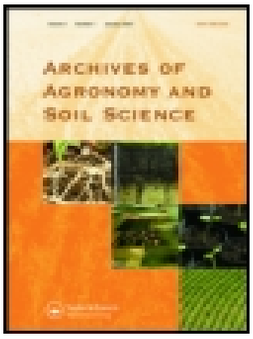

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Soil properties, crop productivity and energetics under different tillage practices in fodder sorghum + cowpea – wheat cropping system

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ABSTRACT

Tillage is an important agricultural operation which influences soil properties, crop yield and environment. Nine combinations of three tillage practices including conventional tillage (CT), minimum tillage (MT) and zero tillage (ZT) were evaluated in fodder sorghum (*Sorghum bicolor*) + cowpea (*Vigna unguiculata*) – wheat (*Triticum durum*) cropping system for 5 years (2009–2014) on clay loam soil under limited irrigation. Continuous ZT practices significantly improved surface soil organic carbon, bulk density, infiltration rate and maximum water holding capacity. Carbon sequestration rate, soil organic carbon stock and soil enzymatic activities were relatively more under ZT than CT-CT practice. Higher fodder yield of sorghum + cowpea was recorded with CT (*kharif*) while wheat grain yield with ZT (*rabi*). However, the system productivity was statistically similar in all the tillage treatments on pooled data basis. The economic benefits were also maximum under ZT-ZT practice. The ZT-ZT practice recorded significantly lowest energy input (17.1 GJ ha^{-1}) which resulted in highest energy use efficiency (13.6) and energy productivity (518 kg GJ^{-1}). Thus, adoption of ZT significantly improved soil health, stabilized crop yield, increased profitability and energy use efficiency in the semi-arid agro-ecosystem.

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Crop yields; economics; energy use efficiency; soil health; tillage

Introduction

Soil tillage is one of the fundamental agriculture operations because of its influence on soil properties (physical, chemical and biological), crop growth, profitability and environment. Conventional agriculture has largely been characterized by intensive tillage. The objectives of tillage include, soil loosening and levelling for seed bed preparation, mixing fertilizer into soil, weed control, and crop residue management (Busari et al. 2015). The conventional agriculture, based on tillage and being highly mechanized, has been responsible for soil erosion, water pollution, more water consumption, biodiversity reduction, low energy efficiency and contribution to global warming (Jat et al. 2012). Continuous soil tillage strongly influences the soil properties. Hence, it is important to follow appropriate tillage practices that avoid soil structure degradation, maintain crop yield as well as ecosystem stability (Sharma et al. 2011). The conventional agriculture

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Supplementary data for this article can be accessed here.

largely characterized by heavy tillage which results in higher cost, energy use and reduced profitability. Therefore, in recent years, interest of farmers has increased in the conservation tillage. The minimum soil disturbance through reduced or zero tillage improves soil biological activity, produces stable soil aggregates, maintains optimum proportions of respiration gases in the rooting-zone, moderates organic matter oxidation, porosity for water movement and limits the re-exposure of weed seeds and their germination (Bhan and Behera 2014). Various on-farm participatory trials have revealed little or no difference in yields of crops under zero-till system compared with conventional tillage (Krishna and Veettil 2014). However, yield variability with zero-tillage still remains a major concern among farmers. Different workers reported ecologically and economically positive effect of direct seeding (Parihar et al. 2016a; Jakhar et al. 2017, 2018a; Kumar et al. 2018) whereas based on 610 studies around the globe, Pittelkow et al. (2015) found negative impact of zero tillage on crop yields. In general, reduced tillage systems required lower operation costs and gave greater economic returns compared with conventional tillage (Sharma et al. 2011).

Energy and economics are mutually dependent (Pimentel et al. 1994). There is a close relationship between agriculture and energy. While agriculture uses energy, it also supplies it in the form of bio-energy. The energy crisis of early seventies forced scientists to conserve energy in all sectors including agriculture. Energy is used for carrying out various operations like tillage, irrigation, sowing, weeding, harvesting and threshing. Since tillage consumes maximum energy (Choudhary et al. 2017) hence, efforts were started world-wide to reduce the energy use by reducing the number of tillage operations to bare minimum for seed bed preparation to get higher or equivalent yield. As the energy and labour are becoming expensive with the passage of time, need is being felt to study the energy budget of production systems.

The benefits of zero tillage are variable over region, season and crop (Derpsch et al. 2010). Many studies in India showed that zero tillage technology is successful in rice-wheat cropping system only and confined to Indo-Gangetic Plains (Derpsch et al. 2010; Jat et al. 2012). Other regions and cropping systems, particularly in rainfed areas are yet to get the benefit of conservation tillage. The advantage of zero tillage is more pronounced in *rabi* (winter) season due to lesser weed growth and assured irrigation (Choudhary et al. 2017). Keeping these facts in view, the present study was undertaken to evaluate the effect of nine different tillage practices on soil properties, crop productivity, profitability and energetics in a prominent fodder – food production system (sorghum + cowpea – wheat) under limited irrigation conditions of semi-arid Central India.

Materials and methods

Study site and soil

A field experiment was carried out at Central Research Farm of Indian Grassland and Fodder Research Institute Jhansi, India (25° 27′ N latitude, 78° 33′ E longitude and 270 m above mean sea level) during 2009–2014. The area has a continental monsoon climate with an average (1939–2015) annual rainfall of 908 mm received mostly during June to September (Rai et al. 2018). The study area was characterized by semi-arid climate with extreme temperature during summer (43 to 46°C) and winter (as low as 2°C). The rainfall and temperature pattern observed during the study period is shown in Table 1. The soil of the experimental site was deep, moderately well drained, brown to dark grayish brown (Typic Haplustept) with clay loam in texture (372 g sand, 345 g silt and 283 g clay kg^{-1} soil). It had pH 7.1, electrical conductivity (EC) 0.12 dS m^{-1}, soil organic carbon 6.7 g kg^{-1}, $KMnO_4$ oxidizable N 257 kg ha^{-1}, 0.5 M $NaHCO_3$ extractable P 22 kg ha^{-1} and 1 N NH_4OAc extractable K 280 kg ha^{-1} in the top 15 cm soil. Saturation water holding capacity of soil was 59.5% (v/v).

Treatment details

Treatments included nine combinations of conventional tillage (CT), minimum tillage (MT) and zero tillage (ZT) practiced in *kharif* and *rabi* season and were evaluated in randomized block design with

Table 1. Monthly total rainfall, mean monthly maximum and minimum temperature prevailed during the experimental period.

Year	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	May
Mean maximum temperature (°C)												
2009–10	42.7	34.5	33.9	34.4	32.9	29.2	24.6	19.9	26.5	36.1	41.8	43.7
2010–11	42.1	35.6	33.0	32.9	34.4	28.1	24.5	20.0	24.8	32.3	37.4	42.5
2011–12	37.0	33.2	32.7	33.1	34.8	30.6	26.1	19.5	24.2	31.8	38.2	42.2
2012–13	41.9	34.0	31.3	33.0	34.3	29.4	25.0	22.5	24.9	32.2	37.1	43.2
2013–14	37.6	32.2	31.3	34.1	31.2	28.0	24.1	18.4	22.5	30.0	37.4	41.0
Mean minimum temperature (°C)												
2009–10	26.7	26.1	25.4	23.2	16.9	11.6	8.7	5.4	11.0	15.1	22.3	25.8
2010–11	26.7	26.4	25.3	23.4	18.4	15.4	6.5	4.9	9.9	30.3	17.9	26.0
2011–12	24.7	24.9	25.5	23.9	17.2	13.4	9.7	6.8	7.6	11.8	19.3	24.1
2012–13	29.4	26.1	25.2	30.5	16.0	9.8	6.8	4.6	10.8	13.6	18.8	24.5
2013–14	26.2	25.0	24.7	24.1	20.2	10.9	8.6	8.4	8.7	12.9	17.1	22.7
Rainfall (mm)												
2009–10	15.4	192.2	139.8	110.6	54.8	10.6	13.8	1.8	13.8	0	1.4	1.6
2010–11	13.0	246.5	166.4	193.4	0	17.2	1.8	0	1.8	0	0	18.4
2011–12	466.0	264.0	175.0	158.2	0	0	0	43.8	2.2	0	15.2	1.2
2012–13	18.5	390.0	217.6	100.8	0	0	0	0	102.6	2.2	5.2	1.2
2013–14	149.2	437.2	527.6	43.4	107.6	2.8	22.9	53.0	66.6	6.2	16.6	10

Source: Agromet Observatory, Division of Crop Production, ICAR-IGFRI, Jhansi, India.

3 replications. The tillage combinations were CT-CT, CT-MT, CT-ZT, MT-CT, MT-MT, MT-ZT, ZT-CT, ZT-MT and ZT-ZT. Here, CT-MT means conventional tillage in *kharif* season (sorghum + cowpea) and minimum tillage in *rabi* season (wheat). In CT plots, two passes of disc harrow, two passes of spring-tyne cultivator followed by one planking operations performed for field preparation. MT comprised of one harrowing with disc harrow and one pass of spring-tyne cultivator followed by planking. In ZT plots, different crops were drilled directly using zero till planter without preparatory tillage. Details of tillage operation performed under different treatments is given in Supplementary Table 1. The plot size was 15 m × 4.8 m.

Crop management

Fodder sorghum variety 'PC-6' was sown with seed rate of 20 kg ha^{-1} in paired row during first fortnight of July every year. Two rows of fodder cowpea (cv 'BL 2') were sown between paired rows of sorghum as intercrop. The distance between each row was 30 cm. Sorghum + cowpea crops were harvested 70–80 days after sowing (50% flowering stage) for green fodder. Glyphosate (N-phosphonomethyl glycine) 41 SL was sprayed at 1.0 kg a.i. ha^{-1} in the ZT plots about 10–12 days before sowing of crops while one hand weeding was done in all the CT plots at 25–30 days after sowing of sorghum + cowpea. After harvesting of *kharif* crops, durum wheat (cv 'HD 4672') was sown using 100 kg seeds ha^{-1} at 20 cm row to row distance in the second fortnight of November each year in same plots. The crops were sown by zero-till seed cum ferti drill in ZT and seed cum ferti drill in CT and MT plots. Sorghum + cowpea received a common fertilizer dose of 60 kg N + 40 kg P_2O_5 + 30 kg K_2O ha^{-1} while wheat was fertilized with 100 kg N + 60 kg P_2O_5 + 40 kg K_2O ha^{-1}. Two third N and whole P and K were applied as basal at the time of sowing, while remaining 1/3rd N was top dressed by broadcasting urea at 25–30 days after sowing. To control broad leaf weeds in wheat, 2–4 D at 0.75 kg a.i. ha^{-1} was sprayed at 28–32 days after seeding in all the plo. Wheat was harvested in the month of April. Sorghum + cowpea was grown as rainfed crops while 3 irrigation including one pre sowing irrigation was applied in wheat.

Soil sampling and analysis

Soil samples (0–15 cm) were collected at randomly distributed points prior to the experiment in 2009 and after wheat harvesting in 2013 from each plot for physical and chemical analysis. The samples were air dried, ground and passed through 2 mm mesh sieve. Soil pH was measured in aqueous soil extract in de-ionized water (1:2.5 soil:water). Soil salinity was measured as the electrical conductivity of the aqueous soil extract in de-ionized water. Soil organic carbon (SOC) was determined by the Walkley–Black method (Walkley and Black 1934). The available N was estimated by alkaline $KMnO_4$ method suggested by Subbiah and Asija (1956) and expressed in kg ha^{-1}. The available P content in soil was estimated by Olsen's method (Olsen et al. 1954). Available K was determined using neutral normal ammonium acetate extraction (flame photometer) method as described by Jackson (1973) and expressed in kg ha^{-1}. Bulk density was measured by the core sampler method (Piper 1950). Particle density (PD) was determined by the pycnometer method (Blake and Hartge 1986) and water infiltration rate (IR) by double-ring infiltrometer (Bouwer 1986). Maximum water holding capacity (WHC) was determined by equilibrating the soil with water through capillary action in a Keen Raczkowald (KR) box (Baruah and Barthakur 1999). KR box is a circular brass box having an internal diameter of 5 cm and a height of 1.6 cm with perforated bottom having numerous holes of 0.75 mm diameter spaced at 4 mm. The SOC stock for a layer of thickness was calculated as given by Lal et al. (1999):

$$SOC\ Stock\ \left(Mg\ ha^{-1}\right) = \frac{SOC\ (\%) \times Bulk\ density\ (Mg\ M^{-3}) \times\ Soil\ depth\ (m) \times 10000}{100}$$

Soil C sequestration rate (Mg C ha^{-1} $year^{-1}$) was calculated as change in the SOC stock (Mg ha^{-1}) divided by duration of experiment (year).

Soil microbial biomass carbon (SMBC) was estimated by chloroform fumigation extraction method as described by Nunan et al. (1998). Soil dehydrogenase activity was estimated by measuring the rate of triphenylformazan (TPF) from triphenyl tetrazolium chloride (Casida et al. 1964) and β-glucosidase by determining the amount of p-nitrophenol released after 1 h of incubation with p-nitrophenyl- β -D-glucopyranoside (Eivazi and Tabatabai 1988). Alkaline phosphatase activities were measured by using p-nitrophenyl (PNP) as per method described by Tabatabai and Bremner (1969).

Crop yield and nutrient uptake

Sorghum + cowpea were harvested at 70–80 days after sowing and weighed for green fodder yield. Random chopped samples of green fodder were sun dried and placed in the oven at 65°C for 72 hours to estimate dry matter percentage and then it was multiplied with respective green fodder yield to calculate dry matter yield. At maturity, wheat crop was harvested manually with the help of sickle from the net plot area after discarding the border area (0.6 m from all the sides of each plot). The grain and straw yields of wheat were estimated from each plot using plot thresher after sun drying. The sorghum + cowpea fodder yield was converted to wheat equivalent yield (WEY) by multiplying green fodder yield with its respective price and divided by the market price of wheat.

The plant samples were collected at harvest, oven dried (70°C), processed and analyzed for nutrient content. The N, P and K were estimated by Kjeldahl, vanado-molybdate yellow color and flame-photometric method, respectively as per procedure described by Jackson (1973). The uptake of nutrients was calculated by multiplying concentration with their respective yield.

Economic analysis

The economic analysis was done by considering the variable production costs only. The variable costs included human labour, use of machinery (tractor, plough, planter, etc.), input cost (seed,

fertilizer, and pesticide), irrigation, harvesting and threshing. Net returns (NR) were calculated by deducting the production cost from gross returns. Benefit to cost ratio was calculated by dividing the net returns value to the production cost in order to determine the economic efficiency. For better comparisons, all the economics data (cost of cultivation and returns) were converted from Indian Rupees (INR) to US$ using an exchange rate (INR/US$) of 60.

Energy input-output relationship

Agricultural inputs like labour, machinery, diesel, fertilizers, pesticides, seed etc. were used for computation of energy consumption on the basis of energy equivalent. Energy output from the product (grain, straw and fodder) was calculated by multiplying the amount of production and its corresponding energy equivalent (Choudhary et al. 2017). The energy use efficiency (EUE) and energy productivity were calculated as given by Devasenapathy et al. (2009).

Energy use efficiency = Energy output (GJ ha^{-1})/Energy input (GJ ha^{-1})

Energy productivity (kg GJ^{-1}) = Wheat equivalent yield (kg ha^{-1})/Energy input (GJ ha^{-1})

Statistical analysis

Statistical analyses were performed using software SAS version 9.3 (Cary, USA). Analysis of variance (PROC MIXED) was performed and means were separated by least significant differences (LSD), when the F-test indicated factorial effects on the significance level of $p < 0.05$.

Results

Weather

The rainfall during *kharif* season (July–October) was the highest (1116 mm) in 2013 followed by 708 mm in 2012 and 606 mm in 2010, whereas 2009 and 2011 seasons received the lowest rainfall (470 and 597 mm, respectively). The rainfall received in three months (July to September) amounting more than 85% of total yearly rainfall during all the study years (Table 1). The rainfall in *rabi* season (November to April) was very low (20–41 mm) during first two years (2009–10 and 2010–11), whereas 61, 110 and 168 mm of rainfall was received during 2011–12, 2012–13 and 2013–14, respectively. In *kharif* 2012, plant population of sorghum + cowpea was not uniform due to continuous rains in the month of July. July, 2013 received the highest monthly rainfall (437 mm) but sowing was possible due to dry spells. The mean monthly maximum and minimum temperatures were almost similar in all the years of study (Table 1).

Soil properties

The tillage practices had significant ($p < 0.05$) effect on bulk density (BD) of 0–15 cm soil depth, while in deeper soil layers (15–30 and 30–45 cm) it was non-significant (data not given) (Table 2). The BD under CT-CT was lowered by 3.4% in 0–15 cm soil profile than ZT-ZT plots after completion of 4 cropping cycle. Tillage practices had no significant effect on particle density of soil. Maximum water holding capacity (WHC) of soil was found in MT-MT (0.67 m^3 m^{-3}) which was statistically at par with ZT-ZT, ZT-MT, MT-ZT and CT-ZT practices. The WHC of soil was improved by 11.9% in ZT-ZT over CT-CT at the end of 4th year. Infiltration rate (IR) was the lowest (6.5 mm h^{-1}) under ZT-ZT and the highest (10.6 mm h^{-1}) under CT-CT plots (Table 2). Omission of tillage reduced IR by 63%. The IR was inversely related to BD ($r = -0.56$).

The different tillage practices had significant ($p < 0.05$) effect on SOC content, SOC stock and carbon sequestration rate (Table 3). The SOC content in ZT-ZT plots were significantly ($p < 0.05$) highest for the soil depths 0–15 and 15–30 cm. The SOC content in all the tillage practices significantly

Table 2. Density and water holding capacity of soil under different tillage practices at the end of four cropping cycle (0–15 cm).

Tillage practices	Bulk density (Mg m^{-3})	Particle density (Mg m^{-3})	Maximum WHC (m^3 m^{-3})	Infiltration rate (mm h^{-1})
CT – CT	1.17^{c}	2.20	0.59^{d}	10.6^{a}
CT – MT	1.17^{c}	2.20	0.63^{bcd}	9.9^{ab}
CT – ZT	1.17^{c}	2.19	0.64^{abc}	8.2^{cde}
MT – CT	1.19^{b}	2.19	0.62^{bcd}	9.0^{abc}
MT – MT	1.18^{bc}	2.21	0.67^{a}	8.3^{bcd}
MT – ZT	1.18^{bc}	2.19	0.65^{abc}	7.0^{de}
ZT – CT	1.18^{bc}	2.21	0.61^{cd}	7.9^{cde}
ZT – MT	1.21^{a}	2.21	0.66^{ab}	8.2^{cde}
ZT – ZT	1.21^{a}	2.20	0.66^{ab}	6.5^{e}

Means followed by a superscripted similar lowercase letter within a column are not significantly different (at $p < 0.05$) according to LSD test. Means without any letter indicate no significant difference (at $p < 0.05$). CT-conventional tillage; MT-minimum tillage; ZT- zero tillage; WHC- water holding capacity.

increased over CT-CT at 0–15 cm soil depth. However, the SOC content of all the treatments were statistically at par for the soil depth 30–45 cm. Furthermore, SOC stock in 0–15 cm soil depth was maximum in ZT-ZT and lowest under CT-CT. The increase in SOC stock in ZT-ZT was 21% higher over CT-CT. After 4 years of study, carbon sequestration rate varied between 0.05 to 0.69 Mg ha^{-1} $year^{-1}$ and the maximum value (0.69 Mg ha^{-1} $year^{-1}$) was observed in ZT-ZT followed by ZT-MT.

Soil pH, EC and available nutrients (N, P and K) did not differ significantly between treatments after 4 years of study (Table 3). A marginal decline in the EC was observed in all the treatments in comparison to initial EC (0.11 dS m^{-1}). However, pH value was almost same as initial pH (7.05) across treatment. The initial available N, P and K status in soil was 257, 22 and 280 kg ha^{-1}. After 4 years, available N in soil was marginally increased in all the treatments in comparison to their initial value. Similarly, available P was also increased in all the treatments except in CT-CT. However, soil available K was decreased.

Tillage practices significantly influenced the biological properties of soil (Table 3). Soil microbial biomass carbon (SMBC) varied from 366.9 to 530.4 mg g^{-1}. Likewise, dehydrogenase (DHA) and alkaline phosphatase activities ranged from 62.3 to 86.1 mg TPF kg^{-1} soil day^{-1} and 73.2 to 99.5 mg þ- nitrophenol kg^{-1} h^{-1}, respectively. Continuous ZT caused an increase of 44.5, 38.2 and 35.9% in SMBC, DHA and alkaline phosphatase activities, respectively, over CT-CT plots. Similarly, highest β glucosidase activity (48.1 µg PNP g^{-1} soil h^{-1}) was observed in ZT-ZT plots.

Different tillage practices significantly influenced the correlation matrix of different soil microbial and enzyme activities (Table 4). The SOC content had a positive and significant ($p < 0.05$) correlation with MBC ($r = 0.87$), DHA ($r = 0.87$), alkaline phosphatase ($r = 0.75$) and β glucosidase ($r = 0.84$). Similarly, MBC had a positive and significant ($p < 0.05$) correlation with DHA, alkaline phosphatase and β glucosidase.

Crop productivity

The tillage practices had significant ($p < 0.05$) effect on green fodder yield (GFY) and dry matter yield (DMY) of sorghum + cowpea except first year (2009) of study (Table 5). In general, CT practice in *kharif* season produced higher GFY and DMY than MT and ZT irrespective of type of tillage in succeeding season. However, any practice of tillage in *rabi* season (within same tillage operations in *kharif* season) did not influence GFY and DMY of sorghum + cowpea in any year. During second year, the green and dry matter yield was the highest in CT-MT followed by CT-CT planting. However, the highest GFY and DMY were found in MT-ZT during third year and in ZT-ZT during last year. The data pooled over four years showed that green and dry matter yield of sorghum + cowpea was significantly ($p < 0.05$) higher by 7.5% and 8.1% in CT-MT compared to ZT-ZT planting, respectively. However, crops planted under CT-CT and CT-ZT yielded at par with CT-MT.

Table 3. Soil pH, EC, SOC, available nutrients and enzymatic activities under different tillage practices at the end of four cropping cycle.

Tillage practices	pH	EC (dS m^{-1})	SOC (g kg^{-1}) 0–15 cm	15–30 cm	30–45 cm	SOC stock, 0–15 cm (Mg ha^{-1})	CSR (Mg ha^{-1} $year^{-1}$)	Soil Available Nutrients (kg ha^{-1}) N	P	K	MBC (mg g^{-1} soil)	DHA (mg TPF kg^{-1} soil day^{-1})	ALP (mg PNP kg^{-1} soil h^{-1})	β glucosidase (µg PNP g^{-1} soil h^{-1})
CT – CT	7.12	0.08	7.1^{b}	4.1^{d}	3.9	12.4^{c}	0.05^{c}	262.0	21.9	254.1	366.9^{d}	62.3^{c}	73.2^{d}	34.2^{d}
CT – MT	6.98	0.09	7.9^{a}	4.2^{bcd}	3.9	13.8^{b}	0.39^{b}	270.0	22.9	273.8	404.0^{cd}	71.1^{bc}	84.5^{bcd}	37.4^{cd}
CT – ZT	7.05	0.09	8.2^{a}	4.3^{ab}	3.9	14.4^{ab}	0.54^{ab}	271.0	23.2	273.6	458.8^{bc}	74.0^{abc}	82.0^{bcd}	43.1^{abc}
MT – CT	7.04	0.08	7.7^{a}	4.2^{cd}	4.0	13.8^{b}	0.38^{b}	274.4	23.8	269.2	429.9^{bcd}	69.0^{bc}	77.9^{cd}	38.0^{bcd}
MT – MT	7.05	0.08	8.1^{a}	4.3^{abc}	4.0	14.3^{ab}	0.52^{ab}	273.3	24.5	271.2	455.9^{bc}	77.7^{ab}	81.4^{bcd}	39.9^{bcd}
MT – ZT	7.02	0.08	8.1^{a}	4.2^{abcd}	4.0	14.4^{ab}	0.53^{ab}	275.2	22.4	277.5	491.7^{ab}	79.3^{ab}	86.0^{bc}	44.6^{ab}
ZT – CT	7.02	0.08	7.7^{a}	4.4^{a}	4.1	13.7^{b}	0.36^{b}	269.0	22.8	267.9	425.3^{bcd}	74.4^{abc}	83.3^{bcd}	41.2^{abcd}
ZT – MT	7.02	0.08	8.1^{a}	4.3^{abc}	3.9	14.7^{ab}	0.61^{ab}	274.9	24.4	269.4	489.2^{ab}	80.5^{ab}	91.2^{ab}	43.3^{abc}
ZT – ZT	7.04	0.09	8.3^{a}	4.4^{a}	4.0	15.0^{a}	0.69^{a}	268.9	23.7	274.1	530.4^{a}	86.1^{a}	99.5^{a}	48.1^{a}

Means followed by a superscripted similar lowercase letter within a column are not significantly different (at $p < 0.05$) according to LSD test. Means without any letter indicate no significant difference (at $p < 0.05$). CT-conventional tillage; MT-minimum tillage; ZT- zero tillage; EC-electrical conductivity; SOC-soil organic carbon; CSR-carbon sequestration rate; MBC- microbial biomass carbon; DHA- dehydrogenase activity; ALP- alkaline phosphatase; TPF- triphenylformazan; PNP- *p* nitrophenol.

Table 4. Pearson correlation matrix of soil microbial activities with soil organic carbon (n = 9) .

Parameters	SOC	MBC	DHA	ALP
MBC	0.87**			
DHA	0.87**	0.95**		
ALP	0.75*	0.86**	0.91**	
BG	0.84**	0.96**	0.93**	0.87**

* and ** indicate significance at 5 and 1% level of probability.
SOC- soil organic carbon; MBC- microbial biomass carbon; DHA- dehydrogenase activity; ALP- alkaline phosphatase; BG – β glucosidase.

Table 5. Green fodder and dry matter yield of sorghum + cowpea under different tillage practices.[a.]

		Green fodder yield (Mg ha^{-1})					Dry matter yield (Mg ha^{-1})				
Kharif tillage	*Rabi* tillage	2009	2010	2011	2013	Pooled	2009	2010	2011	2013	Pooled
CT	CT	32.4	49.6^{ab}	19.6^{abc}	31.8^{d}	33.4^{ab}	7.5	12.4^{ab}	3.9^{abc}	7.3	7.8^{ab}
	MT	32.9	51.6^{a}	19.7^{abc}	33.1^{cd}	34.3^{a}	7.6	12.9^{a}	3.9^{abc}	7.8	8.0^{a}
	ZT	32.7	48.5^{b}	19.3^{abcd}	34.6^{bcd}	33.8^{a}	7.5	12.1^{b}	3.8^{abcd}	8.1	7.9^{a}
MT	CT	30.9	41.2^{c}	18.1^{d}	35.5^{abc}	31.5^{c}	7.0	10.0^{cde}	3.6^{d}	8.2	7.2^{c}
	MT	29.9	42.6^{c}	20.4^{ab}	35.7^{abc}	32.2^{bc}	6.8	10.4^{c}	4.0^{ab}	8.3	7.4^{c}
	ZT	30.0	40.2^{cd}	20.6^{a}	36.2^{abc}	31.7^{c}	6.8	9.8^{cde}	4.0^{a}	8.5	7.3^{c}
ZT	CT	32.0	41.0^{c}	19.0^{bcd}	36.8^{ab}	32.2^{bc}	7.3	10.1^{cd}	3.7^{bcd}	8.7	7.5^{bc}
	MT	32.1	38.2^{d}	19.1^{bcd}	37.4^{ab}	31.7^{c}	7.4	9.4^{e}	3.8^{bcd}	8.8	7.3^{c}
	ZT	32.3	38.3^{d}	18.3^{cd}	38.5^{a}	31.9^{c}	7.4	9.4^{de}	3.7^{cd}	9.0	7.4^{c}

Means followed by a superscripted similar lowercase letter within a column are not significantly different (at $p < 0.05$) according to LSD test. Means without any letter indicate no significant difference (at $p < 0.05$). CT-conventional tillage; MT-minimum tillage; ZT- zero tillage.
[a] In 2012, plant population was not uniform due to continuous rains. Therefore, yield data was not included in the table.

The tillage practices had significant effect on mean (pooled over 5 years) wheat grain yield which was highest in MT-MT plots (4.80 Mg ha^{-1}) compared to CT-CT (4.48 Mg ha^{-1}) and was found at par with all MT and ZT in *rabi* season (Figure 1). However, straw yield of wheat was not affected significantly with different tillage practices.

The tillage practices had significant ($p < 0.05$) effect on system productivity (wheat equivalent yield, WEY) in 2010–11 and 2014–15 (Table 6). In second year (2010–11), the system productivity was the highest in CT-CT and CT-ZT followed by CT-MT. Thereafter (2014–15), WEY was significantly higher (8.6–22.5%) in ZT (*rabi*) compared to CT (*rabi*). The system productivity in first two years of study was higher in CT (*kharif*). Thereafter, it increased in ZT and in fifth year ZT-ZT turned out to be the highest yielder (11.42 Mg ha^{-1}). However, pooled system productivity over 5 years was not significant.

Nutrients uptake

The uptake of N, P and K, as calculated by multiplying the nutrient concentration in the crop with the respective yield, are shown in Figure 2. Differences in N, P and K uptake over the various years were mainly due to the differences in yield (data was not shown). The tillage system did not significantly affect N, P and K uptake. Similar results were reported by Vogeler et al. (2009) who found that tillage did not affect uptake of N or P by maize and field bean. In general, nutrients uptake by sorghum + cowpea and wheat were almost similar. In this cropping system, N, P and K uptake ranged from 216–230, 47–53 and 196–217 kg ha^{-1} in various tillage practices, respectively.

Economics and energetics

The production cost and economic returns of sorghum + cowpea – wheat cropping system under different tillage practices are presented in Table 7. The production cost varied from minimum with

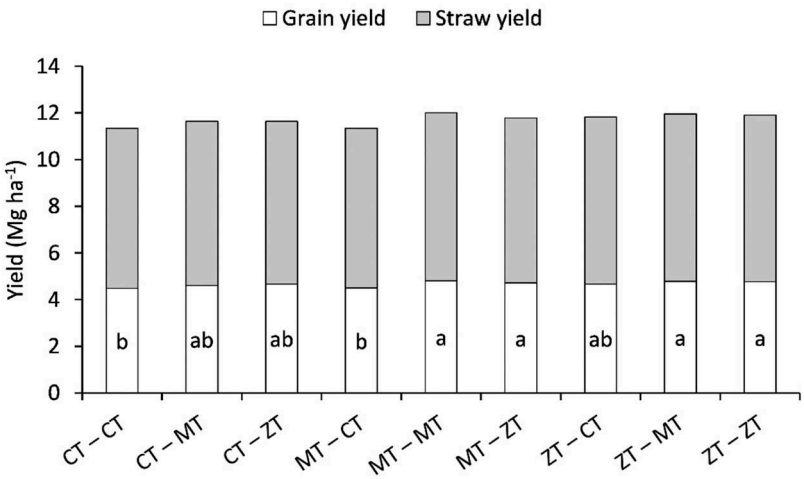

Figure 1. Wheat yield under different tillage practices (Pooled over 5 years). Bar with a similar lowercase letter are not significantly different (at $p < 0.05$) according to LSD test. CT-conventional tillage; MT-minimum tillage; ZT- zero tillage.

Table 6. System productivity in terms of wheat equivalent yield (Mg ha^{-1}) under different tillage practices.

Kharif tillage	*Rabi* tillage	2009–10	2010–11	2011–12	2012–13	2013–14	Pooled
CT	CT	9.30	9.49^{a}	8.45	6.23	9.32^{e}	8.56
	MT	9.16	9.48^{a}	9.23	6.51	9.59^{de}	8.80
	ZT	9.12	9.49^{a}	9.09	6.40	10.04^{cd}	8.83
MT	CT	8.74	8.52^{bc}	8.37	6.31	10.40^{bc}	8.47
	MT	8.95	8.88^{b}	9.46	6.65	10.55^{bc}	8.90
	ZT	8.56	8.52^{bc}	9.42	6.72	10.66^{bc}	8.78
ZT	CT	9.12	8.55^{bc}	8.85	6.41	10.91^{ab}	8.77
	MT	9.09	8.36^{c}	9.02	6.73	11.08^{ab}	8.86
	ZT	8.75	8.48^{bc}	8.92	6.72	11.42^{a}	8.86

Means followed by a superscripted similar lowercase letter within a column are not significantly different (at $p < 0.05$) according to LSD test. Means without any letter indicate no significant difference (at $p < 0.05$). CT-conventional tillage; MT-minimum tillage; ZT- zero tillage.

ZT-ZT (601 US$ ha^{-1}) to maximum under CT-CT (665 US$ ha^{-1}). Pooled data of 5 years showed that ZT-ZT gave significantly the highest net monetary returns (1209 US$ ha^{-1}) and the lowest in CT-CT (1069 US$ ha^{-1}). Similar to net returns, the highest benefit to cost ratio was calculated in MT-MT (2.06) followed by ZT-ZT (2.05) and the lowest in CT-CT (1.67). ZT-ZT practices recorded 13.1 and 22.7% increase in net returns and B:C ratio, respectively over CT-CT.

Among various tillage practices, total energy requirement of the system was the highest in CT-CT (20.4 GJ ha^{-1}) followed by CT-MT (19.6 GJ ha^{-1}) and the lowest in ZT-ZT (17.1 GJ ha^{-1}). The output bio-energy of cropping system was statistically similar across treatments and ranged from 229.2 GJ ha^{-1} (CT- CT) to 235.8 GJ ha^{-1} (CT-MT). However, energy use efficiency and energy productivity differed significantly ($p < 0.05$) among treatments. The highest energy-use efficiency (13.6) and energy productivity (518 kg WEY GJ^{-1}) were computed in ZT-ZT and the least in CT-CT.

Discussion

Soil properties

The higher bulk density in ZT-ZT was attributed primarily to the lack of annual loosening from ploughing in absence of crop residues on the soil surface. The lower bulk density found in CT-CT

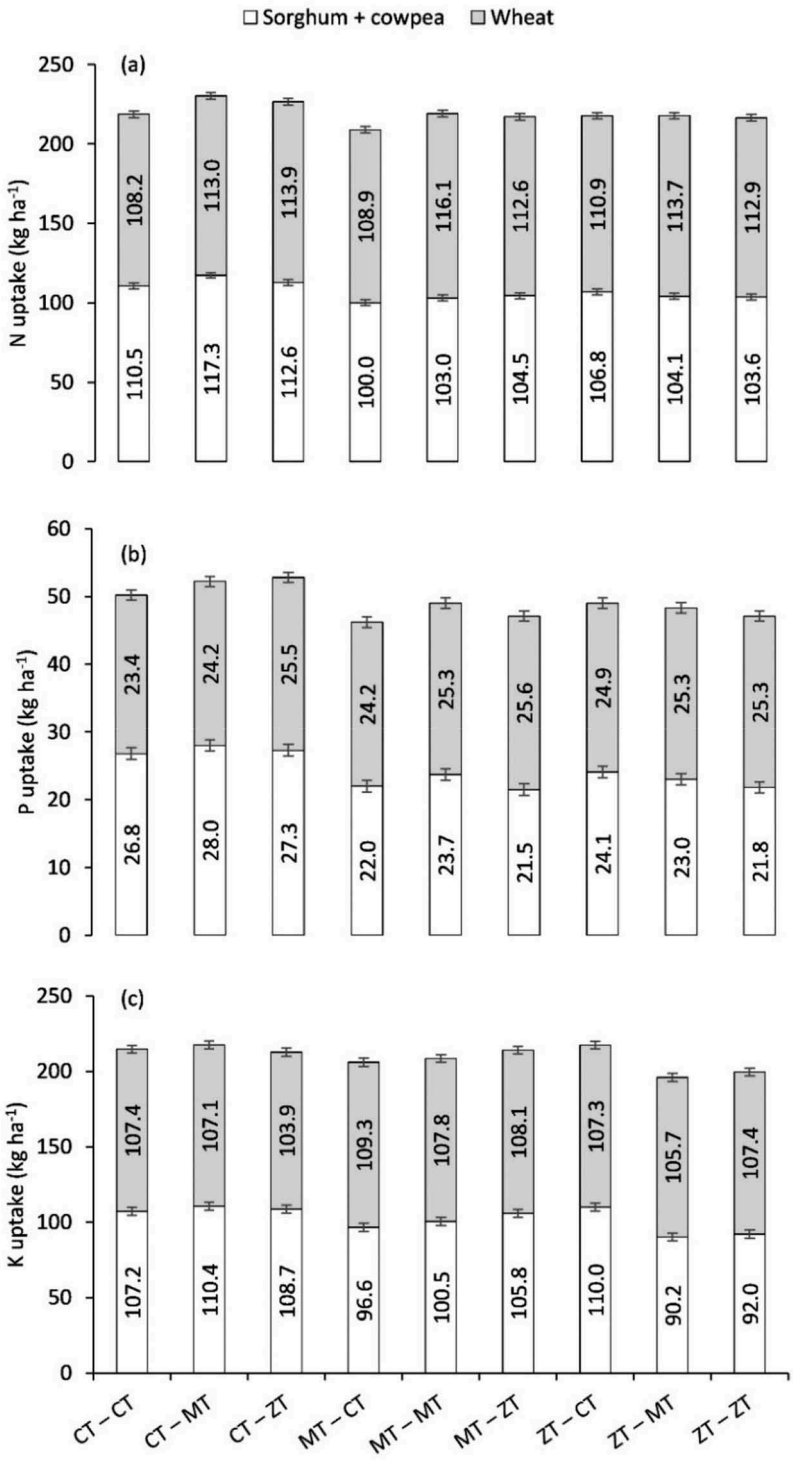

Figure 2. Nutrient uptake under different tillage practices. Error bars represent standard error of the mean. CT-conventional tillage; MT-minimum tillage; ZT- zero tillage.

Table 7. Economics and energetics of (sorghum + cowpea) – wheat cropping system under different tillage practices (pooled data over 5 years).

Kharif tillage	*Rabi* tillage	Cost of production[a] (US$ ha^{-1})	Gross returns (US$ ha^{-1})	Net returns (US$ ha^{-1})	B:C	Input energy (GJ ha^{-1})	Output energy (GJ ha^{-1})	EUE	Energy productivity (kg WEY GJ^{-1})
CT	CT	665	1735^{bc}	1069^{c}	1.67^{e}	20.4	229.2	11.2^{f}	418^{f}
	MT	626	1786^{abc}	1160^{a}	1.92^{bc}	19.6	235.8	12.0^{e}	448^{de}
	ZT	626	1794^{ab}	1168^{a}	1.93^{bc}	18.7	234.6	12.5^{bcd}	472^{bc}
MT	CT	634	1726^{c}	1092^{bc}	1.75^{de}	19.6	223.9	11.4^{f}	432^{ef}
	MT	605	1813^{a}	1208^{a}	2.06^{a}	18.7	234.4	12.5^{cd}	474^{bc}
	ZT	600	1790^{ab}	1190^{a}	2.02^{ab}	17.8	230.6	12.9^{bc}	491^{b}
ZT	CT	636	1787^{abc}	1152^{ab}	1.83^{cd}	18.8	232.6	12.3^{de}	465^{cd}
	MT	602	1807^{a}	1205^{a}	2.04^{a}	18.0	233.1	12.9^{b}	492^{b}
	ZT	601	1810^{a}	1209^{a}	2.05^{a}	17.1	233.0	13.6^{a}	518^{a}

Means followed by a superscripted similar lowercase letter within a column are not significantly different (at $p < 0.05$) according to LSD test. Means without any letter indicate no significant difference (at $p < 0.05$). CT-conventional tillage; MT-minimum tillage; ZT- zero tillage; EUE-energy use efficiency; WEY-wheat equivalent yield; B:C- benefit to cost ratio.

[a] 1 US$ = 60 INR

was likely due to seasonal ploughing which helped in maintaining a fairly loose structure. Our results were in consistent with those of other studies that showed differences in bulk density due to tillage practices. For example, Dam et al. (2005) found that CT had a significantly lower bulk density (1.21 Mg m^{-3}) than ZT (1.36 Mg m^{-3}) on sandy loam soil of Canada in an 11-year study. The lowest infiltration rate observed in ZT-ZT plots might be due to compaction of the soil and top soil sealing in absence of crop residue (Govaerts et al. 2009).

Different tillage practices for four years had no significant effect on soil pH and EC (Table 3). The soil has buffering capacity to resist changes in pH. Our findings are consistent with those reported by Neugschwandtner et al. (2014) in silty loam soil after 7 year of different tillage practices. However, SOC and soil carbon sequestration increased in ZT-ZT systems. The soil tilling increases organic matter decomposition and decreases carbon content by increasing organic matter oxidation (Thomas et al. 2007). The crop roots remain intact in the root zone due to non-disturbance of the soil under ZT, which might facilitate enhancement of organic carbon input in deeper root zones (up to 30 cm) through their decay. This improvement might not cause significant effect in much deeper soil layers (30–45 cm) due to absence of sufficient root biomass. Parihar et al. (2016b) had observed that ZT enhanced the SOC by 23–35% in maize based cropping system over CT. Differences in bulk density of soils among treatments also had an influence on SOC stock. The lower bulk density in CT than ZT practices resulted in lower SOC stock in CT-CT besides lower SOC content. The initial (2009) SOC stock at 0–15 cm soil depth was 12.2 Mg C ha^{-1} and it changed by 0.2 to 2.8 Mg C ha^{-1} in different tillage practices in 4 years (Table 3). This resulted in C sequestration rates of 0.05 to 0.69 Mg C ha^{-1} yr^{-1}.

Soil microbial activity in terms of soil microbial biomass carbon, dehydrogenase activity, alkaline phosphatase and β glucosidase were significantly influenced by the tillage practices (Table 3). These parameters can be used as an indicator of soil quality for assessing the sustainability of agricultural ecosystem. These soil enzymes were maximum in ZT–ZT plots and the lowest in CT-CT. The higher microbial and enzymatic activities under ZT practices was due to less disturbance of soil, better aeration and more organic matter content. Water stable aggregates increases under ZT, and help in increasing soil enzymes, SOC and MBC (Roldan et al. 2003). Positive and significant correlation between SOC and soil microbial and enzymatic activities were evident from our study (Table 4) and SOC was the probable force for enhancing microbial and enzymatic activities. These results are in conformity with the findings of Parihar et al. (2016b).

Crop and system productivity

Green and dry matter yields of sorghum + cowpea were comparable in 2009. The higher yields in 2010 in all treatments were attributed to even distribution of rainfall over crop growing period. However, year 2011 was lower yielder in spite of heavy rainfall (Table 5). In 2013, reverse yield trend of sorghum + cowpea was observed than previous years. In this year, higher yield was obtained in ZT (*kharif*) plots than CT (*kharif*). Heavy rainfall created excessive wet situation for longer period in CT plots than ZT plot which caused yield reduction in CT plots. On the basis of pooled data of 5 years, CT (*kharif*) recorded significantly higher yield of sorghum + cowpea than ZT while vice-versa in wheat. This might be due to more weed infestation in *kharif* season under ZT which caused reduction in yield (Choudhary et al. 2017).

The pooled data over five years clearly showed the positive effects of ZT on grain yield of wheat (Figure 1). The present study results are in consistent with earlier studies which showed higher crop yields under ZT compared to CT in wheat systems (Jat et al. 2013; Singh et al. 2016). The higher yield of wheat in ZT and MT systems could be due to the compound effects of additional nutrients (Blanco-Canqui and Lal 2009; Kaschuk et al. 2010), lesser weed population (Ozpinar 2006; Chauhan et al. 2007), improved soil physical health (Jat et al. 2013; Singh et al. 2016), better water regimes (Govaerts et al. 2009) and improved nutrient use efficiency (Unger and Jones 1998) compared to CT. In initial years of experiment, the system productivity was higher in CT (*kharif*) than ZT practices (Table 6). This relative yield increase in ZT over time and transition period has been attributed to improved soil quality such as organic carbon, soil enzymatic activity, microbial biomass, porosity and structural stability (So et al. 2009). These results indicate the importance of long term experiments.

Economics and energy

The positive effects of ZT on system productivity were reflected in economic benefits (Table 7). The higher net returns in MT-MT and ZT-ZT were attributed mainly to reduced production cost and increased yield particularly of wheat. Lower production cost in MT and ZT practices was mainly due to non- requirement of preparatory tillage unlike in CT where 4 passes of tillage operations were performed before sowing of crops. CT-CT also maintained lower benefit to cost ratio (1.67) due to the higher cost of production and lower yields. Consistent to our results, higher net returns and B:C ratio with ZT were reported by many workers (Gathala et al. 2011; Jat et al. 2013; Choudhary et al. 2016, 2017; Singh et al. 2016; Jakhar et al. 2018b).

Total energy input used in CT-CT was 20.4 GJ ha^{-1}, which is about 19.3% more than that of ZT-ZT (Table 7). Tillage and weeding operations were main factor resulting in excessive energy use in CT-CT. Conventional tillage practices were regarded to be energy intensive and poor in resource utilization. About 25–30% of energy was required for field preparation and crop establishment (Choudhary et al. 2017). Zero tillage practices reduced the energy requirement due to saving of energy in land preparation and weeding operations. Energy-use efficiency and energy productivity was higher in ZT-ZT because of lowest energy input and higher system productivity.

Conclusion

The following conclusions were drawn from this study:

- Bulk density was affected by tillage practices, but only within the top 15 cm soil. Continuous ZT practice increased bulk density relative to CT. None of tillage systems was able to affect soil pH, EC and available nutrients.

- In ZT-ZT practice, SOC concentration and stock were higher as compared to CT-CT plots which ultimately helped to maintain higher carbon sequestration rate. Soil enzymatic activities were also higher in ZT-ZT plots.
- There was no significant tillage effect on system productivity over the 5 years. As with the wheat equivalent yield, the differences in yield between tillage practices over 5 years was minimal (8.47 to 8.90 Mg ha^{-1}) and year-to-year differences were attributed to climatic variation.
- Energy use efficiency and economic benefits were greater in ZT-ZT among all tillage treatments.
- Conventional tillage in *kharif* (sorghum + cowpea) and zero tillage (wheat) in *rabi* season was found to be a better option in terms of crop productivity in semi-arid climate. However, from the point of energy saving, economic benefits and soil health, zero tillage in both the seasons may be considered depending on farm resources.

Disclosure statement

No potential conflict of interest was reported by the authors.

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