT-B. In 2009, the highest grain and stover yield of soybean was recorded in CT-B but ZT-B out-yielded all other treatments from 2010 onwards. The highest gross and net returns were found in ZT-B and ZT-F during the study period. Application of pendimethalin at 0.75 kg ha^{-1} along with one hand weeding at 30 days after sowing recorded the lowest total weed density and biomass. This treatment also recorded higher grain yield but lower net returns compared to pendimethalin 0.75 kg ha^{-1} + imazethapyr 0.075 kg ha^{-1}. Overall, application of pendimethalin as PE and imazethapyr as POE in ZT proved to be the most effective herbicide strategy for weed management in soybean leading to higher grain yield and net returns, irrespective of crop establishment practices. However, high infestation of other weeds species such as *Dactyloctenium aegyptium* (L.) Willd, *Leptochloa chinensis* (L.) Nees, *Eleusine indica* (L.) and *Phyllanthus niruri* (L.) in ZT is a concern. Furthermore, the possible build-up of herbicide residuals and its impact on the environment needs to be studied to devise an effective weed management strategy for soybean.

1. Introduction

Soybean (*Glycine max* (L.) Merrill) is one of the major oilseed crops of India. It contributes 29% to the total vegetable oil production but still an additional 1.3-1.5 million tons of soybean oil is imported annually (ICAR, 2016). The production of soybean in India is 8.7 million tons from 11.1 million hectares with a productivity of 790 kg ha^{-1} only, which is far below the world average of 2310 kg ha^{-1} (FAO, 2016). There are several abiotic and biotic stresses which hamper the full yield potential of soybean.

The reasons behind low soybean production are manifold and associated with low soil fertility, especially low levels of soil organic matter in the major production areas, inadequate weed control and other crop management practices. Intensive tillage-based agriculture practices without recycling of organic resources deteriorate the soil quality (Lal et al., 1994), which then reduce, the overall productivity of soybean. In addition, soybean is mostly grown under rainfed conditions and limited moisture availability at critical growth stages has a strong

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impact on its productivity (Aulakh et al., 2012). Both heavy rainfall and/or long dry spells during growing period severely affect the nodulation of soybean, its vigour, and final yield (Kang et al., 2009).

Conservation agriculture (CA) is a crop management system based on the three principles of minimum soil disturbance, crop residue retention, and crop rotation (FAO, 2010). It has the potential to improve resource-use efficiency, crop productivity and soil health, while maintaining the environment (Kassam et al., 2009).

CA has been promoted in the rice–wheat cropping system in the Indo-Gangetic Plains of India (Jat et al., 2009). The major reason for its promotion is to reduce the cost of production, save water and nutrients, enhance yields, and utilize resources efficiently (Hobbs, 2001). However, CA also contributes significantly to improvements in soil quality, which makes this a viable option for farmers in India. Blanco-Canqui and Lal (2004) reported that soil cover with residues gave greater soil aggregation and increased total soil organic carbon. Likewise, surface mulch reduces water loss from the soil by minimizing evaporation and moderates soil temperature.

Various researchers have comprehensively reviewed the benefits and challenges of CA (Kassam et al., 2009; Thierfelder and Wall, 2012). Despite the numerous benefits that have been reported from CA systems, effective control of weeds is a major impediment to its productivity as weed infestations compromise crop yields (Kumar et al., 2008). It was reported that soybean yields are reduced by 58–85%, depending on the severity of weed species and their infestation (Chhokar and Balyan, 1999). Hazra et al. (2011) found a significant reduction in soybean yield as a result of increased density of annual weeds. Though surface residue retention in zero-tillage suppresses weed emergence to a certain extent, residues also restrict manual or mechanical weed control (Mhlanga et al., 2016). The major reason for tillage practices is to uplift or cut the weeds and bury them deep into the soil (Blackshaw et al., 2001). However, in zero tillage systems, mechanical soil movement is restricted to the sowing area only.

The most common weed control practice by smallholders in India is still repetitive soil tillage followed by manual weeding (Bajwa et al., 2015). As manual weeding is labour intensive, hikes in labour prices have made this practice uneconomical. Weed control with herbicides is, therefore, one of the potential options in CA systems, due to its low labour and production costs, and high efficiency in controlling weeds. Singh and Jolly (2004) reported that a pre-emergence (PE) application of pendimethalin 0.5 kg ha^{-1} followed by hand weeding at 30 days after sowing (DAS) increased soybean yield by 35–55%. Likewise, application of sequential herbicides in soybean such as flumioxazin as PE and imazethapyr as post-emergence (POE) gave 25% higher weed control efficiency than applying it only as POE (Taylor-Lovell et al., 2002).

The findings of weed species shifts under CA have been inconsistent (Chauhan et al., 2006). Several studies have indicated that CA causes an increase in the density of perennial weeds (Malik et al., 2002). Continued weed control under CA on the other hand influences weed population and density over time, and declines have been reported by Muoni et al. (2016) using different weed control strategies. The present study was designed to develop sustainable soybean production system while addressing unresolved issues of weed control under CA. The objective of the study was to: (a) evaluate the shift in weed flora under different tillage and crop establishment techniques in response to herbicide application over the years, and (b) evaluate the most effective and most profitable weed control strategy for soybean in a soybean-wheat system.

2. Materials and methods

2.1. Site description

The field experiment was conducted for four years during cropping seasons 2009/10 to 2012/13 at the research farm of the Indian

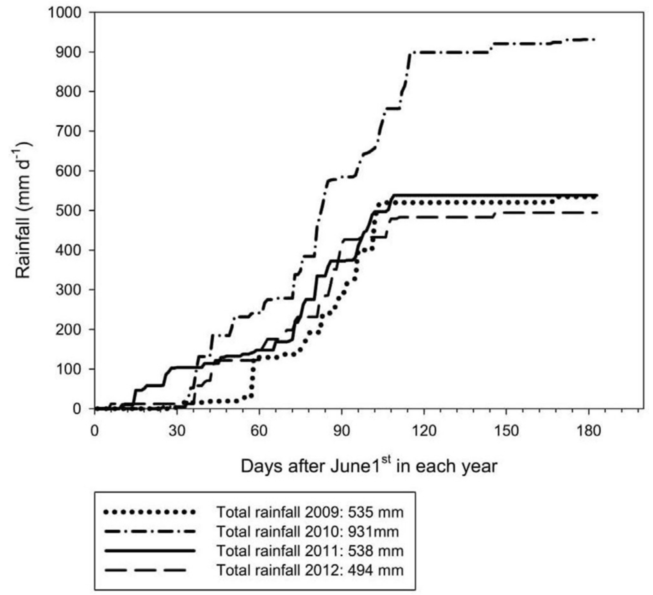

Fig. 1. Cumulative rainfall at the study site at the Indian Agricultural Research Institute, New Delhi, 2009–2012.

Agricultural Research Institute (28° 40′ N, 77°12′ E at an altitude of 228 masl), New Delhi, India. The experimental site falls in the agro-climatic zone of "Trans Indo-Gangetic Plains" (Planning Commission, 1989), having a sub-tropical and semi-arid climate, with hot summers and cold winters with mean annual maximum and minimum temperatures of 40.5° C and 6.5° C, respectively. The mean annual rainfall is 670 mm and its distribution is unimodal. Approximately 70–80% of rainfall is confined to three months from July to September. The quantity of rainfall received during the years of experimentation was variable and amounted to 535, 931, 538, and 494 mm during 2009, 2010, 2011 and 2012, respectively (Fig. 1). The mean annual temperature was almost similar to the long-term mean and ranged from a maximum of 44 °C to a minimum of 12 °C during the growing season. Prior to the experiment, a cotton-wheat rotation was established at the trial site for 3 consecutive years under different tillage and residue management practices.

The soil of the experimental field has a sandy loam texture up to 30 cm soil depth and can be classified as typic Haplustept or Inceptisol. The surface soil layer of 0–15 cm has a neutral pH of 7.5, organic C (Walkley and Black, 1934) content of 0.38%, $KMnO_4$-oxidizable N (Subbiah and Asija, 1956) of 167 kg ha^{-1}, and $NaHCO_3$-extractable P (Olsen et al., 1954) of 12.3 kg ha^{-1}, and NH_4OAc-exchangable K (Hanway and Heidel, 1952) of 265 kg ha^{-1}. The soil bulk density was 1.54 Mg m^{-3} from the 0–15 cm soil depth.

2.2. Treatment details

The trial had four main treatments and four sub-treatments in a split-plot design with three replications. The study was conducted on gross plot size of 6.0 m × 2.8 m with a net plot size of 5.0 m × 1.4 m during each year in the same plot. The main plot treatments included:

- Conventional-tillage with raised bed (CT-B);
- Conventional-tillage with flat bed (CT-F);
- Zero-tillage with raised bed (ZT-B) and
- Zero-tillage with flat bed (ZT-F).

The following treatments were allocated to sub-plots:

- Unweeded control (W1);
- Pendimethalin 0.75 kg ha^{-1} as pre-emergence (PE) followed by one

hand weeding at 30 days after sowing (DAS) (W2);
- Pendimethalin 0.75 kg ha^{-1} as PE followed by imazethapyr 0.075 kg ha^{-1} as post-emergence (POE) (W3); and
- Imazethapyr 0.075 kg ha^{-1}as POE (W4)

The CT-F treatment plot was ploughed four times (2 harrowings + 2 cultivators up to 15 cm soil depth) followed by levelling before sowing of the crop in each year. The ploughing was done with a disc-harrow followed by a cultivator and a rotovator. The soil was not tilled under ZT-F. The same ploughing intensity as in a case of CT-F was followed for making CT-B. The raised bed with the dimensions of 37 cm width at the top of the bed alternated with furrow of 30 cm in width and a height of 15 cm was formed with a tractor-mounted raised bed planter. The beds were dismantled by ploughing and levelling with cultivators after harvesting of crops at the end of each growing season. In ZT-B, the raised bed had the same dimensions as in CT-B, but no other tillage intervention.

Raised beds under ZT-B were not dismantled at the end of each growing season and remained permanent. However, reshaping of beds was done by a raised bed planter with minimal soil disturbance before sowing of soybean in each year. A pre-sowing irrigation (75 mm) was applied each year to allow the germination of weed seeds. Thereafter, a spray of glyphosate 1.25 kg a.i. ha^{-1} was done one week before sowing of the crop to kill the existing and newly emerged weeds. The herbicide treatments were imposed after sowing of soybean and wheat crop (wheat data was not included in this analysis). A pre-emergence application of pendimethalin 0.75 kg ha^{-1} was made within two days of sowing in the respective treatments. Thereafter, the plots were hand weeded at 30 DAS with hand hoes in respective treatments. Post-emergence application of imazethapyr 0.075 kg ha^{-1} was done at 25 DAS. The herbicide applications were done with a hand operated knapsack sprayer.

2.3. Crop management

The wheat crop was harvested manually leaving 10 cm high anchored stubbles. In ZT-B and ZT-F, the crop residues were maintained at 3.0 t ha^{-1} by adding additional loose amounts of wheat straw in the following soybean crop. Similarly, soybean was manually harvested at 5 cm above ground level. The stover was retained at a rate of 1.5 t ha^{-1} for the following wheat crop in both ZT-B and ZT-F conditions. In conventional tillage systems, all crop residues were removed. A popular soybean variety (cv PS 9072) was sown using a seed rate of 80 kg ha^{-1} to obtain a target plant population of 80,000 ha^{-1}. The raised bed planter was used to sow the crop on beds. It was adjusted to sow two rows of soybean at 25 cm apart in both the ZT and CT system. A multi-row crop planter was used to sow the crop at 30 cm on flat beds in both tilled systems. An inter-row plant spacing of 5–7 cm was maintained throughout the trial. A uniform dose of 20 kg N ha^{-1}, 26 kg P ha^{-1}, and 33 kg K ha^{-1} was applied as a basal dressing. The N, P and K were applied through urea, single super phosphate and muriate of potash, respectively. The irrigations were applied whenever soil moisture tension reached up to −40 kPa in the 30 cm soil surface layer. A spray of imidacloprid 30.5% SC was done to control thrips infestation in soybean. The crop was sown during the first week of July and harvested during the first week of November in each year.

2.4. Grain and stover yields

The yield attributes such as pods $plant^{-1}$ and seeds pod^{-1} were recorded from 10 random plants from each treatment. The grain and stover yields of soybean were obtained from the net plot area (5.0 m × 1.4 m) and thereafter sun dried. The grain and stover yields were recorded at the moisture content of 12.5% and 18.0%, respectively.

2.5. Weed observations

The data on weeds were recorded using a quadrat of 0.5 m × 0.5 m. The quadrat was randomly placed four times in each plot. Inside the quadrat, the number of weed species present was recorded. The samples for weed biomass were collected and oven dried at 65 °C for 72 h, thereafter, weighed and expressed in g m^{-2}. Sampling for weed species count and biomass was done at 30 days interval during the entire growing season in each year.

2.6. Economic analysis

A partial budget analysis was conducted to assess the economic benefits of each weed control strategy (CIMMYT, 1988). A comparison was done for the total cost of production, gross receipts, and net benefits of the treatments. The cost of inputs (seed, fertilizer, and pesticide) and labour for field operations was taken for calculating the total cost of production. The prevailing minimum support price for the soybean was considered and gross returns were worked out by multiplying the quantity and price of produce. Further, net benefits were calculated by deducting the total cost of production from gross receipts every year.

2.7. Statistical analysis

All data (weed density, weed biomass and yield) were subjected to Kolmogorov-Smirnov and Levene tests for normality and homogeneity of variance. The uniformity in error variance was found non-significant. Hence, the data were pooled over the years. The data were subjected to ANOVA to assess the treatment effects using STATISTIX Version 9.0 (Statistix, 2008). Once significant differences (Fisher's test) were discovered, the least significant difference (LSD) test was applied at the $P < 0.05$ probability level to compare the differences among treatment means. A linear regression analysis was done to work out the relationship between grain yield, weed density and weed biomass.

3. Results

3.1. Weather parameters

The amount of rainfall and distribution varied during the 4 years of the experimental period (Fig. 1). The amount of rainfall was 535 mm, 931 mm, 538 mm, and 494 mm during 2009, 2010, 2011 and 2012, respectively during the growing season (June–October). There was not much variation in maximum and minimum temperature during the period of study.

3.2. Combined-ANOVA for weed and crop observations

The effects of tillage and crop establishment (TCE), weed management, and interactions on weed density and weed biomass were presented in combined ANOVA (Table 1). Year × weed management interaction was found significant on *E. colona* and *D. arvensis* at 30 and 60 DAS. The interaction of TCE and weed management was found significant on *E. colona* at 60 DAS, and *D. arvensis* at 30 and 60 DAS. Year × TCE × weed management interactions were also found significant on *D. arvensis* at 30 and 60 DAS, and weed biomass. TCE and weed management interaction was non-significant on pods $plant^{-1}$, seeds pod^{-1}, grain and stover yield (Table 2). Grain and stover yield was influenced by TCE and weed management practices. However, year × TCE × weed management interaction was found non-significant on seeds pod^{-1}, grain and stover yield.

3.3. Density of *E. colona* and *D. arvensis*

Echinochloa colona (Link.) and *Digera arvensis* (Forssk) among the narrow, and broad- leaved categories, respectively were the prominent

Table 1
Analysis of variance (F values) showing year, tillage and crop establishment, and weed management effects on weed density and weed biomass.

Source of variation	Degrees of freedom	Density at 30 DAS (no m^{-2})		Density at 60 DAS (no m^{-2})		Total weed biomass ($g\ m^{-2}$) at 60 DAS
		E .colona	*D. arvensis*	*E .colona*	*D. arvensis*	
Replication	2	14.03	8.57	7.02	27.13	53.83
Year (Y)	3	40.90**	1132.63**	18.56**	251.14**	11645.31**
Error (a)	6	5.49	2.64	5.12	2.84	55.61
Tillage and crop establishment (TCE)	3	7.09 ns	9.46 ns	19.56 ns	6.17 ns	1186.1**
Y × TCE	9	2.19 ns	12.05**	6.49**	47.21**	551.45**
Error (b)	24	2.67	1.86	1.69	7.98	39.76
Weed management (WM)	3	1036.86**	1897.61**	1944.33**	2981.19***	710624.85**
Y × WM	9	12.48**	100.80**	40.90**	185.25**	11835.86**
TCE × WM	9	6.77 ns	13.10**	29.48**	18.91*	152.44 ns
Y × TCE × WM	27	1.9 ns	6.06**	2.06 ns	20.68**	180.84**
Error (c)	96	1.30	0.98	1.44	2.96	68.00

*Significant at the p < 0.05 5% probability test; **Significant at the p < 0.01 1* probability test.

Table 2
Analysis of variance (F values) showing year, tillage and crop establishment, and weed management effects on yield attributes and yield of soybean.

Source of variation	Degrees of freedom	No. of pods $plant^{-1}$	No. of seeds pod^{-1}	Grain instead of seed yield ($t\ ha^{-1}$)	Stover yield ($t\ ha^{-1}$)
Replication	2	53.05	0.026	0.011	0.521
Year (Y)	3	3575.13**	9.57**	2.92**	17.35**
Error (a)	6	84.25	0.02	0.01	0.05
Tillage and crop establishment (TCE)	3	733.9*	0.85**	0.42**	2.39**
Y × TCE	9	48.93 ns	0.12 ns	0.04**	0.25**
Error (b)	24	48.35	0.05	0.01	0.06
Weed management (WM)	3	4056.13**	3.85**	3.45**	14.19**
Y × WM	9	225.6**	0.11 ns	0.09**	0.74**
TCE × WM	9	49.34 ns	0.08 ns	0.02 ns	0.03 ns
Y × TCE × WM	27	66.97*	0.11 ns	0.01 ns	0.01 ns
Error (c)	96	37.76	0.07	0.01	0.03

*Significant at the P < 0.05 5% probability test.
**Significant at the P < 0.01 1% probability test.

Table 3
Tillage and crop establishment × weed management interaction mean across years (n = 4) and replications (n = 3) for *E .colona* and *D. arvensis* density at 30 and 60 DAS.

Parameters	*E. colona* (no m^{-2})				*D. arvensis* (no m^{-2})			
30 DAS								
Tillage and crop establishment	W1	W2	W3	W4	W1	W2	W3	W4
CT-B	13.03	1.97	2.50	3.32	15.72	2.72	2.61	4.32
CT-F	12.54	2.78	2.43	4.12	14.65	3.50	4.08	4.85
ZT-B	10.87	2.59	3.66	4.72	15.07	1.77	3.66	4.48
ZT-F	13.41	3.27	3.21	4.54	18.54	2.18	3.56	4.58
LSD (P ≤ 0.05)	0.98				0.55			
60 DAS								
Tillage and crop establishment	W1	W2	W3	W4	W1	W2	W3	W4
CT-B	18.20	2.40	4.71	6.47	21.90	4.85	5.55	8.34
CT-F	19.58	2.45	6.41	6.55	23.61	3.56	5.66	8.95
ZT-B	15.98	2.36	6.59	8.66	19.86	3.80	8.31	8.13
ZT-F	16.33	3.08	7.31	11.13	22.20	4.62	8.19	8.33
LSD (P ≤ 0.05)	1.58				2.15			

For full abbreviations of treatment details see materials and methods section.

weed species. Besides, *Dactyloctenium aegyptium* (L.) Willd, *Leptochloa chinensis* (L.), *Cyperus rotundus* (L.), *Eleusine indica* (L.), *Phyllanthus niruri* (L.), and *Trianthema portulacastrum* (L.) also occurred but relatively at low frequency. As the season progressed, *Commelina benghalensis* (L.), *Chenopodium album* (L.) and *Amaranthus viridis* (L.) were also observed.

There was a significant (P ≤ 0.05) decrease in the density of *E. colona* and *D. arvensis* at 30 and 60 DAS with the weed management practices (Table 3). The lowest density of *E. colona* as well as *D. arvensis* in unweeded control was under ZT-B, which decreased when pendimethalin + hand weeding was applied. The density of both the weed species decreased significantly with the application of pendimethalin and imazethapyr compared with unweeded control. The best control of *E. colona* was obtained by pendimethalin + hand weeding, followed by pendimethalin + imazethapyr. Interactions revealed that weed control treatments made a variable impact under different TCE practices. Pendimethalin with hand weeding or imazethapyr recorded equal effect on *E. colona* under CT at 30 DAS, but at 60 DAS, pendimethalin + imazethapyr had significantly higher density than pendimethalin + hand weeding. On the other hand, ZT-F showed a greater density of *E. colona,* particularly at 60 DAS. The effect of post-emergence imazethapyr alone was relatively poor than when pendimethalin was applied as pre-emergence. In the case of *D. arvensis* also, pendimethalin + hand weeding proved more effective than pendimethalin + imazethapyr or imazethapyr alone under all TCE practices. In general, *D. arvensis* density was higher under flat-bed than raised-bed conditions, irrespective of TCE practices. Interaction showed a variable response to different treatments, with pendimethalin relatively superior under bed than flat conditions. All TCE practices showed the equal density of *D. arvensis* at 30 DAS under imazethapyr alone but at 60 DAS, ZT showed significantly greater infestation than CT conditions.

3.4. Total weed density and biomass

At 60 DAS, the total weed density and weed biomass significantly decreased with weed management practices, while TCE had a less marked impact (Table 4). ZT-B recorded the lowest weed density under unweeded control, which declined further with the application of pendimethalin and imazethapyr. Pendimethalin along with hand weeding or imazethapyr was found comparable in reducing the total weed density. Interaction showed that CT-F recorded the highest weed density, irrespective of weed management practices. Pendimethalin + hand weeding recorded the lowest weed density, followed by pendimethalin + imazethapyr. The total weed biomass was the highest under CT-F under unweeded control, which showed a 6-fold decrease with pendimethalin and imazethapyr applications. Interaction showed that pendimethalin and imazethapyr had an equal effect on weed biomass. Overall, ZT recorded the lowest weed biomass compared to CT. The weed density at 60 DAS varied with TCE and weed management practices over the years (Figs. 2 and 3). ZT-F and CT-F recorded higher weed density throughout the study period. The weed density consistently increased in unweeded control, while pendimethalin + hand weeding showed either similar or reduced weed density from second

Table 4
Tillage and crop establishment × weed management interaction mean across years (n = 4) and replications (n = 3) for total weed density and total weed biomass at 60 DAS.

Tillage and crop establishment	Total weed density (no. m^{-2})				Total weed biomass (g m^{-2})			
	W1	W2	W3	W4	W1	W2	W3	W4
CT-B	183.81	30.28	47.08	70.75	283.00	39.85	45.92	56.72
CT-F	197.29	33.71	45.23	74.13	303.00	46.58	54.33	69.16
ZT-B	185.02	29.51	48.32	90.50	288.20	38.87	46.69	47.73
ZT-F	189.20	32.73	48.20	97.61	291.00	44.83	52.64	53.68
LSD ($P \leq 0.05$)	6.67				12.55			

For full abbreviations of treatment details see materials and methods section.

year onwards. The weed biomass at 60 DAS also varied with tillage and weed management practices over the years (Figs. 4 and 5). ZT-B gave the lowest weed biomass, while application of pendimethalin and imazethapyr reduced the weed biomass over the period. However, the differences among the TCE and weed control were not significant.

3.5. Soybean yield

Grain and stover yield of soybean varied significantly with weed management and TCE practices (Table 5). Evidently, the lowest yields were recorded in unweeded control, which increased significantly under pendimethalin and imazethapyr applications. In ZT-B, pendimethalin + hand weeding recorded an increase of 58.3% in grain yield as compared to unweeded control. The interaction between TCE and weed management showed that in ZT-B, pendimethalin + hand weeding recorded 6.3% increase in grain yield over pendimethalin + imazethapyr. The lowest grain yield was found in CT-F. In the case of stover yield, ZT-B along with pendimethalin + hand weeding recorded the highest stover yield. The only application of imazethapyr as POE was found less effective in enhancing stover yield. During the study period, the lowest grain yield was recorded in 2012, irrespective of TCE and weed management practices (Figs. 6 and 7). Further, ZT-F and CT-F recorded the lowest grain yield in 2009. On the other hand, bed planting recorded the highest grain yield in both CT and ZT conditions. Pendimethalin + hand weeding, followed by pendimethalin + imazethapyr enhanced the grain yield. A negative correlation was found between grain yield, weed density and weed biomass at 60 DAS (Fig. 8). There was a decrease of 1.4 t ha^{-1} in soybean grain yield with an increase of weed density by 100 plants m^{-2}. Similarly, grain yield decreased by 1.5 t ha^{-1} with an increase of 100 g m^{-2} of weed biomass. In other words, the grain yield can be increased by the similar magnitude by reducing the weed density or biomass in soybean.

3.6. Economics

The cost of cultivation differed according to treatments during the study period (Table 6). CT-F/B had the highest cost due to additional expenditure involved in land preparation and bed making. The inclusion of pendimethalin + hand weeding and imazethapyr increased the cost over unweeded control. The lower cost of cultivation was in ZT-F. The gross and net returns remained higher in ZT-B. Pendimethalin + hand weeding recorded the highest gross returns; however, the net returns and B: C ratio were highest with pendimethalin + imazethapyr application.

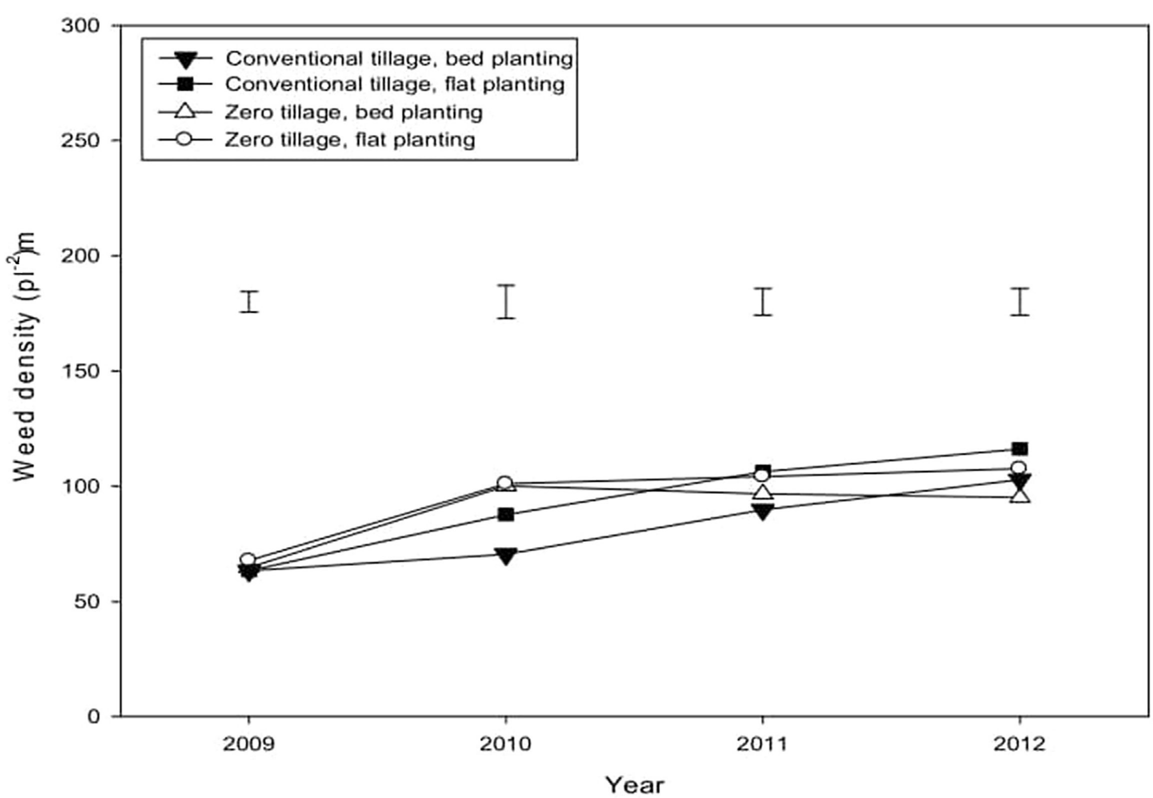

Fig. 2. Weed density in relation to year (averaged over weed management practices).

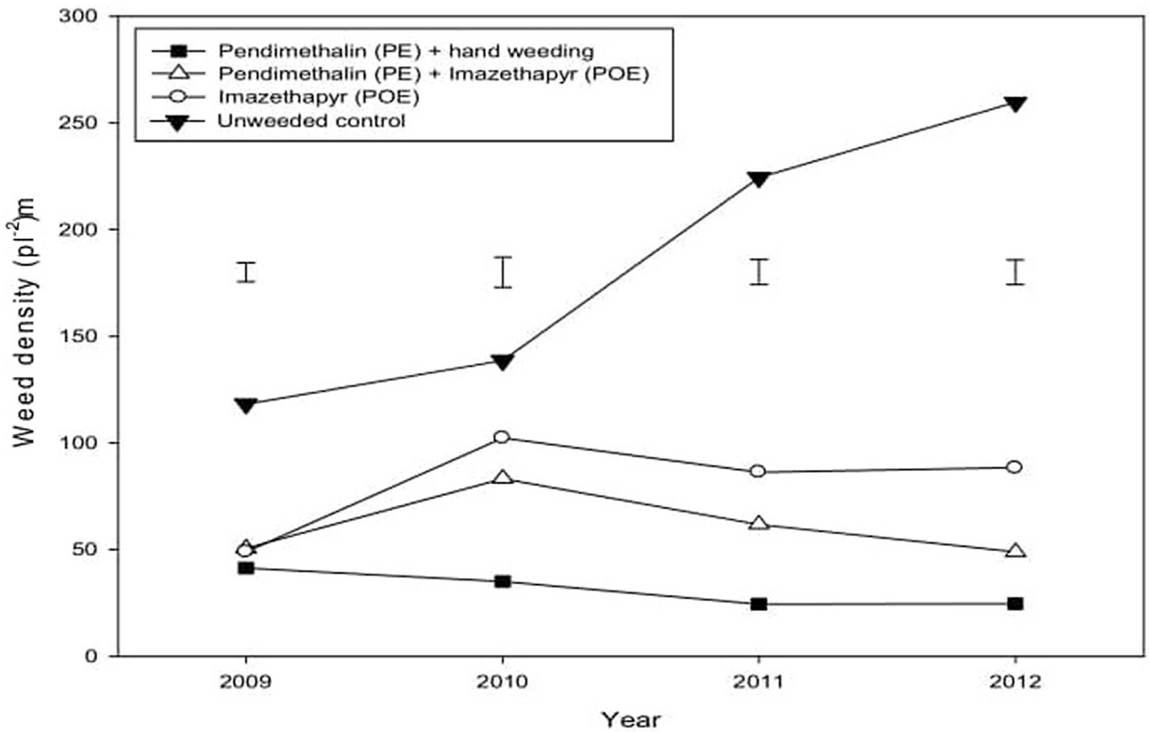

Fig. 3. Weed density in relation to year (averaged over tillage and crop establishment).

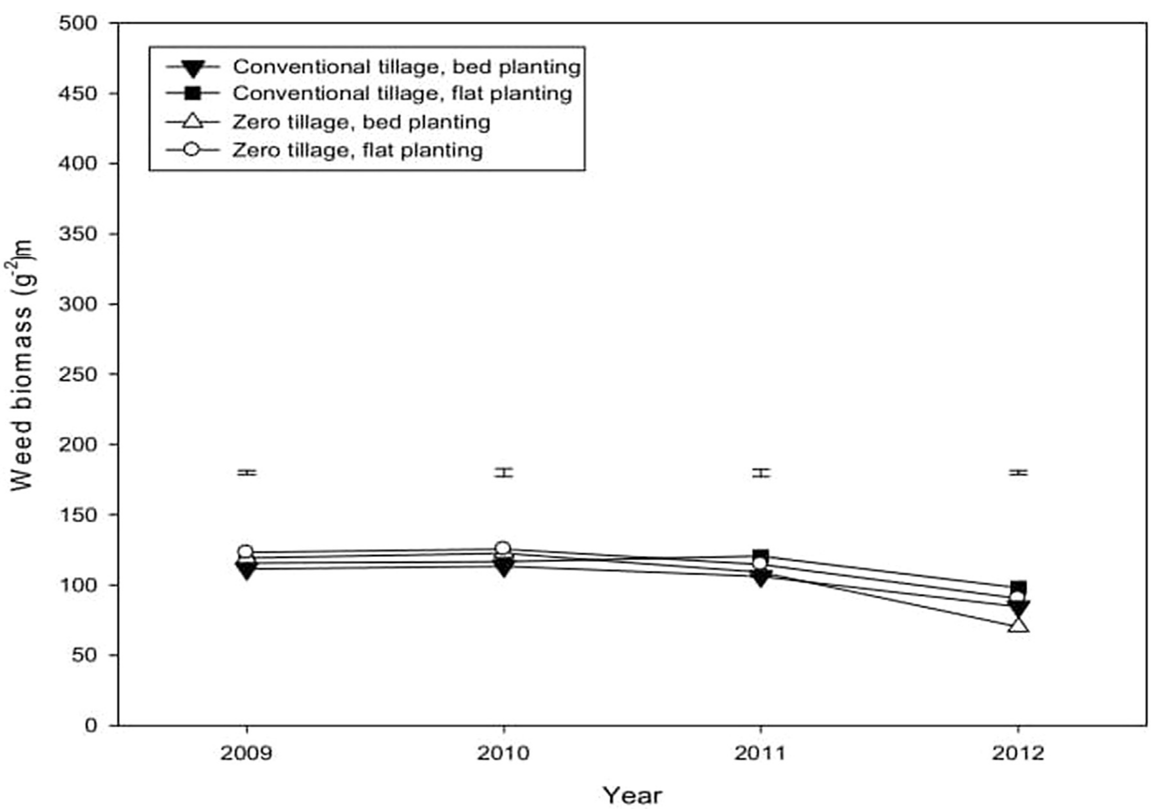

Fig. 4. Weed biomass in relation to year (averaged over weed management practices).

4. Discussion

We tested the effect of different tillage, crop establishment and weed control practices on the weed dynamics, productivity and profitability of soybean grown after wheat over a period of 4 cropping cycles.

The weed density of *E. colona* and *D. arvensis* at 30 and 60 DAS, and total weed density at 60 DAS was significantly influenced with TCE over the years. The high infestation of weeds was observed in ZT initially as compared to CT, where weeds were buried mechanically into the soil. In ZT systems, tillage was only confined to the sowing operations, thus the weed seeds of most of the species remained on the soil

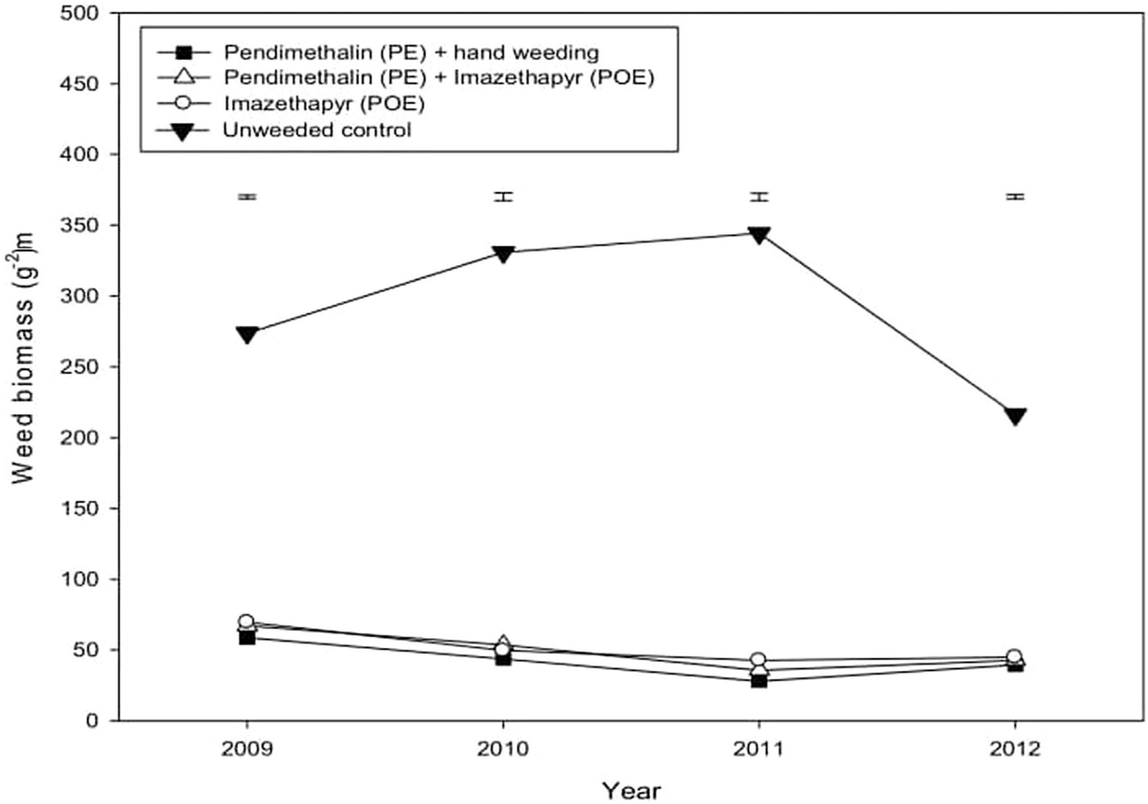

Fig. 5. Weed biomass in relation to year (averaged over tillage and crop establishment).

Table 5
Tillage and crop establishment × weed management interaction mean across years (n = 4) and replications (n = 3) for seed and stover yield.

Tillage and crop establishment	Seed yield (t ha^{-1})				Stover yield (t ha^{-1})			
	W1	W2	W3	W4	W1	W2	W3	W4
CT-B	1.17	1.84	1.73	1.66	3.18	4.50	4.26	4.13
CT-F	1.06	1.72	1.56	1.44	2.88	4.14	3.91	3.79
ZT-B	1.24	1.89	1.76	1.65	3.31	4.62	4.37	4.25
ZT-F	1.16	1.71	1.55	1.49	3.03	4.10	3.94	3.83
LSD (P ≤ 0.05)	0.13				0.06			

For full abbreviations of treatment details see materials and methods section.

surface (Gill and Arshad, 1995). The abundance of moisture and favorable temperature conditions on the soil surface led to germination of most weeds in a single flush (Bagavathiannan and Norsworthy, 2013). In ZT, application of non-selective herbicide i.e. glyphosate was done to desiccate the previously-grown weeds before sowing of the soybean crop (Williams and Wuest, 2011). This practice gradually reduced the density of *E. colona* and *D. arvensis* over the years. Therefore, the weed management × year interaction was found significant on reducing the weed density of *E. colona* and *D. arvensis* at 30 and 60 DAS, and total weed biomass at 60 DAS. The weeds were further effectively controlled by the application of selective herbicides such as pendimethalin and imazethapyr. Over the years, application of pendimethalin controlled the initial flush of broad- as well as narrow-leaved weeds, and thereafter, manual weeding at 30 DAS checked the growth of late-emerging weeds. This could be the reason behind the decline in the density of both species and weed biomass with the weed management practices over the years (Pandey et al., 2007).

The other weed species such as *D. aegyptium*, *E. indica*, *C. album* and *A. viridis*, which appeared later in the season were not effectively controlled with the herbicidal application due to specific activity of herbicides. Therefore, the effect of TCE × weed management was found non-significant on the total weed biomass at 60 DAS. The total weed density substantially declined in ZT over time which was also reported by several workers (Chhokar and Balyan, 1999). The retention of crop residues in ZT inhibited the weed seed germination. The direct contact of sunlight to the upper soil surface is limited when the soil surface is covered with crop residues (Chauhan et al., 2012). Hence, weed seeds lying on the soil surface were withered, dried out, attacked by fungi or subjected to predation by insects and bacteria (Ramesh, 2015). Furthermore, pre- and post-emergence application of herbicides effectively checked the weed growth. This practice exhausted the weed seed bank in the soil and reduced the density of *D. arvensis*, and other weeds at 60 DAS with the different tillage × weed management practices over the years. Therefore, the year × TCE × weed management interaction effects were found significant on the density of *D. arvensis* at 30 and 60 DAS, and total weed biomass at 60 DAS.

Hand weeding is the most common practice in India especially if family labour is used. However, the hike in labour prices makes hand weeding uneconomical. Thus, alternatives are required for controlling weeds through herbicides such as pendimethalin and imazethapyr. A post-emergence application is necessary to control the second flush of weeds during the growing season. Pendimethalin application as pre-emergence was particularly effective against *E. colona,* which is a grassy and prolific seed bearer weed (Taylor-Lovell et al., 2002). Likewise, post-emergence application of imazethapyr was found effective against broad-leaved weeds only, specially *D. arvensis*. The second flush of *E. colona* at 30 DAS was not effectively controlled, and increased over the years. This could be the reason that year × TCE × weed management interactions were found non-significant on the *E. colona* density at 30 and 60 DAS. Hazra et al. (2011) from a 2-year study also found a high infestation of grassy weeds in soybean crop under ZT conditions. Nevertheless, it is not adequate to make assumptions on shifts in weed population from a study with such a short duration and more years data would be required to confirm this trend. Further, this also highlights

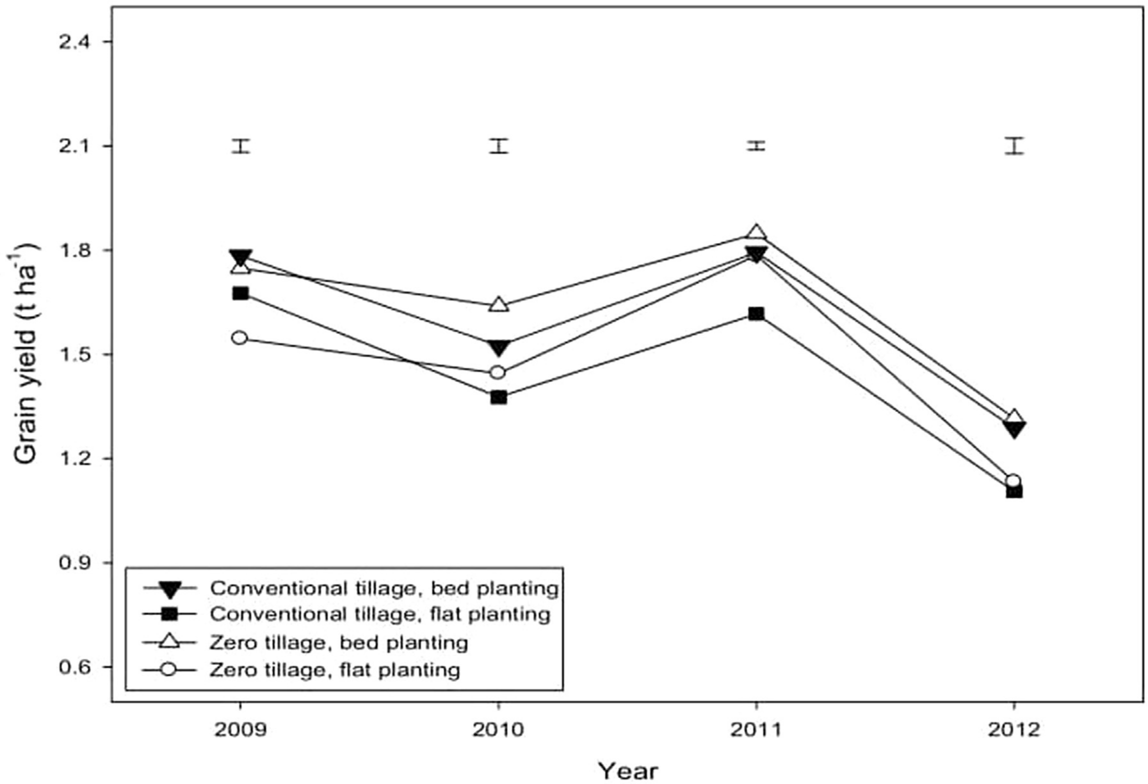

Fig. 6. Grain yield in relation to year (averaged over weed management practices).

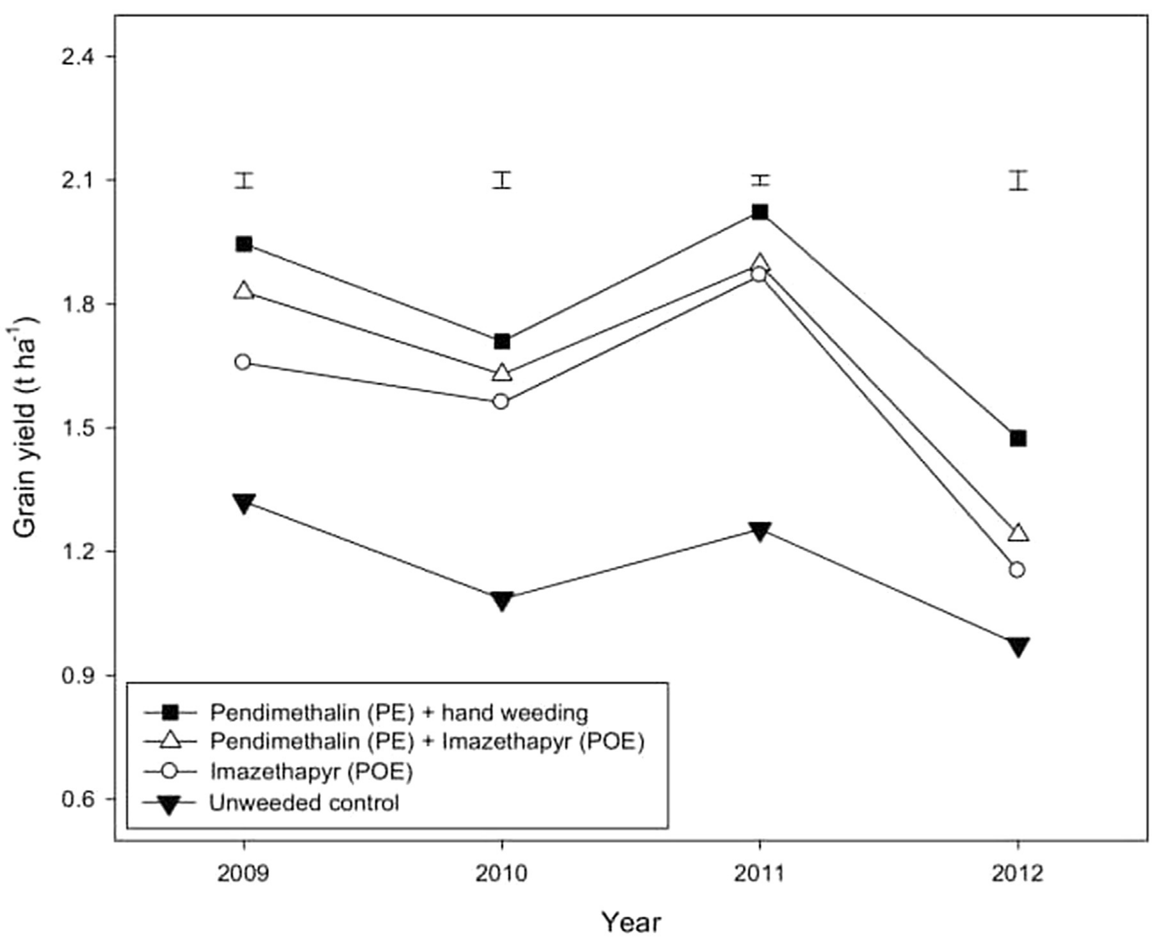

Fig. 7. Grain yield in relation to year (averaged over tillage and crop establishment).

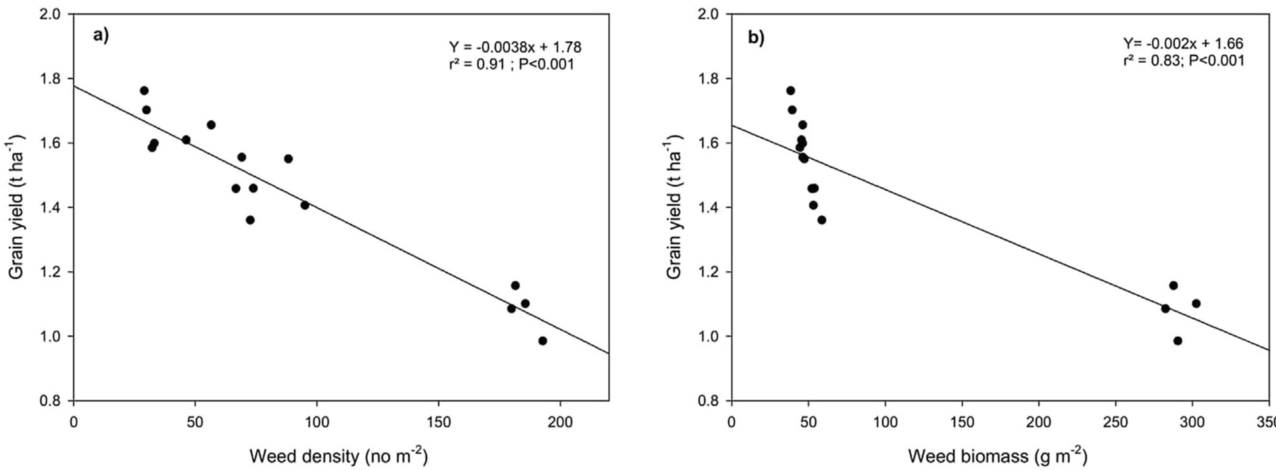

Fig. 8. Relationship of grain yield with total weed density and total weed biomass.

that reliance on single herbicide could lead to shifts in weed flora over the years. Weed management in ZT needs to be promoted with a range of herbicide combinations along with other ecological practices to avoid shifts in weed spectra to complicated and unmanageable weed species (Nawaz and Farooq, 2016).

The pods plant^{-1}, seeds pod^{-1}, grain and stover yield varied yearly during the experiment period. In 2010, rainfall was high and resulted in lower yield attributes and grain yield. The raised–beds on light–-textured soil were disfigured which affected the growth of soybean. On the other hand, the crop season in 2012 was characterized by prolonged dry spells but gave the higher yield attributes and grain yield. The reason could be that the retention of wheat residue in ZT reduced the run-off during the excessive high rainfall period. Similarly, retention of residues also facilitated consistent availability and use of soil moisture during the dry spell (Thierfelder and Wall, 2012). Furthermore, the better growth of soybean on raised beds gave the higher grain and stover yield during all the years, irrespective of ZT and CT system. Therefore, year × TCE interactions were found significant on grain and stover yield of the soybean. Year × weed management also influenced the no. of pods, grain and stover yield of soybean. Application of pendimethalin along with manual weeding at 30 DAS or with imazethapyr application controlled the weeds effectively. The less competition for water and nutrients between weed and crop resulted in to higher no. of pods, grain and stover yield of soybean over the years. However, weed management practices were found equally better in controlling weed growth under different tillage practices, and, therefore, interaction effect was found non-significant on the pods plant^{-1}, seeds pod^{-1}, grain and stover yield of soybean.

The Y × TCE × weed management interactions were found non-significant on the seeds pod^{-1}, grain and stover yield of soybean. In ZT-B, the better weed control with weed management practices exhausted the weed seed bank over the years. The low weed density provided the less competition between crop and weed for uptake of nutrients and water (Chhokar and Balyan, 1999). Furthermore, the wheat residues are also reported to have an allelopathic effect on weed germination, and conserve the moisture in the soil during the dry spell (Kumar et al., 2008). The low amount of residue retention in our experiment was found not sufficient for checking the initial weed growth. Malik et al. (2006) reported that rice residues retention up to 5 t ha^{-1} in wheat crop suppressed the weed growth and enhanced the wheat yield by 12%. However, the economical value of wheat straw for livestock feed was considered, and retention of wheat straw at 3 t ha^{-1} was applied in ZT conditions. All these factors consistently led to the higher no. of seeds pod^{-1}, grain and stover yield in ZT-B over the years.

The increase in net returns in 2012 compared to 2009 was due to fluctuations in the market prices of output and cost of cultivation. Further, the cost of cultivation and gross returns were higher in CT-B/F treatments due to the extra cost incurred in the tillage operations. The ZT-B/F treatment gave higher net returns due to consistent higher yields and lower cost of cultivation. The application of pendimethalin followed by imazethapyr controlled the narrow-/broad-leaved weeds and sedges infestation, and improved the yield over the years, which

Table 6
Economics of soybean cultivation as influenced by tillage and crop establishment, and weed management (mean of 4 years).

Treatment	Common cost of cultivation (INR × 10^3 ha^{-1})	Treatment cost (INR × 10^3 ha^{-1})	Total cost of cultivation (INR × 10^3 ha^{-1})	Gross returns (INR × 10^3 ha^{-1})	Net returns (INR × 10^3 ha^{-1})	Net benefit: cost ratio
CT-B W1	9.75	6.64	16.39	22.48	6.09	0.37
CT-B W2	9.75	12.04	21.79	34.63	12.84	0.59
CT-B W3	9.75	8.64	18.39	32.44	14.04	0.76
CT-B W4	9.75	8.24	17.99	31.46	13.47	0.75
CT-F W1	9.75	4.84	14.59	20.34	5.80	0.40
CT-F W2	9.75	10.24	19.99	32.29	12.30	0.62
CT-F W3	9.75	6.84	16.59	29.26	12.67	0.76
CT-F W4	9.75	6.44	16.19	22.12	10.93	0.67
ZT-B W1	9.75	3.04	12.79	23.91	11.12	0.87
ZT-B W2	9.75	8.44	18.19	35.74	17.55	0.96
ZT-B W3	9.75	5.04	14.79	33.18	18.39	1.24
ZT-B W4	9.75	4.64	14.39	31.30	16.91	1.17
ZT-F W1	9.75	1.24	10.99	22.05	11.06	1.01
ZT-F W2	9.75	6.64	16.39	32.42	16.03	0.98
ZT-F W3	9.75	3.24	12.99	29.28	16.28	1.25
ZT-F W4	9.75	2.84	12.59	28.12	15.53	1.23

For full abbreviations of treatment details see materials and method section; 1 US $ = INR 65.

resulted in higher returns. Application of pendimethalin followed by hand weeding recorded lower weed population and higher yields. However, the cost of cultivation was increased and became less economical due to extra cost involved in hand weeding. The alternative of this practice could be imazethapyr after pendimethalin application. However, other cultural practices such as a stale seedbed, use of clean seed, rotations with competitive green manure and/or retention of adequate residues are also necessary to reduce the reliance on chemical weed control and harness the full benefits of conservation agriculture.

5. Conclusions

This 4-year study suggested that application of pre- and post-emergence herbicides is an effective strategy to control weeds under different tillage and crop establishment methods in soybean under semi-arid conditions. The lowest population of *Echinochloa colona* and *Digera arvensis* was found in zero tillage-raised bed conditions over the years. The higher seed yield and net returns of soybean were recorded in ZT compared to CT practices. The application of pendimethalin 0.75 kg ha^{-1} as pre-emergence followed by hand weeding at 30 DAS recorded the lowest weed density and biomass. The other treatment i.e. pendimethalin 0.75 kg ha^{-1} as pre-emergence followed by imazethapyr 0.075 kg ha^{-1} as post-emergence application was found comparable in terms of soybean productivity but more economical in terms of net B:C ratio. We conclude that soybean could be grown successfully with zero-tillage raised bed following herbicide based weed control strategy in the alluvial soils of North-Western India.

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