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RESEARCH ARTICLE

Long-term tillage and weed management effects on weed shifts, phyto-sociology and crops productivity

Sachin Kumar*, Surinder Singh Rana[1], Neelam Sharma[1]

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ABSTRACT

The understanding of the diverse weed flora composition and weed shift in conservation agriculture production system is important to identify weed management component to increase agro-ecosystem sustainability. Hence, in this study, different tillage and weed management practices were assessed to evaluate their impact on diverse weed flora composition and shift in maize-wheat cropping system in North Western Himalaya from 2018-20 in an ongoing long-term experiment being conducted since 2013. Fifteen treatment combinations comprising of five tillage treatments, *viz*. conventional tillage (CT) in maize-CT in wheat; CT-zero tillage (ZT); ZT-ZT; ZT-zero tillage in combination with residue retention (ZTR) and ZTR-ZTR and three weed management treatments, *viz*. recommended herbicide (H) in maize-recommended herbicide (H) in wheat; integrated weed management (IWM)-IWM and hand weeding (HW)-HW were evaluated in a strip plot design. In CT, annual weed species were dominant, whereas, perennial weeds dominated in zero tillage (ZT). A shift in weed species with greater dominance of monocots and a marginal decrease in dicots was observed. *Parthenium hysterophorus*, an obnoxious weed, was observed in the experimental field in maize only during 2018. The monocot weed (*Echinochloa colona*) had higher relative density (RD), relative abundance (RA), relative frequency (RF) and important value index (IVI) compared to the dicot weeds in maize crop. In *Rabi* (winter) season, *Avena ludoviciana* (monocot grass) had higher RD, RF and IVI values, while, *Daucus carota* (perennial weed) had higher RA when compared to the other annual and biennial weeds. The grain yield of main and intercrop and system productivity were higher in conservation agriculture-based production systems in combination with recommended herbicide (ZTR+H-ZTR+H) in maize-wheat based cropping systems.

Keywords: Conservation agriculture, Conventional tillage, Integrated weed management, Weed phyto-sociology, Zero tillage

INTRODUCTION

Globally, modern agricultural production systems are extremely intensive and cause environmental degradation (Sial *et al*. 2021). The traditional agricultural method involving intensive tillage, inefficient pesticide applications, and excessive irrigation can lead to soil and water contamination and deterioration of natural resources negatively (Penescu *et al*. 2001, Pratibha *et al*. 2021). Thus, conservation agriculture (CA) with three interlinked principles, *viz*. (i) minimum or no mechanical soil disturbance (ii) permanent soil cover and (iii) diversification of cropping system either through sequences and/or rotations, along with good agronomic practices is a sustainable land management approach (FAO 2019, Bhattacharyya *et al*. 2019, Naeem *et al*. 2021). The main barriers to low adoption of CA are the lack of availability of CA machines, competing demands for crop residues for alternative uses, greater competition between crops and weeds, and weed management (Farooq *et al*. 2011). The zero tillage (ZT) has many environmental benefits such as reducing soil and water pollution, reducing run-off and soil degradation and stimulating soil macro and micro flora (Holland 2004). Recently, CA is being adopted and promoted for sustainable intensification of crops under various ecosystems (FAO 2011, Saad *et al*. 2016). Despite the low level of soil disturbance, weed seeds remain near or on the soil surface in ZT (Naeem *et al*. 2021), resulting in increased weeds problem which is preventing the adoption of ZT at a large scale among farmers (Yang *et al*. 2018). The benefits of CA systems may be counterbalanced by heavy weed infestations, weed community shifts either increase, decrease, or extinction of weed species (Yang *et al*. 2018, Zhang and Wu 2021), as there are many ecological and agronomic factors that influence weeds.

Farmers employ a variety of weed management strategies to reduce crop loss due to weeds (Zhang

Centre of Geo Informatics Research and Training, CSK HPKV, Palampur, Himachal Pradesh 176062, India

[1] Department of Agronomy, CSK HPKV, Palampur, Himachal Pradesh 176062, India

* Corresponding author email: schnagri@gmail.com

and Wu 2021). Presently, farmers are preferring herbicides use alone to manage diverse weed flora, which is leading to serious problems of resistance among weeds and eco-system damages (Annett *et al.* 2014, Gu *et al*. 2019). Crop residue retention is a potential weed control practice that reduces the penetration of light directly into the soil surface (Yang *et al*. 2018), which minimizes weed diversity, density and biomass accumulation (Campiglia *et al.* 2012, Yang *et al*. 2018). In the early competition between crops and weeds, the amount and type of covering material delay the germination of weeds (Teasdale and Mohler 2000, Chauhan and Mahajan 2012). Some researchers have found crop residues can release allelo-chemicals that reduce the germination and emergence of weed seeds (Duke 2015). However, mulch cover in CA makes hand-weeding and mechanical weed management strategies more difficult due to which dependency on chemical weed control measure increases. Furthermore, there has been a significant shift from easily controlled annual weeds to perennials that are difficult to control in crop lands (Armengot *et al*. 2016).

Weed community, diversity, and crop yields vary with tillage systems (Alarcon *et al*. 2018). It is therefore vital to understand the interactions among different components of CA to develop control measures that consistently minimize weed abundance. Generally, CA is criticized for its increased dependence on non-selective herbicides to control perennial weeds. The herbicides efficacy is determined by weather conditions; specifically, the timing and quantity of rainfall have a considerable impact on the efficacy of pre-emergence and post-emergence herbicides (Jursik *et al.* 2011). The over reliance and indiscriminate use of herbicides lead to weed shift and herbicide-resistant weed varieties (Farooq *et al.* 2011), ecological adversity (Owen *et al*. 2007) and human health risks. In CA, weed control and herbicide resistance to weeds are major challenges, therefore, Farooq *et al.* (2011) suggested a fourth pillar of CA to the IWM options with cautionary use of herbicides.

There are a limited research reports on influence of varied tillage intensities and residue management along with weed management strategies on weed shifts in CA systems (Han *et al*. 2013, Vanlauwe *et al.* 2014, Hosseini *et al*. 2016, Yang *et al*. 2018). Therefore, the objective of the present study was to monitor weed flora shifts over time in response to varied tillage (CT, ZT or ZTR) and residue levels in combination with weed management strategies in maize-wheat cropping system.

MATERIAL AND METHODS

Study area

The experiment was conducted at Research Farm (32°62 N, 76°32 E), Department of Agronomy, College of Agriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur (H.P.), India. The results reported in this paper were collected during rainy (*Kharif*) 2018 to winter (*Rabi*) season 2019-20 in an ongoing experiment being conducted since 2013. The experimental location has a sub-temperate mid hill zone at 1290 m above mean sea level. Experimental site has silty clay loamy soil (21% clay, 43% silt and 36% sand), according to USDA classification (**Table 1**). The soil properties of the experimental site before the start of the experiment are in **Table 1**. The second year was relatively hotter and humid, whereas, first year received higher amount of rainfall (**Figure 1**). During 2018-19, ~20% higher rainfall was received than 2019-20. The crops were irrigated when ever needed with a good drainage system.

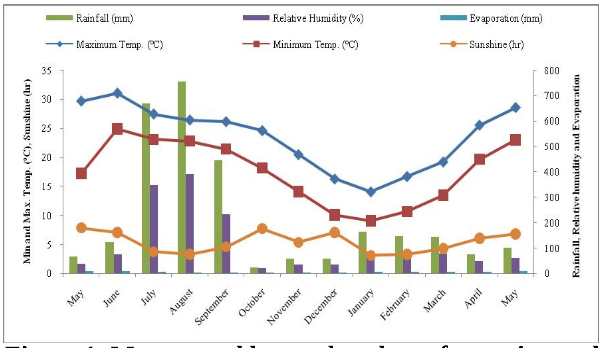

Figure 1. Mean monthly weather data of experimental site (2018-2020)

Table 1. The physic-chemical properties of 0-15 cm soil at the beginning of the experiment

Particulars	Sand (%)	Silt (%)	Clay (%)	BD (g/m^3)	SOC (g/kg)	Av. N (kg/ha)	Av. P (kg/ha)	Av. K (kg/ha)
Content	21	43	36	1.18	11.0	323.0	25.8	276.4
Analytical Method employed	International pipette method (Piper 1966)			Core Method (Singh 1980)	Walkley and Black, rapid titration method (Piper 1966)	Alkaline permanganate method (Subbiah and Asija 1956)	Olsen, method (Olsen *et al.* 1954)	Ammonium acetate extraction method (AOAC 1970)

SOC: Soil organic carbon; Av. N: Available Nitrogen; Av. P: Available Phosphorus; Av. K: Available Potassium

Experimental details

The details of the experimental treatments are given in **Table 2**. Maize crop was sown in *Kharif* (rainy) and wheat in *Rabi* (winter) season. Pre sowing irrigation at depth 5 cm was given during both *Kharif* and *Rabi* seasons of both the years. Except for ZT treatment, the plots were prepared with the help of a rotary power tiller. During seedbed preparation, crop stubble and weeds were removed to facilitate the planting operations in conventional tilled plots. The left-over weeds were removed and the plots were leveled to have uniform sowing and germination thereof. The conventional tillage (CT) plots were ploughed to a fine tilth before the start of experiment through single ploughing, harrowing twice and then leveling. The seeds of maize variety '*Kanchan 51 hybrid*' were sown in rows 60 cm apart in the first week of June and harvested in the mid to end of September every year. Sowing was done with hand plough by the kera (dropping of seeds by hand into the burrows, which have been opened by the local plough) method. Common dosage of 120 kg N, 60 kg P, and 40 kg K/ha respectively, was supplied through urea (46% N), IFFCO (12:32:16), and MOP (60% K). Intercrop of soybean, grown in additive series with maize, was not given any additional fertilizer dose. The net plot size was 2.7 m × 4.5 m. The crops water requirement was fulfilled according to the prevailing climatic conditions. Wheat crop variety '*HPW 368*' was sown during the first fortnight of November at a spacing of 20 cm using a seed rate of 120 kg/ha. The crop was fertilized with 120 kg N, 60 kg P, and 30 kg K/ha. Half N and whole P and K were applied at the time of sowing. Four irrigations were given in order to avoid drought stress. The remaining nitrogen was top-dressed in two equal splits at tillering and earing stage. The crop was harvested by the mid of May each year.

In both crops, all other production practices, except tillage and weed control treatments were followed as per recommendations in the package of practices. All the crops (main crops and intercrops) were harvested manually.

System productivity

In order to calculate the productivity of the maize-wheat cropping system, the equivalent yield of maize cob was calculated by using the following formula:

Maize cob equivalent yield (MEY) = Maize cob yield (kg/ha) + soybean seed yield (kg/ha) × price of soybean seed (₹/kg)/price of maize cob/(₹/kg) + wheat grain yield (kg/ha) × price of wheat grain (₹/kg)/price of wheat seed/(₹/kg) + mustard seed yield (kg/ha) × price of mustard seed (₹/kg)/price of maize cob/(₹/kg)

Data analysis

In both crops, weeds were counted at monthly interval from 0.5 × 0.5 m quadrat placed randomly at 2 places in each experimental treatment plots and then mean value of two was calculated. Individual weed species population was added to calculate the total weed density in a particular treatment. Statistical analysis of system productivity was performed with ANOVA techniques (Gomez and Gomez 1984) for the strip-plot design and the treatment means were tested with LSD at (p=0.05) at a 5% level of significance to interpret the treatment differences.

Weed phyto-sociology

Importance value index (IVI) of each of the weed species was calculated by using the following formulae:

$$\text{Density} = \frac{\text{Total number of individuals of a species in all quadrats}}{\text{Total number of quadrates studied}}$$

$$\text{Frequency (\%)} = \frac{\text{Total number of quadrates in which the species occurred}}{\text{Total number of quadrats studied}}$$

$$\text{Abundance} = \frac{\text{Total number of individuals of a species in all quadrats}}{\text{Total number of quadrats in which the species occurred}}$$

IVI = Relative density + Relative frequency + Relative abundance

Table 2. Treatments adopted in the experiment

Maize crop	Wheat crop	Notation
Tillage and residue management		
T_1 - Conventional tillage (CT)	T_1 - Conventional tillage (CT)	CT-CT
T_2 - Conventional tillage (CT)	T_2 - Zero tillage (ZT)	CT-ZT
T_3 - Zero tillage (ZT)	T_3 - Zero tillage (ZT)	ZT-ZT
T_4 - Zero tillage (ZT)	T_4 - Zero tillage + residue (ZTR)	ZT-ZTR
T_5 - Zero tillage + residue (ZTR)	T_5 - Zero tillage + residue (ZTR)	ZTR-ZTR
Weed management treatment		
W_1 - Recommended herbicides (atrazine *fb* 2,4-D)	W_1 - Recommended herbicides (isoproturon *fb* 2,4-D)	H-H
W_2 - IWM (intercropping* + pendimethalin spray + one HW)	W_2 - IWM (intercropping** + isoproturon spray + HW)	IWM-IWM
W_3 - Hand weeding (hand hoeing) twice	W_3 - Hand weeding (hand hoeing) twice	HW-HW

*Intercropping of soybean in maize crop; **Intercropping of mustard in wheat crop; HW: Hand weeding

RESULTS AND DISCUSSION

Weed flora shift

There were changes in weed flora in maize-wheat cropping system as per observations taken during *Kharif* 2018 to *Rabi* 2019-20 from those taken at the initiation of the experiment during *Rabi* 2013-14 and at the mid of experiment (Anonymous 2014) (**Table 3)**. Ball and Miller (1990) also reported that tillage practices (minimum or zero tillage) cause changes in the abundance and diversity of weed species in cropping systems.

Weed flora shift during *Kharif* (rainy) season

In *Kharif* (rainy) season maize, *Echinochloa colona* and *Panicum dichotomiflorum* were observed in *Kharif* 2014, 2018, 2019 and were not recorded during *Kharif* 2016. Per cent population of *Ageratum conyzoides*, *Echinochloa colona* and *Commelina benghalensis* were 33, 30 and 15%, respectively, of the total weed flora during 2014. Whereas, during *Kharif* 2016, the relative density of *Ageratum conyzoides* and *Commelina benghalensis* increased to 47 and 23%, respectively. *Digitaria sanguinalis*, *Panicum dichotomiflorum* and *Cyperus iria* constituted 10, 9 and 3%, respectively, of the total weed flora in maize during 2014. *Cynodon dactylon* was the new invasion in the experimental field during 2016. *Cyperus iria*, *Digitaria sanguinalis* and *Cynodon dactylon* constituted 11, 10 and 9%, respectively, of the total weed flora of maize in 2016. During *Kharif* 2018, *A. conyzoides* and *C. benghalensis* were the major weeds constituting 23.8 and 21.4%, respectively of the total weed flora. Occurrence of *Parthenium hysterophorus* and *Bidens pilosa* was also seen during *Kharif* 2018 constituting around 2.0 and 6.3% of the total population, respectively, which were otherwise not present earlier and during *Kharif* 2019. *Polygonum alatum* which was observed only during *Kharif* 2019 with relative density of about 11% (**Figure 2**). Bajwa (2014) reported that small seeded and perennial weeds are more abundant in CA. Surface residue retention caused limited germination and growth of small-seeded annuals because of restricted light availability, physical growth barriers and potential allelopathic effects (Nichols *et al*. 2015).

Weed flora shift in wheat crop: During 2013-14, *Avena ludoviciana, Coronopus didymus* and *Phalaris minor* were major weeds with relative density of 41, 20 and 18%, respectively. *Lolium temulentum* and *Vicia sativa* constituted 11 and 10% of total weed density, respectively, in wheat during 2013-14. Among these weeds, *Phalaris*, *Avena* and *Lolium* were not recorded during 2016-17, which were further present during *Rabi* 2018-19 and 2019-20. *Erodium cicutarium*, *Euphorbia hirta* and *Oxalis corniculata* were observed only during 2016-17 with higher relative density of 38, 17 and 17%, respectively of the total weed flora. *Vicia sativa* constituted 11% of the weed flora in wheat in 2016-17. *Avena ludoviciana* and *Daucus carota* were the dominant weeds constituting 26.4 and 25.1% relative density during 2018-19 and 25.2and 24.4% during 2019-20, respectively.

Lolium temulentum, *Poa annua*, *Vicia sativa* and *Phalaris minor* constituting about 15.55, 13.8, 9.6 and 5.8% during *Rabi* 2018-19 and about 15.9, 12.6, 10.5 and 5.8% during *Rabi* 2019-20. *Poa annua* and *Daucus carota* were seen only during the last years of experiment which were however not visible during earlier years of research trial. Nichols *et al*. (2015) reported that minimum tillage may shift weed communities from annual dicots to grassy annuals and perennials. A weed shift is 'the change in the

Table 3. Weeds occurred in the experimental field from 2013-14 to 2019-20

Weed species	Year								
	Maize					Wheat			
	2014	2016	2018	2019		2013-14	2016-17	2018-19	2019-20
Cyperus iria	+	+	+	+	*Coronopus didymus*	+	-	+	+
Commelina benghalensis	+	+	+	+	*Vicia sativa*	+	+	+	+
Digitaria sanguinalis	+	+	+	+	*Lolium temulentum*	+	-	+	+
Ageratum conyzoides	+	+	+	+	*Phalaris minor*	+	-	+	+
Cynodon dactylon	+	-	-	-	*Avena ludoviciana*	+	-	+	+
Bidens pilosa	-	-	+	-	*Anagallis arvensis*	-	+	-	-
Echinochloa colona	+	-	+	+	*Euphorbia hirta* (L.)	-	+	-	-
Panicum dichotomiflorum	+	-	+	+	*Oxalis corniculata* (L.)	-	+	-	-
Parthenium hysterophorus	-	-	+	-	*Erodium cicutarium* (L.)	-	+	-	-
Polygonum alatum	-	-	-	+	*Poa annua*	-	-	+	+
					Daucus carota	-	-	+	+

+: Presence of the weed; -: Absence of the weed composition, abundance or relative frequencies of weeds in a weed population or community in response to natural or man-influenced changes' (Rana *et al.* 2020). Weedy and invasive species can easily adapt to changes in production practices in order to take advantage of the available niches (Rana and Rana 2015).

Weed phyto-sociology in maize

Studies of weed phyto-sociology are useful in identifying the species that are most important during distinct periods of crop growth. Phyto-sociological attributes, *viz*. relative density (RD), relative abundance (RA) relative frequency (RF) and important value index (IVI) were estimated based on seasonal observations and pooled values of both the years (**Table 4** and **5)**. A total of eight annual weed species were identified in the experimental area. The overall RD, RA and RF were higher for *Echinochloa colona* followed by *Commelina benghalensis* and *Ageratum conyzoides*. Mekonnen and Markos (2016) also found that *Ageratum conyzoides* were higher in abundance in maize-based cropping system in CT-based cropping system. Among different treatments combinations, CT+H-ZT+H had higher RD, RA and RF for *Cyperus iria* in maize crop. ZTR+IWM-ZTR+IWM resulted in higher RD, RA and RF for *Commelina benghalensis*. For *Digitaria sanguinalis*, higher RD was recorded in ZT+H-ZT+H, while its RA and RF were higher in ZTR+H-ZTR+H. Froud-Williams (1988) also found that *Digitaria sanguinalis* population was higher under zero tilled plots. Higher RD of *Ageratum conyzoides* was in CT+IWM-CT+IWM, whereas, its RA and RF was higher in CT+IWM-ZT+IWM. Mekonnen and Markos (2016) also reported that *Ageratum conyzoides* was most abundant in CT in maize-cowpea intercropping system. However, RD, RA and RF of *Digitaria* sp. were higher in CT+HW-CT+HW in maize crop. The CT+HW-CT+HW resulted in higher RD, RA and RF of *Bidens pilosa*. *Echinochloa colona* had higher RD, RA and RF per cent in ZT+HW-ZT+HW. CT+HW-CT+HW had maximum RD of *Parthenium hysterophorus* and *Polygonum alatum*. However, CT+IWM-CT+IWM have RA and RF of *Parthenium hysterophorus* and *Polygonum alatum*.

Phyto-sociology of weeds showed the trend of variation in weed populations within a crop and variations are interlinked to production practices adopted, which further used to support varied weed management strategies (Concenço *et al.* 2017). Weeds IVI varied with tillage and weed management treatments and the dominant weed species would have high important value index (**Table 5**). Maximum averaged IVI among all the weeds was recorded for *Echinochloa colona* (55.90%) followed by *Commelina benghalensis* (54.83%) and *Ageratum conyzoides* (50.28%).

Amongst all the weeds, highest IVI of *Echinochloa colona* was found in ZTR+H-ZTR+H followed by ZT+HW-ZT+HW. However, higher IVI of *Commelina benghalensis* was recorded in ZT+H-ZTR+H followed by ZT+IWM-ZTR+IWM. Among all weeds, lowest averaged IVI was of *Parthenium hysterophorus* (4.10%), while its IVI was higher in CT+HW-ZT+HW during *Kharif* season. Rana *et al.* (2019) also reported that *Ageratum conyzoides*, *Echinochloa colona* and *Commelina benghalensis*

Table 4. Effect of treatments on relative density (RD) and relative abundance (RA) of associated weed species in maize crop

Treatment	Weed species																	
	Cyperus iria		*Commelina benghalensis*		*Digitaria sanguinalis*		*Ageratum conyzoides*		*Bides pilosa*		*Panicum dichotomiflorum*		*Echinochloa colona*		*Parthenium hysterophorus*		*Polygonum alatum*	
	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA
CT+H-CT+H	20.08	20.06	17.52	14.26	15.61	13.31	22.60	21.84	2.90	5.42	3.54	7.29	16.02	13.76	0.00	0.00	1.74	4.09
CT+IWM-CT+IWM	7.90	9.35	21.61	17.19	8.20	8.26	32.56	29.40	4.76	4.55	3.68	8.52	12.41	13.73	1.91	3.64	6.98	5.38
CT+HW-CT+HW	14.70	13.85	15.67	14.95	12.28	11.38	14.69	17.04	10.00	9.83	5.83	5.27	16.65	17.58	0.00	0.00	10.20	9.22
CT+H-ZT+H	25.45	24.75	12.65	11.99	8.81	10.42	17.48	17.22	3.55	6.70	9.46	4.19	15.96	18.85	0.00	0.00	6.67	5.89
CT+IWM-ZT+IWM	1.96	7.96	20.98	14.84	11.84	11.14	34.06	32.27	3.41	9.31	6.05	5.94	12.92	12.08	0.00	0.00	8.79	6.48
CT+HW-ZT+HW	13.93	15.46	19.10	15.60	7.26	10.25	8.68	15.74	1.02	2.78	8.65	7.50	21.80	21.92	7.15	0.00	12.43	10.78
ZT+H-ZT+H	8.90	10.90	21.46	16.37	19.97	14.95	14.00	28.33	4.27	6.51	4.93	1.66	20.96	15.89	1.94	0.00	3.59	5.40
ZT+IWM-ZT+IWM	9.24	9.36	18.89	13.31	15.75	14.57	28.32	28.20	3.95	6.13	0.95	5.53	12.75	19.16	5.70	0.00	4.48	3.75
ZT+HW-ZT+HW	18.63	15.35	11.55	11.55	11.67	10.56	10.63	15.89	5.14	6.48	6.02	4.90	32.85	30.11	0.00	0.00	3.53	5.17
ZT+H-ZTR+H	17.46	15.12	24.15	18.30	8.95	8.83	17.05	28.18	3.47	4.58	5.94	4.73	22.99	20.28	0.00	0.00	0.00	0.00
ZT+IWM-ZTR+IWM	5.19	10.23	25.52	16.56	17.24	16.84	18.04	21.26	8.62	9.08	0.00	0.00	17.21	19.13	0.00	0.00	8.21	6.91
ZT+HW-ZTR+HW	13.27	10.96	14.96	18.02	15.83	13.48	15.28	22.86	6.85	7.71	7.20	3.45	24.90	19.56	0.00	0.00	1.74	3.98
ZTR+H-ZTR+H	12.09	16.16	20.54	19.57	18.40	22.34	7.15	15.65	0.45	2.94	8.04	0.00	29.33	23.36	4.02	0.00	0.00	0.00
ZTR+IWM-ZTR+IWM	21.95	18.08	28.16	19.04	9.36	18.06	6.08	13.70	1.60	5.25	7.18	8.54	21.44	17.34	4.26	0.00	0.00	0.00
ZTR+HW-ZTR+HW	11.28	12.99	15.61	14.14	17.53	18.19	15.04	15.63	3.75	5.71	7.18	6.23	21.18	20.50	0.84	0.00	7.63	6.62
Overall	14.32	14.04	20.27	15.71	14.16	13.51	18.27	21.55	4.25	6.20	6.28	4.92	21.26	18.88	1.72	0.25	5.75	4.91

RD, Relative density; RA, Relative abundance; CT, conventional tillage; ZT, zero tillage; ZTR, zero tillage in combination with residue; H, recommended herbicides; IWM, integrated weed management; HW, hand weeding; CT+H-CT+H, Conventional tillage in maize in combination with recommended herbicides in maize-wheat

Table 5. Effect of treatments on relative frequency (RF) and important value index (IVI) of associated weed species in maize crop

Treatment	Weed species																	
	Cyperus iria		*Commelina benghalensis*		*Digitaria sanguinalis*		*Ageratum conyzoides*		*Bides pilosa*		*Panicum dichotomiflorum*		*Echinochloa colona*		*Parthenium hysterophorus*		*Polygonum alatum*	
	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI
CT+H-CT+H	20.06	55.90	14.26	50.75	13.31	46.80	21.84	60.20	5.42	12.50	7.29	18.20	13.76	46.65	0.00	0.0	4.09	9.0
CT+IWM-CT+IWM	9.35	30.55	17.19	57.10	8.26	27.35	29.40	78.15	4.55	16.80	8.52	19.15	13.73	39.65	3.64	9.30	5.38	21.95
CT+HW-CT+HW	13.85	44.95	14.95	47.05	11.38	40.05	17.04	44.60	9.83	28.35	5.27	19.00	17.58	48.70	0.00	0.0	9.22	27.30
CT+H-ZT+H	24.75	66.25	11.99	39.90	10.42	32.35	17.22	50.65	6.70	14.50	4.19	27.80	18.85	47.55	0.00	0.0	5.89	21.05
CT+IWM-ZT+IWM	7.96	14.40	14.84	58.95	11.14	39.35	32.27	83.70	9.31	15.95	5.94	19.65	12.08	42.35	0.00	0.0	6.48	25.55
CT+HW-ZT+HW	15.46	42.85	15.60	55.45	10.25	29.80	15.74	28.85	2.78	6.75	7.50	26.60	21.92	60.05	0.00	15.95	10.78	33.65
ZT+H-ZT+H	10.90	32.50	16.37	58.20	14.95	55.25	28.33	49.95	6.51	16.00	1.66	13.00	15.89	56.15	0.00	5.05	5.40	13.85
ZT+IWM-ZT+IWM	9.36	33.60	13.31	53.50	14.57	46.50	28.20	71.55	6.13	15.20	5.53	7.70	19.16	43.05	0.00	12.10	3.75	16.75
ZT+HW-ZT+HW	15.35	53.25	11.55	39.70	10.56	39.35	15.89	35.15	6.48	18.00	4.90	20.90	30.11	79.40	0.00	0.0	5.17	14.25
ZT+H-ZTR+H	15.12	51.10	18.30	63.45	8.83	34.10	28.18	54.65	4.58	14.15	4.73	22.00	20.28	60.60	0.00	0.0	0.00	0.0
ZT+IWM-ZTR+IWM	10.23	24.00	16.56	67.85	16.84	50.85	21.26	53.60	9.08	25.75	0.00	0.0	19.13	52.80	0.00	0.0	6.91	25.10
ZT+HW-ZTR+HW	10.96	41.55	18.02	46.80	13.48	46.50	22.86	47.90	7.71	21.20	3.45	24.45	19.56	62.70	0.00	0.0	3.98	8.85
ZTR+H-ZTR+H	16.16	42.35	19.57	62.90	22.34	58.65	15.65	26.45	2.94	4.60	0.00	17.80	23.36	79.55	0.00	7.70	0.00	0.0
ZTR+IWM-ZTR+IWM	18.08	61.45	19.04	73.50	18.06	35.35	13.70	27.40	5.25	9.60	8.54	23.35	17.34	60.90	0.00	8.40	0.00	0.0
ZTR+HW-ZTR+HW	12.99	37.90	14.14	47.40	18.19	51.40	15.63	41.35	5.71	14.90	6.23	22.40	20.50	58.40	0.00	3.0	6.62	23.25
Overall	14.04	42.17	15.71	54.83	13.51	42.24	21.55	50.28	6.20	15.62	4.92	18.80	18.88	55.90	0.25	4.10	4.91	16.04

RF, Relative frequency; IVI, Important value index; CT, conventional tillage; ZT, zero tillage; ZTR, zero tillage in combination with residue; H, recommended herbicides; IWM, integrated weed management; HW, hand weeding; CT+H-CT+H, Conventional tillage in maize in combination with recommended herbicides in maize-wheat

were the most important weeds in the maize field during survey in 2008 as well as in 2018 in the North Western Indian Himalaya. Pala *et al.* (2020) reported that change in IVI values might be due to change in climate, nature of soil and management factors. However, Pala and Mennan (2018) also reported that *Avena fatua* with a high important value index in wheat crop. Due to the abundance of weed seeds in soil, *A. conyzoides* and *D. absynicum* tend to dominate most cropping systems and tillage practices (Thomas and Frick 1993).

Weed phyto-sociology in wheat crop

Relative density (RD), relative abundance (RA) relative frequency (RF) and important value index (IVI) of weeds in wheat crop indicated that among seven (six annual and one perennial) weed species during *Rabi* season in wheat crop, overall percent RD and RF was higher for *Avena ludoviciana*, whereas, RA was higher for *Daucus carota* (**Table 6** and **7)**. Among tillage and weed treatments combination, CT+IWM-CT+IWM had higher RD of *Lolium temulentum*, *A. ludoviciana*, *P. minor*, *D. carota* and *V. sativa*, whereas, ZT+HW-ZT+HW had higher RD for *Poa annua*. Thomas and Frick (1993) also found that in no-till systems, broad leaf perennials are less abundant. CT+IWM-ZT+IWM had higher RD value for *Lolium temulentum*, whereas, ZT+H-ZT+H had higher RF percent value. CT+H-CT+H had higher RA value, whereas, ZT+H-ZT+H resulted in higher value of RF for *L. temulentum*. ZTR+H-ZTR+H had high percent value of *A. ludoviciana*, whereas, CT+H-CT+H resulted in higher RF. CT+IWM-CT+IWM resulted in higher RA per cent value of *P. minor* and *C. didymus* in wheat crop, whereas, CT+H-CT+H had higher value of RF of these weeds. CT+H-ZT+H had higher value of RF for *Daucus carota*, however, ZTR+IWM-ZTR+IWM had higher RF for *Vicia sativa.* ZT+IWM-ZTR+IWM resulted in higher RA for *D. carota*. Kells and Meggitt (1985) also reported that no-tillage systems favored perennial weeds. Froud-Williams (1988) and Kells and Meggitt (1985) also found that no-till systems tend to favor annual grass species over annual broadleaf species. Highest averaged overall IVI value was reported for *A. ludoviciana* (76.99%) followed by *Poa annua* (58.55%) and *L. temulentum* (47.69%) (**Table 7**). Among all the weeds, *Coronopus didymus* (15.66%) had lowest averaged IVI. Among different treatment combinations, highest IVI for *A. ludoviciana* was recorded in CT+H-CT+H followed by ZTR+H-ZTR+H.

Lolium temulentum had higher IVI in CT+H-CT+H followed by CT+IWM-ZT+IWM. *P. minor* had higher IVI value in CT+H-ZT+H followed by ZT+H-ZT+H. ZT+IWM-ZTR+IWM followed by ZT+HW-ZTR+HW had highest IVI value for *D. carota* among all the treatments combinations. However, *Vicia sativa*, a annual broad-leave weed had higher IVI value in ZT+IWM-ZT+IWM followed by ZTR+HW-ZTR+HW and ZTR+IWM-ZTR+IWM.

System productivity

In a maize-wheat cropping system, tillage and weed control treatments made significant contributions to the grain yield of main and intercrop

Table 6. Effect of treatments on relative density of associated weed species in wheat crop

Treatment	Weed species													
	Lolium temulentum		*Avena ludoviciana*		*Phalaris minor*		*Coronopus didymus*		*Daucus carota*		*Poa annua*		*Vicia sativa*	
	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA
CT+H-CT+H	5.56	12.58	72.74	40.92	11.91	20.22	0.00	0.00	2.39	16.18	7.42	10.11	0.00	0.00
CT+IWM-CT+IWM	57.50	15.58	94.67	22.63	62.72	22.95	18.14	4.65	70.04	19.55	12.91	7.27	46.77	7.39
CT+HW-CT+HW	24.98	29.99	22.46	25.72	8.03	17.36	19.18	0.00	8.23	13.29	10.49	6.37	6.65	7.28
CT+H-ZT+H	13.95	25.99	23.51	20.88	23.91	18.48	0.00	0.00	20.31	18.61	12.36	5.71	5.98	10.35
CT+IWM-ZT+IWM	32.14	34.48	19.50	19.69	1.52	3.77	0.00	0.00	26.53	28.72	13.40	5.52	6.92	7.82
CT+HW-ZT+HW	7.22	20.97	18.23	22.54	8.94	10.41	13.13	0.00	31.93	33.32	19.81	8.68	0.75	4.10
ZT+H-ZT+H	19.55	20.04	49.98	29.18	17.71	17.42	0.40	0.00	3.90	16.11	1.54	6.06	6.93	11.21
ZT+IWM-ZT+IWM	26.51	31.05	23.58	20.05	7.07	9.37	0.00	0.00	15.83	25.86	18.06	7.44	8.95	6.25
ZT+HW-ZT+HW	1.58	15.88	10.27	13.79	13.52	9.51	5.22	0.00	34.38	39.40	28.04	13.17	7.01	8.26
ZT+H-ZTR+H	17.29	20.80	14.80	16.11	2.84	6.35	0.00	0.00	34.78	34.93	20.20	9.67	10.10	12.15
ZT+IWM-ZTR+IWM	3.24	8.91	12.68	13.11	4.29	5.20	3.84	0.00	64.72	59.43	3.40	5.35	7.84	8.01
ZT+HW-ZTR+HW	6.44	30.14	28.81	22.11	11.33	11.22	8.12	0.00	30.13	25.86	11.84	5.39	3.36	5.29
ZTR+H-ZTR+H	8.77	19.51	41.52	38.02	8.37	6.80	10.04	0.00	19.50	24.02	1.85	3.89	9.97	7.78
ZTR+IWM-ZTR+IWM	13.81	19.49	26.97	31.96	6.31	6.06	4.27	0.00	21.41	25.63	8.04	4.64	19.22	21.56
ZTR+HW-ZTR+HW	3.62	16.03	16.00	11.91	9.05	6.64	5.12	0.00	33.79	33.27	20.22	10.01	12.22	8.56
Overall	16.15	21.43	31.71	24.15	13.17	11.45	5.83	0.31	27.86	27.61	12.64	7.28	10.18	8.40

RD, Relative density; RA, Relative abundance; CT, conventional tillage; ZT, zero tillage; ZTR, zero tillage in combination with residue; H, recommended herbicides; IWM, integrated weed management; HW, hand weeding; CT+H-CT+H, Conventional tillage in maize in combination with recommended herbicides in maize-wheat

Table 7. Effect of treatments on relative frequency (RF) and important value index (IVI) of associated weed species in wheat crop

Treatment	Weed species													
	Lolium temulentum		*Avena ludoviciana*		*Phalaris minor*		*Coronopus didymus*		*Daucus carota*		*Poa annua*		*Vicia sativa*	
	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI
CT+H-CT+H	13.04	31.20	52.17	165.85	17.39	21.80	0.00	27.75	4.35	9.65	13.04	34.50	0.00	9.30
CT+IWM-CT+IWM	17.21	61.25	20.65	72.90	14.92	50.25	8.04	11.70	16.60	48.20	9.97	30.80	12.62	24.90
CT+HW-CT+HW	20.74	67.85	22.21	70.30	4.41	41.35	9.74	26.95	17.15	17.90	16.81	56.25	8.96	19.45
CT+H-ZT+H	12.02	63.00	25.00	64.15	12.02	54.60	0.00	2.70	25.00	28.25	18.91	64.40	7.05	22.95
CT+IWM-ZT+IWM	20.02	66.75	21.26	61.35	3.75	11.35	0.00	8.70	20.00	50.65	21.24	70.75	13.74	30.50
CT+HW-ZT+HW	8.12	47.00	18.95	90.50	8.12	37.95	19.60	31.05	22.96	42.25	19.60	46.45	2.66	4.75
ZT+H-ZT+H	24.62	72.60	43.49	96.40	11.60	51.25	1.47	6.70	7.23	8.45	2.90	38.35	8.70	26.30
ZT+IWM-ZT+IWM	17.88	47.90	24.84	55.10	6.90	35.15	0.00	12.90	13.12	34.90	20.03	77.35	17.24	36.80
ZT+HW-ZT+HW	2.30	36.75	17.25	45.55	13.22	46.25	13.80	12.60	20.11	43.45	20.69	85.25	12.65	30.15
ZT+H-ZTR+H	19.25	39.45	21.52	51.35	4.62	29.20	0.00	7.80	23.09	49.90	20.76	106.65	10.78	15.75
ZT+IWM-ZTR+IWM	9.45	33.90	25.20	62.15	10.23	22.35	4.73	13.85	28.35	88.65	7.88	53.35	14.18	25.75
ZT+HW-ZTR+HW	4.17	37.85	25.01	86.70	9.73	42.95	13.17	18.30	22.93	53.60	18.06	51.30	6.95	9.40
ZTR+H-ZTR+H	9.26	37.55	22.23	101.80	11.12	36.75	22.23	25.15	16.67	46.15	3.67	36.20	14.82	16.40
ZTR+IWM-ZTR+IWM	14.68	47.95	17.39	76.35	9.77	46.75	6.52	12.30	17.39	35.30	15.22	50.70	19.02	30.60
ZTR+HW-ZTR+HW	4.68	24.30	12.86	54.40	12.28	41.60	10.53	16.40	21.06	51.30	19.89	75.90	18.71	36.15
Overall	13.16	47.69	24.67	76.99	10.00	37.97	7.32	15.66	18.40	40.57	15.24	58.55	11.20	22.61

RF, Relative frequency; IVI, Important value index; CT, conventional tillage; ZT, zero tillage; ZTR, zero tillage in combination with residue; H, recommended herbicides; IWM, integrated weed management; HW, hand weeding; CT+H-CT+H, Conventional tillage in maize in combination with recommended herbicides in maize-wheat

along with system productivity in terms of MEY (maize cob equivalent yield) (**Table 8**). In ZTR-ZTR, higher grain yield of maize and wheat crop was recorded which was statistically similar to the CT-CT and CT-ZT. Consequently, higher MEY was recorded in ZTR-ZTR (13.12 t/ha) which remained statistically (p=0.05) alike with CT-CT (12.60 t/ha) and CT-ZT (12.47 t/ha). In case of weed management treatments, application of recommended herbicides (H-H) resulted in higher maize and maize cob equivalent yield; whereas, HW-HW had higher wheat grain yield. Prasai *et al.* (2018) also reported that

Table 8. Effect of tillage and weed management treatments on grain yield of maize, wheat and intercrop (soybean, mustard) and maize equivalent yield (MEY) (t/ha) (mean of 2 year's)

	Maize cob yield (t/ha)	Soybean grain yield (t/ha)	Wheat grain yield (t/ha)	Mustard grain yield (t/ha)	MEY (t/ha)
Tillage					
CT-CT	7.47[ab]	0.15[a]	5.45[ab]	0.04[bc]	12.60[a]
CT-ZT	7.26[bc]	0.10[b]	5.75[a]	0.03[c]	12.47[a]
ZT-ZT	6.93[c]	0.07[c]	4.72[c]	0.03[c]	11.17[b]
ZT-ZTR	7.00[c]	0.06[c]	5.01[bc]	0.05[b]	11.51[b]
ZTR-ZTR	7.74[a]	0.08[bc]	5.92[a]	0.07[a]	13.12[a]
LSD (p=0.05)	0.35		0.64		0.70
Weed management					
H-H	7.57[a]	0.00	6.28	0.00	12.81[a]
IWM-IWM	7.57[a]	0.27	3.32	0.14	11.60[b]
HW-HW	6.69[b]	0.00	6.51	0.00	12.11[ab]
LSD (p=0.05)	0.46	0.11	0.83	0.04	0.84

CT, conventional tillage; ZT, zero tillage; R, residues; H, herbicide; IWM-IWM, integrated weed management; HW, hand weeding; MEY, wheat grain equivalent yield; figures with the same sign as superscript mean statistically (p=0.05) similar

conservation agriculture resulted in higher system productivity compared to the conventional till plots.

Weed control is a major challenge for the adoption of CA-based production systems. Conservation production system (ZTR-ZTR) had higher system productivity compared to the conventional tilled plots and zero tilled plots in maize-wheat cropping system. Different tillage operations and weed management practices influenced the weed shifts and weeds phyto-sociology, but consistent relationship between weed species dominance with tillage and weed management system was not observed which indicate that aside from tillage, residues incorporation and the weed management practices could play a role in influencing weed shifts and weed population diversity. Although, CA in combination with recommended herbicides had higher system productivity, it is necessary to continuously identify economically feasible weed management practices to effectively manage the weeds shifts over time in CA.

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