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Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains

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ABSTRACT

Continuous rice-wheat (RW) rotation with conventional agronomic practices has resulted in declining factor productivity and degrading soil resources. A farmer's participatory research trial was conducted in Karnal, India to evaluate 8 combinations of cropping systems, tillage, crop establishment method and residue management effects on key soil physico-chemical and biological properties. Treatments (T) 1–4 involved RW and 5–8 maize-wheat (MW) with conventional tillage (CT) and zero tillage (ZT) with (+ R) and without (− R) residue recycling. Residue was either incorporated (R*i*) or mulched (R*m*). Treatment 1 (RW/CT − R) had the highest bulk density (BD) (1.47 Mg m^{-3}) and T8 (MW/ZT + R*m*), the lowest (1.34 Mg m^{-3}). After 3 years of cropping, soil accumulated more organic C in (a) MW (9.33 Mg ha^{-1}) than RW (8.5 Mg ha^{-1}), (b) ZT (9.25 Mg ha^{-1}) than CT (8.58 Mg ha^{-1}), and (c) + R (10.18 Mg ha^{-1}) than –R (7.65 Mg ha^{-1}). MW system with ZT and residue (T8: MW/ZT + R*m*) registered 208, 263, 210 and 48% improvement in soil microbial biomass C (MBC) and N, dehydrogenase activity (DHA) and alkaline phosphatase activity (APA), whereas RW system in T4 (RW/ZT + R*m*) registered 83, 81, 44 and 13%, respectively as compared with T1 (RW/CT − R), the business as usual scenario. Treatment 8 (MW/ZT + R*m*) recorded the highest microbial population viz. bacteria, fungi and actinomycetes. The most abundant micro-arthropods present in the soil of experimental plot were *Collembola, Acari* and *Protura* which varied with treatments. Soil MBC, APA, BD and micro-arthropod population were identified as the key indicators and contributed significantly towards soil quality index (SQI). MW system with ZT and R*m* (T8) recorded the highest SQI (1.45) followed by T6 (1.34) and the lowest score (0.29) being in T1 (RW/CT − R). The SQI was higher by 90% in MW compared to RW, 22% in ZT compared to CT, and 100% in residue recycling compared with residue removal. System yield was strongly related to key soil quality indicators and also positively correlated with SQI. Longer-term studies are essential to realize maximal effects of improvements in soil health on crop yields.

1. Introduction

The Indo-Gangetic Plains (IGP) in India, the cradle of Green Revolution (GR) covers about 20% and 27% of the total geographical and net cultivated area, respectively and produces about half of the food consumed in the country (Dhillon et al., 2010). Rice-wheat (RW) system is the lifeline of millions of food producers and consumers in IGP. With the advent of GR, the RW system, has so far, successfully maintained the balance between food supply and population growth. This was possible with the use of improved seeds, chemical fertilizers, irrigation and farm mechanization along with expansion of area under cultivation. However, resource intensive RW production system has caused negative environmental externalities and second generation problems such as groundwater depletion, soil health degradation and

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loss of nutrients through emission and leaching, declining factor productivity and shrinking farm profits (Chauhan et al., 2012). Due to these negative effects of the production practices, productivity of RW system has plateaued or even declined, posing a threat to the sustainability of this important cropping system (Bhatt et al., 2016).

To address the aforementioned challenges, conservation agriculture (CA, based on the principle of minimal mechanical disturbance of soil and permanent organic soil cover coupled with efficient crop rotations) has been a subject of intensive scientific investigation for cropping system management studies (Ladha et al., 2016; Sithole et al., 2016). Zero-tillage (ZT) has been an attractive strategy for wheat farmers to facilitate early planting, lower production cost and increase yield so as to increase overall productivity and profitability (Nawaz et al., 2017). With the development of "Turbo Happy Seeder" that can directly drill seed and fertilizer through the previous crop residue (Sidhu et al., 2015), farmers of IGP are also retaining crop residue and gradually moving towards full CA-based RW systems. Further, to address the problem of water and labour shortages, maize-wheat (MW) system is emerging as an alternative to RW system due to less water and labour requirement of maize than rice (Gathala et al., 2014). Over the last decade, several researchers have reported the effect of different tillage, residue management and cropping sequences on agronomic productivity (Jat et al., 2014), nutrient- water- and energy-use-efficiency (Devkota, 2011; Gathala et al., 2014), soil physical properties (Alam et al., 2017), greenhouse gas (GHG) emissions (Sapkota et al., 2015), economic profitability (Nawaz et al., 2017), adapting to climate risks (Jat et al., 2016) and overall sustainability (Ladha et al., 2003) of the systems. To our knowledge, effect of these improved management practices on soil fauna, flora and associated soil biological activities and processes is scanty. Food and Agriculture Organisation (FAO) gives slogan of '*Healthy soils for healthy life*' during 'International Year of Soils-2015' and laid emphasis on sustainable management of soils which can be possible only by knowing health of soil by assessing its quality (http://www.fao.org/soils-portal/en/).

Soil organisms play major role in improving soil health and can be used as an important soil quality indicator (Doran and Zeiss, 2000). Soil productivity primarily depends on its biological health, which includes the magnitudes of microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and enzymatic activities. Microbes function as agents of transformation of organic matter, nutrient cycling, and energy flow among other functions (Six et al., 2004) that impinge on sustainability. Soil microbial biomass and enzyme activity have been suggested as potential indicators of soil quality because of their relationship to soil biology, and rapid response to changes originated by management and environmental factors (Mohammadi, 2011). In soil biota, micro-arthropods are considered to be one of the very important biotic components of soil ecosystem being involved in decaying organic material and thereby increase its availability for micro-organisms and to stimulate nutrient turnover (Petersen et al., 2002).

Alterations in tillage, residue recycling, and crop rotation practices induces significant changes in the quantity and quality of plant residue entering the soil, their seasonal and spatial distribution, the ratio between above- and below-ground inputs and nutrient dynamics, all of which influence soil microorganisms and soil microbial processes (Govaerts et al., 2007). In arable soils, micro-arthropods depend on the input of crop and root residues or organic manures as source of food whereas, the amount and quality of organic input is decisively determined by the agronomic management interventions (Sapkota et al., 2012).

Individual soil parameters alone may not be sufficient for decision making regarding sustainability of the cropping system (Mandal et al., 2005). Soil quality index (SQI) is an important tool to access the suitable combination of soil properties. The higher values of SQI denote the better quality of soil to perform in better way to produce at higher and sustainable level. Indexing of soil quality under different soil and crop management practices is important for identifying the critical key indicators of soil health (Mandal et al., 2005). Throughout the globe, researchers used different parameters and techniques for estimation of SQI under different situations (Doran and Jones, 1996; Lima et al., 2013; Mandal et al., 2005; Masto et al., 2007; Mohanty et al., 2007; Sharma et al., 2005; Stott et al., 2013; Yao et al., 2013). In CA based management systems in IGP, studies on various soil parameters especially physico-chemical properties and few reports on biological properties have been documented but in isolation. Comprehensive information on soil quality indexing using all parameters (physico-chemical and biological) in CA-based management systems and their relationships with crop yield is very limited. Thus, this study was aimed to identify key soil quality indicators under different conservation agricultural management practices. We hypothesize that higher SQI would result in maize–based cropping system with CA than without CA-based maize and in rice-based cropping system with CA than non-CA rice. Overall, maize–based cropping system with CA would lead to higher SQI than rice-based cropping system. Therefore, the present study was carried out to assess the influence of CA-based management practices such as tillage, crop establishment method, residue management and crop rotation on soil quality improvement in rice and maize based cropping system in North-western IGP.

2. Materials and methods

2.1. Study site

A farmers' participatory field experiment was set up during monsoon 2012 at Tarawari village of Karnal district in Haryana, India (29°48′ N; 76°55′ E). Climate of the region is semi-arid sub-tropical with extreme weather conditions with hot and dry to wet summers (May–October) and cool, dry winters (November–April). The average annual temperature is 24°C and average annual rainfall is 670 mm, 75–80% of which is received during southwest monsoon (July to September). The soil type is Typic Ustocrept. Before start of the experiment, the study site has clay loam soil (Sand 32%, Silt 30%, Clay 38%) with slightly alkaline reaction (pH 7.94) and EC (0.44 dS m^{-1}). Oxidizable organic carbon at 0–15 cm soil layer was 0.44%. The field had low available nitrogen (alkaline permanganate fraction; 146.8 kg ha^{-1}), medium available phosphorus (Olsen P; 15.0 kg ha^{-1}) and exchangeable potassium (ammonium acetate extract; 241.86 kg ha^{-1}).

2.2. Experimental treatments and agronomic management

The field experiment was laid-out in randomized block design with three replicates of each eight cropping system treatments varying in crop sequence, tillage and residue management. The plot size was 20 m × 5.4 m and the distance between plots and blocks was 1.0 and 1.5 m, respectively. A summary of the treatment details is presented in Table 1.

2.3. Soil sampling and analysis

After three cropping system cycles (2012–2015), soil samples were collected from surface layer (0–10 cm) randomly from five places within each plot by using a soil auger (5 cm internal diameter) after harvesting of wheat in summer 2015. Five samples within a plot were thoroughly mixed to make a composite sample. The initial soil properties (pH, EC, organic carbon and available N, P, K) were also measured from air dried samples. Soil pH and electrical conductivity (EC) in soil: water ratios of 1:2 were determined by following standard methods (Jackson, 1973). The oxidizable soil organic carbon (SOC) was determined using wet oxidation method (Walkley and Black, 1934), available N by alkaline permanganate method (Subbiah and Asija, 1956), available phosphorus (Olsen P) by ascorbic acid reductant method (Olsen et al., 1954) and available potassium (K) by flame

Table 1
Treatment details: crop rotation, tillage, crop establishment, and management of residue, water, weed and fertilizer.

Cropping system	Rice- Wheat (RW)				Maize- Wheat (MW)			
Tillage	CT		ZT		CT		ZT	
Residue	− R	+ R	− R	+ R	− R	+ R	− R	+ R
Treatment abbreviation and No.	RW/CT − R (T1)	RW/CT + R*i* (T2)	RW/ZT − R (T3)	RW/ ZT + R*m* (T3)	MW/CT − R (T5)	MW/CT + R*i* (T6)	MW/ ZT − R (T7)	MW/ ZT + R*m* (T8)
Crop establishment	Rice: Conventional till (8 tillage) puddled transplanted rice (TPR). Wheat: Conventional till (5 tillage) followed by drill seeding	Same as in T1	Rice (direct seeded; DSR) and wheat were planted using zero-till seed drill machine	Rice (DSR) and wheat were planted using turbo happy seeder	Maize: Conventional till (5 tillage) followed by seeding using multi crop planter Wheat: Same as in T1	Same as in T5	Maize and wheat were planted using multi crop planter	Maize and wheat were planted using multi crop planter/ turbo happy seeder
Residue management	All residue removed (− R)	100% of rice and anchored residues of wheat were incorporated (+ R*i*)	All residue removed	100% rice and anchored wheat residue retained on soil surface/ mulched (+ R*m*)	All residue removed	65% of maize, and anchored residue of wheat were incorporated	All residue removed	65% of maize, anchored wheat residue were retained on soil surface/ mulched
Water management	Rice: Continuous flooding of 5 ± 2 cm depth for 1 month followed by irrigation applied at hair-line cracks Wheat: Irrigation at the critical crop growth stages	Same as in T1	Rice: Kept soil wet for first 20 days followed by irrigation at − 20 to − 30 kPa matric potential Wheat: Irrigation at − 40 to- 50 kPa matric potential	Same as in T3	Maize: 2–3 need based irrigation was applied Wheat: same as in T1	Same as in T5	Same as in T5	Same as in T5
Fertilizer management	Rice: 150:60:60 kg $N:P_2O_5:K_2O$ ha^{-1} Wheat: 150:60:60 kg $N:P_2O_5:K_2O$ ha^{-1}	Same as in T1	Same as in T1	Same as in T1	Maize: 150:60:60 kg $N:P_2O_5:K_2O$ ha^{-1} Wheat: Same as in T1	Same as T5	Same as in T5	Same as in T5
Residue load (t ha^{-1})	Nil	26.50	Nil	24.53	Nil	28.59	Nil	29.75

Where CT- conventional till; ZT- zero-till; R*i*- residue incorporated; R*m*- residue mulched.

photometer using neutral 1 *N* ammonium acetate extractant (Jackson, 1973). Soil bulk density was measured using a core sampler *in situ* by core method (Blake and Hartge, 1986) by collecting soil cores at 0 to 10 cm depth, using 5-cm-long and 5-cm diameter metal cores. SOC stock was calculated by using following formula (Datta et al., 2015).

$$\text{C stock in soil} = \text{C content} \times \text{Bulk density} \times \text{Soil depth} \quad (1)$$

where, C content is given in g C kg^{-1}, BD in Mg m^{-3}, soil depth in m and C stock in Mg ha^{-1}.

Fresh soil samples were passed through a 2-mm sieve and transferred to laboratory for analysis of different soil biological properties (MBC, MBN, dehydrogenase activity, alkaline phosphatase activity, and microbial count). MBC and MBN were estimated by chloroform fumigation method (Vance et al., 1987). Dehydrogenase and alkaline phosphatase activities were estimated as described by Dick et al. (1996).

2.4. Microbial count and diversity

Total bacterial count was done on nutrient agar medium by pour plating method (Zuberer, 1994). The plates were incubated at 32°C and colonies were counted after 3 days. Total fungal count was done on rose bengal agar medium (RBA) supplemented with streptomycin (30 μg ml^{-1}) to inhibit bacterial growth (Martin, 1950). The plates were incubated at 30°C for 5 days. The total actinomycetes count was done on actinomycetes isolation agar (AIA) plates supplemented with nalidixic acid (50 μg ml^{-1}) to restrict fungal growth (Himedia, 2009). AIA plates were incubated for 7 days at 28°C. Data from triplicate readings were expressed as colony forming units (CFU) g^{-1} dry soil.

2.5. Sampling, extraction and identification of micro-arthropods

Soil samples (2 kg) collected for micro-arthropods extraction (two soil blocks of 10 cm × 5 cm × 10 cm) were taken to laboratory as undisturbed as possible. The soil samples were placed on a Berlese–Tullgren funnel for extraction (Parisi et al., 2005) for 7 days. The funnel was fitted with a 60 W lamp 25 cm above the soil samples to ensure drying, and downward movement of micro-arthropods into preservative liquid (75% ethanol: glycerol 2:1) placed underneath. The extraction system was kept free from vibrations and other disturbance. Extracted specimens were observed under a stereomicroscope at low magnification (range 5–100 ×; usually 20–40 × is sufficient) in the same preservative liquid.

2.6. Soil quality index (SQI) calculation

To determine the soil quality index, four main steps were followed: 1) define the goal, 2) select a minimum data set (MDS) of indicators that best represent the soil function, 3) score the MDS indicators based on their performance of soil function, and 4) integrate the indicator score into a comparative index of soil quality (Sharma et al., 2005). The ultimate outcome of good soil quality is yield or economic produce because it serves as a plant bioassay of the interacting soil characteristics. In the present study, the system yield for each treatment was defined as the goal variable because the farmers like to get more productivity per unit land area.

The dataset (of 12 attributes) was reduced to a minimum dataset of soil quality indicators through principal component analysis (Andrews et al., 2002). Principal components (PC) for a data set are defined as linear combinations of variables that account for maximum variance within the set by describing vectors of closet fit to the nth observation in p-dimensional space, subject to being orthogonal to one another. The principal components receiving high eigen values and variables with high factor loading were assumed to be variables that best represented system attributes. Therefore, only the PCs with eigen values > 0.9 and those that explained at least 5% of the variation in the data were examined. Within each PC, only highly weighted factors were retained for MDS. Highly weighted factor loadings were defined as having absolute values within 10% of the highest factor loading. When more than one factor were retained under a single PC, multivariate Pearson's correlation coefficients were employed to determine if the variables could be considered redundant and therefore eliminated from the MDS (Andrews et al., 2002). As a check of how well the MDS represented the management system goals, multiple regression or Pearson's correlation was performed using the indicators retained in the MDS as independent variables and the end point measures like system yield as dependent variable. If any variable within the MDS did not contribute to the coefficient of determination of multiple regressions of the variables, it was also dropped from the MDS.

After determining the MDS indicators, every observation of each MDS indicator was transformed in order to standardize its value using a non-linear scoring method (Bastida et al., 2006) by following formula:

$$y = \frac{a}{1 + \left(\frac{X}{X_0}\right)^{-b}} \quad (2)$$

where, a is the maximum value reached by the function, in our case, a = 1, X is the unknown of the equation, corresponding to the value of the parameter in question in each case, X_0 is the mean value of each parameter corresponding to the soils of different treatments, b is the value of the slope of the equation. Using different values of b for different selected parameters, we obtained curves that fit a sigmoidal tending to 1 for all the proposed parameters. The above value (y) provides curves that vary between 0 and 1. The b value was optimized for different selected indicators.

The MDS variables for each observation were weighted by using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage, divided by the total percentage of variation explained by all PCs with eigen vectors > 0.9, provided the weighted factor for variables chosen under a given PC. The weighted MDS variables scores for each observation were then summed up using the following equation:

$$\text{SQI} = \sum_{i=1}^{n} W_i S_i \quad (3)$$

where S = indicator score, W = the weighing factor obtained from PCA.

Higher index scores were assumed to mean better soil quality or greater performance of soil function.

2.7. Yield and validation of SQI

The rice, wheat and maize crops (2014–2015 cycle) were harvested manually from 4 m × 4 m randomly selected two places from each plot for recording the grain yield. To express the overall impact of treatments, system productivity was calculated on wheat equivalent yield (WEY) basis for rice and maize grain yield. Grain yield was reported at 12% moisture. System productivity (Mg ha^{-1}) was computed using Eq. (4)

$$\text{Wheat Equivalent Yield (t ha}^{-1}) = \frac{\text{Rice/maize yield (t ha}^{-1}) \times \text{MSP of Rice/maize (INR t ha}^{-1})}{\text{MSP of wheat (INR t ha}^{-1})} \quad (4)$$

The SQIs estimated from the above method were validated against wheat equivalent yield/system yield after 3 years by computing multiple regression as well as Pearson's correlation coefficients.

2.8. Statistical analysis

Data were subjected to the analysis of variance (ANOVA) using SAS (9.2) JMP software. Separation of means and treatment interactions were done using the Tukey's HSD test method at $p = 0.05$. The mean effects of cropping systems, tillage and residue were determined using linear contrast or individual factor in the JMP. Bivariate Pearson's correlation coefficients and regression equations were also computed along with PCA of the 12 soil attributes namely pH, EC, SOC, BD, DHA, APA, MBC, MBN, fungi, bacteria, actinomycetes and microarthropod population to evaluate relationships between the response variables and performance of the soil and crop management practices.

3. Results and discussion

3.1. Soil pH and EC

Changes in soil physico-chemical properties under different treatments are presented at Table 2. Results showed that soil pH (7.88 to 7.96) remained unchanged across the treatments but the EC varied (0.38 to 0.54 dS m^{-1}) among these treatments. Compared to initial EC value of 0.44 dS m^{-1}, T8 (MW/ZT + R*m*) had the lowest EC (0.38 dS m^{-1}) which was similar to those of T7, T6, T5 and T2 (MW/ZT − R, MW/CT + R*i*, MW/CT − R and RW/CT + R*i*). EC values were substantially lower in all treatments ruling out much effect on crop yield and soil biological properties (Munns et al., 2006). The EC was significantly influenced by systems, tillage and residue with their interactions (Table 2). The MW system (0.39 dS m^{-1}) had lower EC than RW system (0.50 dS m^{-1}). The systems × tillage interaction showed greater influence of ZT in MW than in RW but the trend was reversed in RW where CT had lower EC (0.43 dS m^{-1}). System × residue interaction showed lower EC in RW with residue recycling than MW. The residue incorporation in CT had more influence on EC than residue retention in ZT to maintain lower EC.

3.2. Soil bulk density

The treatment effects on soil BD were significant and it ranged from 1.34 to 1.47 Mg m^{-3} (Table 2). Soil BD in different treatments followed highest to lowest order as: T1 (RW/CT − R) > T2 (RW/CT + R*i*) ≥ T5 (MW/CT − R) = T6 (MW/CT + R*i*) ≥ T3 (RW/ZT − R) ≥ T4 (RW/ZT + R*m*) = T7 (MW/ZT − R) > T8 (MW/ZT + R*m*). Higher BD in T1 (RW/CT − R) is because of soil compaction due to puddling in rice (Gathala et al., 2011). The T8 (MW/ZT + R*m*) had 9% lower BD (1.34 Mg m^{-3}) than T1 (RW/CT − R; 1.47 Mg m^{-3}). Lower BD in MW system with ZT with or without residue (T7, T8 and T4) is likely due to loose soil and more pore space created (Bhattacharyya et al., 2015). The systems, tillage and residue had positive effect on BD. The MW system had lower BD (1.36 Mg m^{-3}) than RW system (1.40 Mg m^{-3}). The lower BD was measured under ZT than CT and similarly residue recycling reduced BD by 2% than residue removed although residue recycling had significant influence on BD (Table 2). ZT with residue helps in improving soil aggregation and reducing BD (Gathala et al., 2011; Govaerts et al., 2009). The interaction effects of system × tillage, system × residue, tillage × residue and systems × tillage × residue on BD were significant (Table 2). CT had higher bulk density in RW system than MW system whereas ZT maintained similar BD in both systems. This may be due to the higher soil organic matter in ZT than CT and within CT higher in MW system than RW system because of higher biomass of maize (Chen et al., 2014) and residue recycling (Table 1). Higher amounts of organic carbon can result in lesser soil BD in some cases because of its lower particle density than mineral particles (Logsdon and Karlen, 2004).

3.3. Soil organic carbon

Soil organic carbon (SOC) significantly varied among the treatments ranging from 6.8 to 10.5 Mg ha^{-1} (Table 2). CT without residue recycling in RW (T1) had the lowest SOC (6.8 Mg ha^{-1}). Treatment 4 (RW/ZT + R*m*) and T8 (MW/ZT + R*m*) with ZT and residue mulch, and T6 with CT and residue incorporation (MW/CT + R*i*) resulted in an increase of SOC by 54, 50 and 56%, respectively over T1. Addition of organic matter through residue incorporation/retention helps in improving SOC irrespective of crop rotations (Paudel et al., 2014; Govaerts et al., 2009; Singh et al., 2016). Soil puddling and plough tillage promotes the decomposition of organic matter which explains the lower SOC in T1 (RW/CT − R). The SOC stock was significantly influenced by systems, tillage and residue after 3 crop cycles. The MW system maintained higher SOC (9.3 Mg ha^{-1}) than RW system (8.5 Mg ha^{-1}), similarly higher SOC was observed under ZT than CT

Table 2
Soil properties as influenced by systems, tillage and residue after the 3 crop cycles.

Cropping system	Tillage	Residue	Treatment number[a]	pH	EC (dS m^{-1})	BD (Mg m^{-3})	SOC stock (Mg ha^{-1})
Rice-Wheat (RW)	CT	− R	T1	7.91 ± 0.12a	0.52 ± 0.01a	1.47 ± 0.06a	6.8 ± 0.11d
		+ R*i*	T2	7.90 ± 0.03a	0.43 ± 0.01b	1.40 ± 0.06b	9.4 ± 0.06b
	ZT	− R	T3	7.89 ± 0.07a	0.54 ± 0.01a	1.37 ± 0.06bcd	7.3 ± 0.06c
		+ R*m*	T4	7.88 ± 0.03a	0.52 ± 0.02a	1.35 ± 0.12 cd	10.5 ± 0.12a
Maize-Wheat (MW)	CT	− R	T5	7.96 ± 0.02a	0.41 ± 0.01b	1.38 ± 0.06bc	7.5 ± 0.06c
		+ R*i*	T6	7.90 ± 0.05a	0.40 ± 0.01b	1.38 ± 0.12bc	10.6 ± 0.12a
	ZT	− R	T7	7.92 ± 0.04a	0.39 ± 0.01b	1.35 ± 0.12 cd	9.0 ± 0.12b
		+ R*m*	T8	7.91 ± 0.07a	0.38 ± 0.01b	1.34d ± 0.09	10.2 ± 0.09a

Linear contrast	pH	EC	BD	SOC stock
Systems (S)	0.5428	< 0.0001	< 0.0001	< 0.0001
Tillage (T)	0.7250	0.0249	< 0.0001	< 0.0001
Residue (R)	0.6178	0.0009	< 0.0001	< 0.0001
S × T	0.9556	0.0003	0.0002	0.0140
S × R	0.8096	0.0167	0.0005	0.0005
T × R	0.7811	0.0540	0.0317	0.0009
S × T × R	0.8096	0.0368	0.0012	< 0.0001

Where CT- Conventional till; ZT- Zero till; R- residue; *i*- incorporated; *m*- mulched; EC- Electric Conductivity; BD- Bulk density; SOC- Soil organic carbon.
For all variables $n = 3$ ± standard error of mean.
Means of column followed by the same letters within each column not statistically different ($p \le 0.05$, Tukey's HSD test).
[a] Refer Table 1 for treatment description.

because ZT decreases SOC decomposition by minimizing breakdown of macro aggregates (Gathala et al., 2011). Higher biomass of maize (Chen et al., 2014) under MW system than RW system as well as more residue recycling (Table 1) also contributed to higher SOC in soil. Tillage disturbs/breaks soil aggregates and increases soil temperature and soil organic matter decay which results in decline of soil C content (Aziz et al., 2013). Residue recycling increased SOC by 33% over residue removal. The interaction effect of soil, tillage and residue were found significant among each other (Table 2).

3.4. Microbial biomass carbon and nitrogen

Both MBC and MBN were highly influenced by cropping system, tillage and residue treatments at the end of third cropping cycle (Table 3). Among treatments, MBC and MBN ranged from 646 to 1990 and 210 to 729 μg g^{-1} dry soil, respectively with lowest in T1 (RW/CT − R) and highest under T8 (MW/ZTR + R*m*). Compared to CT and residue removal, ZT and residue cycling increased MBC by 29% and 56%, respectively whereas, MBN increased by 27% and 84%, respectively. Retention of crop residue under ZT improved microbial biomass C and N (Masto et al., 2007) which in turn enhanced soil biological activities (Gajda et al., 2013; Govaerts et al., 2007). Higher levels of microbial biomass under ZT with residue mulch can be explained by greater availability of substrate to sustain the microbial biomass (Wang et al., 2008). The MW cropping system had 48% and 73% higher MBC and MBN, respectively than that of RW system due to relatively greater amounts of crop residue recycling as well as varied soil edaphic conditions in former than later. System × tillage and system × residue interaction effect on MBC and MBN were significant. The system × tillage × residue interaction effect was significant to MBC (Table 3). The systems with highest dry matter yield and residue accumulation shows higher microbial biomass in upper soil layers (Venzke Filho et al., 2004). Significant variation was observed in MBC: MBN ratio among the treatments (Fig. 1) although the values are low. Among the treatments ZT with RW (T4:2.54) and MW (T8:2.73) system with residue mulch led to lowest MBC/MBN ratio. Treatment MW/CT − R (T5:3.72) and RW/ZT − R (T3:3.68) showed significantly higher MBC/MBN ratio than others (Fig. 1). The MBC/MBN ratio is often used to describe the structure and the state of the microbial community and reflect the abundance of either fungi or bacteria in the soil. A high MBC/MBN ratio (7 to 12) indicates that the microbial biomass contains a higher proportion of fungi, whereas a low value (2 to 6) suggests that bacteria predominate in the microbial population (Moore et al., 2000). We observed higher bacterial population than fungi in all the treatments (Table 4) that is also explained by the low MBC: MBN ratio and slightly alkaline pH, which is congenial for bacterial growth. Therefore, our study corroborates the findings of Moore et al. (2000) which provides basis for assumption that the plant residue treatments influenced the population dynamics of both bacteria and fungi in the soil.

3.5. Soil enzymes

Soil dehydrogenase activity (DHA) and alkaline phosphatase activity (APA) in different crop rotations, tillage and residue management practices are presented in Table 3. The DHA ranging from 180 to 558 μg TPF g^{-1} soil 24 h^{-1} found in order of T8 (MW/ZT + R*m*) > T6 (MW/CT + R*i*) > T7 (MW/ZT − R) ≥ T4 (RW/ZT + R*m*) ≥ T2 (RW/CT + R*i*) ≥ T5 (MW/CT − R) > T3 (RW/ZT − R) = T1 (RW/CT − R). Compared to T1 (RW/CT − R), DHA was 210% higher in T8 (MW/ZT + R*m*) and 444% higher in T4 (RW/ZT + R*m*). Treatment 6 (MW/CT + R*i*) also showed 107% higher DHA than T5 (MW/CT − R). Soil enzyme activities are highly correlated with ZT (Bandick and Dick, 1999) and negatively correlated with CT (Roldan et al., 2005) and it also depends upon amount of substrates (organic matter) for microbial growth (Chandra, 2011).

The DHA was significantly influenced by the systems; tillage and residue mulch (Table 3). DHA was increased by 73% in MW system than RW system. Interactions among treatments were significant. System × tillage and system × residue interaction effect on DHA were significant.

The APA ranged from 144 to 213 μg p-nitrophenol g^{-1} h^{-1} in different treatments. Treatment 8 (MW/ZT + R*m*) followed by T6 (MW/CT + R*i*) had similar APA but differed from those of other treatments (Table 3). The lowest APA in T1 (RW/CT − R) was similar to T3 (RW/ZT − R) and T4 (RW/ZT + R*m*) was similar to T5 (MW/CT − R). Treatment 8 (MW/ZT + R*m*) had 48% higher APA than T1 (RW/

Table 3
Effect of systems, tillage and residue on soil microbial properties after 3-crop cycles.

Cropping system	Tillage	Residue	Treatment number[a]	Microbial biomass carbon (μg g^{-1} dry soil)	Microbial biomass nitrogen (μg g^{-1} dry soil)	Dehydrogenase activity (μg TPF g^{-1}soil 24 h^{-1})	Alkaline Phosphatase activity (μg p-NP g^{-1} h^{-1})
Rice-Wheat (RW)	CT	− R	T1	646 ± 10.3e	201 ± 1.9d	180 ± 8.7e	144 ± 5.4d
		+ R*i*	T2	1113 ± 33.6c	343 ± 27.7c	256 ± 12.5d	176 ± 4.7c
	ZT	− R	T3	890 ± 33.4d	239 ± 2.2d	196 ± 7.4e	153 ± 8.0d
		+ R*m*	T4	1182 ± 31.8c	364 ± 14.8c	260 ± 17.4d	163 ± 1.2 cd
Maize-Wheat (MW)	CT	− R	T5	895 ± 3.0d	244 ± 10.7d	219 ± 6.0de	157 ± 0.9 cd
		+ R*i*	T6	1500 ± 32.8b	590 ± 6.8b	453 ± 21.8b	208 ± 13.2a
	ZT	− R	T7	1278 ± 16.4c	416 ± 2.8c	313 ± 9.1c	188 ± 2.0b
		+ R*m*	T8	1990 ± 37.5a	729 ± 4.5a	558 ± 16.2a	213 ± 1.2a
Linear contrast							
Systems (S)				< 0.0001	< 0.0001	< 0.0001	< 0.0001
Tillage (T)				< 0.0001	< 0.0001	< 0.0001	0.0067
Residue (R)				< 0.0001	< 0.0001	< 0.0001	< 0.0001
S × T				< 0.0001	< 0.0001	< 0.0001	0.2364
S × R				< 0.0001	< 0.0001	< 0.0001	0.4921
T × R				0.3961	0.1698	0.2031	0.1672
S × T × R				0.0024	0.6278	0.6346	0.2839

Where CT- Conventional till; ZT- Zero till; R- residue *i* - incorporated; *m*- mulched.
For all variables n = 3 ± standard error of mean.
Means of column followed by the same letters within each column not statistically different ($p \leq 0.05$, Tukey's HSD test).
[a] Refer Table 1 for treatment description.

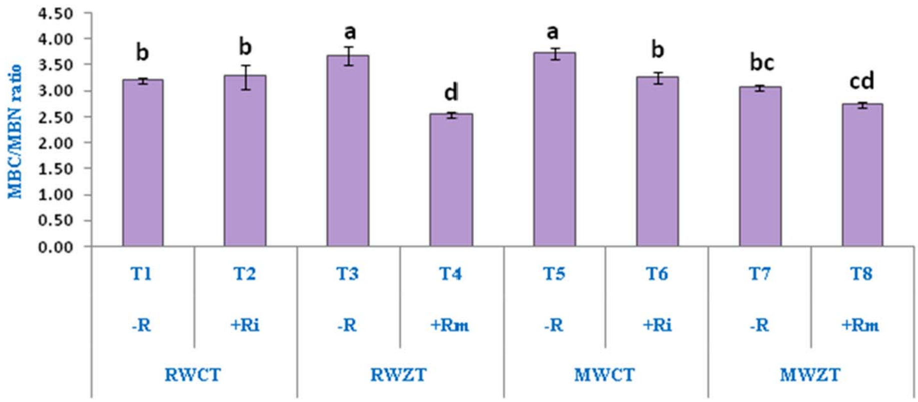

Fig. 1. MBC/MBN ratio as influenced by different CA based agricultural practices.
Where RW- rice, wheat; MW- maize, wheat; CT- Conventional till; ZT- Zero till; R*i* - residue - incorporated; R*m*- residue mulched.
Vertical bars indicate ± S.E. of mean of the observed values. The same letters are not statistically different ($p \leq 0.05$, Tukey's HSD test).

CT − R) whereas T6 (MW/CT + R*i*) showed 32% and 44% higher APA than T5 (MW/CT − R) and T1 (RW/CT − R), respectively. A higher level of APA has earlier been reported with zero tillage (Omidi et al., 2008) and crop residue retention (Wang et al., 2011). Linear contrast showed a large influence of system, tillage and residue on APA (Table 3). It was higher by 20%, 5% and 18% in MW, ZT and residue recycling compared to RW, CT and residue removed, respectively.

DHA and APA were associated with higher microbial activities including MBC and MBN through release of organic substances thereby also creating a positive "rhizosphere effect" (Roldan et al., 2005; Chandra, 2011) on enzymes secretion in soil.

3.6. Microbial population

Microbial population viz. bacteria, fungi and actinomycetes vary among the treatments (Table 4). Population of bacteria was higher compared to fungi and actinomycetes. Lowest microbial population was recorded in T1 (RW/CT − R). Compared to T1 the counts of bacteria, fungi and actinomycetes were 29%, 71% and 100% higher in T8 (MW/ZT + R*m*) and 27%, 62%, 53% higher in T6 (MW/CT + R*i*), respectively. Higher microbial population is likely to be the result of improved food source availability supplied by residue amendment (Govaerts et al., 2008; Nicolardot et al., 2007). The trends of microbial counts tend to be similar in treatments resulting in following order T8 (MW/ZT + R*m*) ≥ T6 (MW/CT + R*i*) > T7 (MW/ZT − R) ≥ T4 (RW/ZT + R*m*) ≥ T2 (RW/CT + R*i*) ≥ T5 (MW/CT − R) > T3 (RW/ZT − R) > T1 (RW/CT − R) (Table 4). Microbial counts were 5–11% higher in MW than RW; 11–25% higher in ZT than CT and 9 to 37% higher in residue treatment than without residue. The interaction between system × residue was significant for actinomycetes population, while tillage × residue interaction was significant to microbial population. Conservation tillage practices increase fungal and bacterial population (Helgason et al., 2009). Maintaining cover crop residues on the surface (ZT) or incorporation (CT) provides a stimulating substrate for microbial growth (Ghimire et al., 2014). Residue retention induced higher population counts of total bacteria, fluorescent *Pseudomonas*, and actinomycetes compared to residue removal under ZT and conventional tillage (Govaerts et al., 2008).

3.7. Soil micro-arthropods

Total micro-arthropod population varied significantly among the treatments. Highest micro-arthropod population was observed in T3 (RW/ZT − R) followed by T2 (RW/CT + R*i*) > T4 (RW/ZT + R*m*) > T1 (RW/CT − R) > T6 (MW/CT + R*i*) > T8 (MW/ZT + R*m*) > T5 (MW/CT − R) > T7 (MW/ZT − R) (Table 5). ZT

Table 4
Effect of systems, tillage, and residue on soil microbial populations after 3-crop cycles.

Cropping system	Tillage	Residue	Treatment number[a]	Total bacteria (CFU × 10^4 g^{-1} soil)	Fungi (CFU × 10^2 g^{-1} soil)	Actinomycetes (CFU × 10^4 g^{-1} soil)
Rice-Wheat (RW)	CT	− R	T1	74.7 ± 0.7f	45.3 ± 0.09f	35.5 ± 0.8f
		+ R*i*	T2	84.0 ± 1.6cde	58.8 ± 2.2 cd	48.2 ± 0.2 cd
	ZT	− R	T3	79.3 ± 1.3ef	52.0 ± 0.1e	41.2 ± 1.4e
		+ R*m*	T4	86.7 ± 1.7 cd	64.3 ± 1.5bc	50.8 ± 1.0bc
Maize-Wheat (MW)	CT	− R	T5	81.6 ± 1.0def	54.3 ± 1.9de	45.8 ± 0.2d
		+ R*i*	T6	94.5 ± 1.0ab	73.2 ± 1.8a	69.3 ± 0.7a
	ZT	− R	T7	88.8 ± 1.0bc	66.3 ± 1.2b	54.2 ± 1.1b
		+ R*m*	T8	96.2 ± 1.0a	77.3 ± 0.2a	71.0 ± 0.6a
Linear contrast						
Systems (S)				< 0.0001	< 0.0001	< 0.0001
Tillage (T)				0.0002	< 0.0001	< 0.0001
Residue (R)				< 0.0001	< 0.0001	< 0.0001
S × T				0.6530	0.3314	0.4939
S × R				0.3038	0.3314	< 0.0001
T × R				0.0418	0.0386	0.0009
S × T × R				0.3038	0.1144	0.1430

Where CT- Conventional till; ZT- Zero till; R- residue *i* - incorporated; *m*- mulched; CFU- Colony forming unit.
For all variables n = 3 ± standard error of mean.
Means of column followed by the same letters within each column not statistically different ($p \leq 0.05$, Tukey's HSD test).
[a] Refer Table 1 for treatment description.

Table 5
Variation in micro-arthropod population (number per 2 kg soil) under different CA-based practices after 3 crop cycles.

Cropping system	Tillage	Residue	Treatment number[a]	Collembola	Acari	Protura	Diplura	Araneae	Hymenoptera	Total population	Evenness	Richness	QBS
Rice-Wheat (RW)	CT	− R	T1	12.3 ± 8.4	1.0 ± 0.6	0.3 ± 0.3	–	0.7 ± 0.7	–	17.0	0.393	4	55
		+ R*i*	T2	30.0 ± 13.1	2.7 ± 2.2	–	–	0.3 ± 0.3	–	34.7	0.306	3	35
	ZT	− R	T3	35.7 ± 16.5	4.0 ± 3.1	–	–	0.3 ± 0.3	–	40.0	0.339	3	45
		+ R*m*	T4	10.0 ± 5.2	2.3 ± 0.3	–	–	–	0.3 ± 0.3	18.7	0.541	3	35
Maize-Wheat (MW)	CT	− R	T5	2.3 ± 0.3	1.0 ± 0.6	–	–	–	–	4.0	0.881	2	40
		+ R*i*	T6	6.3 ± 1.9	1.7 ± 1.2	0.0 ± 0.5	–	–	0.3 ± 0.3	8.7	0.600	3	65
	ZT	− R	T7	1.3 ± 0.3	–	–	0.3 ± 0.3	0.3 ± 0.3	–	2.3	0.790	3	45
		+ R*m*	T8	4.3 ± 2.8	1.0 ± 1.0	–	0.3 ± 0.3	–	–	6.0	0.617	3	60

Where CT- Conventional till; ZT- Zero till; R- residue *i* - incorporated; *m*- mulched; QBS- Biological soil quality/*Qualita biological del Suolo*.
For all variables n = 3 ± standard error of mean and "-" indicates zero values.
[a] Refer Table 1 for treatment description.

and residue retention improved the growth and multiplication of micro-arthropods, thereby protecting them from soil desiccation during summer (Sapkota et al., 2012; Wardle, 1995). The most abundant micro-arthropod was *Collembola* followed by *Acari* and *Protura*. *Collembola* population also followed a similar trend as total micro-arthropod population. Total micro-arthropods population was recorded higher in RW system compared to MW system irrespective of treatment combinations. It might be due to uneven covering of the soil surface with maize residues as compared to rice residues which caused more soil desiccation of the micro-arthropods leading to lower population than rice-wheat cropping system.

In MW system, higher biological soil quality (QBS) value was observed in those treatments where crop residues were retained or incorporated but reverse happened in RW system (Table 5). Residue cover, suitable microclimate and food resources for different types of microarthropod might have caused higher number, evenness and QBS values under different treatments (Sapkota et al., 2012). Residue quality of crops might also play an important role in variation of micro-arthropod population under different cropping systems. Chemical composition of plant residues probably influenced the densities of detritivore and phytophage microarthropods in addition to microclimatic conditions imposed by vegetation cover (Badejo et al., 1995). Higher densities of microarthropods were reported under rice straw mulching than maize stover and other mulching (Badejo et al., 1995). The age of the experiment is an important factor. As our experiment is continuing for 3 years only there was not much significant difference in micro-arthropod population/QBS/richness among the treatments.

3.8. Relations among the soil properties

Most of the biological soil properties showed significant correlations ($p < 0.01$ and $p < 0.05$) among each other (Table 6). Bacteria ($r = -0.71$, $p < 0.05$) and actinomycetes ($r = -0.72$, $p < 0.05$) population were significantly and negatively correlated with pH of soil. Neutral to slightly alkaline soil pH is congenial for the growth of bacteria and actinomycetes above which growth hampers. Ghorbani-Nasrabadi et al. (2013) observed negative correlation between the number of actinomycetes and soil pH ($r = -0.59$, $n = 15$, $p < 0.001$) in pasture. Davies and Williams (1970) observed lowest numbers of actinomycetes at high pH values and low moisture content. The negative correlation between pH and bacterial population is probably due to the narrow pH ranges for optimal growth of bacteria (Rousk et al., 2010). Soil OC had significant positive correlation with all the soil biological properties except microarthropod population (Table 6). Soil enzymes viz. DHA ($r = 0.73$, $p < 0.05$) and APA ($r = 0.78$, $p < 0.05$), MBC ($r = 0.80$, $p < 0.05$), MBN ($r = 0.79$, $p < 0.05$), microbial population such as fungi ($r = 0.89$, $p < 0.05$), bacteria ($r = 0.87$, $p < 0.01$) and actinomycetes ($r = 0.83$, $p < 0.05$) were significantly and positively correlated with OC. MBC and MBN were significantly and positively correlated with DHA ($r = 0.97$ and 0.99, $p < 0.01$), APA ($r = 0.94$ and 96, $p < 0.01$) and fungi ($r = 0.96$ and 0.95, $p < 0.01$), bacteria (r = 0.96and 0.96, $p < 0.01$) and actinomycetes ($r = 0.95$ and 0.97, $p < 0.01$) population, respectively. Soil microarthropod population did not show significant relation with any of the soil properties which might be due to the duration (3 years) of the experiment. Okur et al. (2009) reported that SOC significantly positively correlated to MBC, DHA and APA in organically and conventionally managed soils under Mediterranean conditions in western Turkey. The significant correlation between enzyme activity and organic C is likely due to higher C levels supporting greater microbial biomass and activity. Furthermore, increasing organic matter provides a better environment for stabilizing and protecting extracellular enzymes (Balota et al., 2004). Our findings corroborated with the findings of Jamuna et al. (2016) who observed significant positive correlation between SOC and bacteria, fungi and actinomycetes population. Organic carbon improved biological properties of soil due to residue

Table 6
Relationships among the soil parameters under different CA based practices.

	Bivariate Pearson's Correlation											
	EC	pH	OC	BD	DHA	APA	MBC	MBN	Fun	Actino	Bac	Microarth
EC	1											
pH	− 0.52											
OC	− 0.41	− 0.44										
BD	0.09	0.39	− 0.60									
DHA	− 0.07	− 0.69	0.73*	− 0.52								
APA	− 0.07	− 0.78	0.78*	− 0.55	0.95**							
MBC	− 0.14	− 0.66	0.80*	− 0.68	0.97**	0.94**						
MBN	− 0.15	− 0.67	0.79*	− 0.56	0.99**	0.96**	0.98**					
Fun	− 0.16	− 0.68	0.89**	− 0.72*	0.93**	0.95**	0.96**	0.95**				
Actino	− 0.08	− 0.72*	0.83*	− 0.61	0.97**	0.97**	0.95**	0.97**	0.97**			
Bac	− 0.12	− 0.71*	0.87**	− 0.70	0.93**	0.96**	0.96**	0.96**	0.99**	0.99**		
Microarth	− 0.53	0.60	− 0.28	0.21	− 0.44	− 0.40	− 0.38	− 0.41	− 0.45	− 0.46	− 0.46	1

[Where EC: Electrical conductivity; OC: Oxidizable organic C; BD: Bulk density; DHA: Dehydrogenase activity; APA: Alkaline Phosphatase activity; MBC: Microbial biomass carbon; MBN: Microbial biomass N; Fun: Fungal population; Actino: Actinomycetes population; Bac: Bacterial population; Microarth: Microarthropod population.]

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

retention/incorporation in soil under CA-based agricultural practices which is manifested by the significant positive correlation between SOC and other biological soil properties.

3.9. Principal component analysis (PCA) and soil quality index (SQI)

In the PCA of 12 variables, three PCs were extracted with eigen values > 0.9 and explained 91.18% of the variance (Fig. 2). DHA, APA, MBC MBN, bacteria, fungi and actinomycetes populations were the highly weighted variables in PC1 (68.57% of total variance). Minimum variables need to be selected to avoid redundancy. So correlations study (Pearson's correlation) was performed for all the 7 variables (DHA, APA, MBC, MBN, bacteria, fungi and actinomycetes population). Among the seven variables in PC1, MBC and APA were chosen for the MDS. Soil microbial biomass is considered as one of the most sensitive indicators of changes in soil quality (Stenberg, 1999). Garcia-Gil et al. (2000) showed that highest MBC and MBN values were found in the most fertile soils. Microbial activity, microbial biomass and enzyme

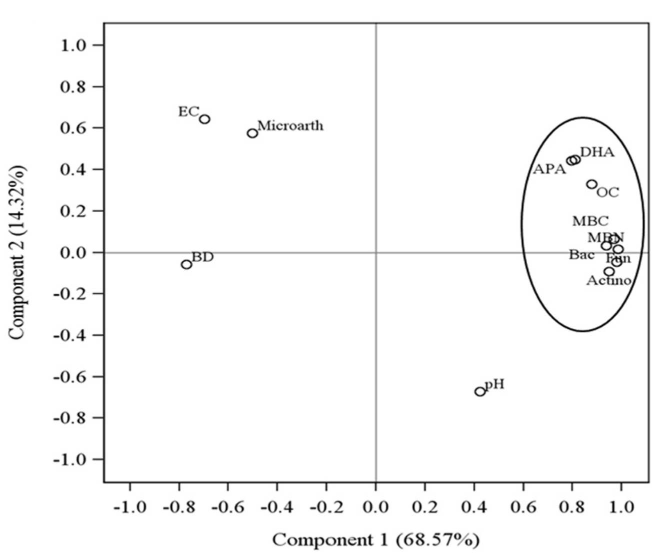

Fig. 2. Principal component plot of soil physicochemical properties, enzyme activities and microbial parameters under different CA-based agricultural practices.
EC: Electric Conductivity; SOC: Soil organic carbon; BD: Bulk density; DHA: Dehydrogenase activity; APA: Alkaline Phosphatase activity; MBC: Microbial biomass carbon; MBN: Microbial biomass N; Fun: Fungal population; Actino: Actinomycetes population; Bac: Bacteria population; Microarth: Microarthropod population.

activities of soils are correlated to SOM contents (Chaer et al., 2009). Soil microbial properties were all significantly correlated with MBC ($p < 0.05$) but not always with SOM. Therefore, soil MBC may be an accurate indicator for assessing soil quality. DHA is highly related to MBC and dropped from the MDS to avoid redundancy. Therefore, APA remains and selected in the MDS. In PC2 (14.32% of total variance) and PC3 (8.29% of total variation), micro-arthropod population and soil BD were considered highly weighted eigen vectors and therefore were selected in the MDS. Though soil EC had higher factor loadings in PC2, it was not retained in the MDS as EC did not have any effect on crop growth. The final MDS consisted of MBC, APA, soil BD and micro-arthropod population.

Based on PCA, the four parameters (MBC, APA, micro-arthropod population, and soil BD) with most weights were chosen to estimate the SQI and therefore qualified as key soil quality indicators. We used b value of − 6.5 for MBC, APA, microarthropod population and 6.5 for soil BD to obtain a sigmoidal curve using the non-linear equation of Bastida et al. (2006). In the present study, as all the indicators except BD that were retained in the minimum data set were considered good when in increasing order, they were scored, as "more is better" whereas BD was scored as "less is better". Elliott and Coleman (1988) used 'more-is-better' function for MBC, while 'less is-better' function was used for BD (Grossman et al., 2001). After scoring, each score was multiplied by the respective weight as obtained during PCA analysis. Then summation of these values provided the soil quality indices for each treatment (Eq. 5 and Table 7):

$$\text{SQI} = \Sigma\,(\text{MBC score} \times 0.775) + (\text{APA score} \times 0.775) + (\text{Microarthropod population score} \times 0.168) + (\text{BD score} \times 0.057) \quad (5)$$

Treatments showed significant differences (Table 7) for SQI. Treatment 8 (MW/ZT + R*m*) had the SQI of 1.40 followed by 1.34 in T6 (MW/CT + R*i*). The lowest SQI of 0.29 and 0.36 were scored by T1 (RW/CT − R) and T5 (MW/CT − R) due to deterioration of soil physico-chemical and biological properties (Chaudhury et al., 2005; Masto et al., 2007). The SQI values were validated against system yield by computing regression as well as Pearson's correlation coefficient. System yield was significantly ($p < 0.05$, $R^2 = 0.60$) correlated to SQI values under different CA based treatments (Fig. 3) indicating their effectiveness in predicting crop yield. Pearson's correlation coefficient between system yield and SQI values was 0.68 ($p < 0.01$) suggesting strong positive relationship between them (Mukherjee and Lal, 2014).

The contribution of individual indicators towards SQI was also calculated (Fig. 44). Averaged across treatments the individual

Table 7
Effect of systems, tillage, and residue on soil quality index (SQI) and system yield (t ha^{-1}) after 3 crop cycles.

Cropping system	Tillage	Residue	Treatment number[a]	Soil quality index value	System yield
Rice-Wheat (RW)	CT	− R	T1	0.29 ± 0.03f	11.1 ± 0.12c
		+ R*i*	T2	0.78 ± 0.03c	11.7 ± 0.17bc
	ZT	− R	T3	0.47 ± 0.02de	12.1 ± 0.18b
		+ R*m*	T4	0.58 ± 0.03d	12.3 ± 0.18ab
Maize-Wheat (MW)	CT	− R	T5	0.36 ± 0.02ef	11.2 ± 0.03c
		+ R*i*	T6	1.34 ± 0.04a	12.0 ± 0.15b
	ZT	− R	T7	0.93 ± 0.02b	12.3 ± 0.13ab
		+ R*m*	T8	1.40 ± 0.03a	12.80 ± 0.10a

Linear contrast	Soil quality index value	System yield
Systems (S)	< 0.0001	0.0063
Tillage (T)	< 0.0001	< 0.0001
Residue (R)	< 0.0001	0.0001
S × T	< 0.0001	0.3559
S × R	< 0.0001	0.2139
T × R	< 0.0001	0.0897
S × T × R	0.0986	0.9321

Where CT- Conventional till; ZT- Zero till; R- residue *i* - incorporated; *m*- mulched.
For all variables n = 3 ± standard error of mean.
Means of column followed by the same letters within each column not statistically different ($p \leq 0.05$, Tukey's HSD test).
[a] Refer Table 1 for treatment description.

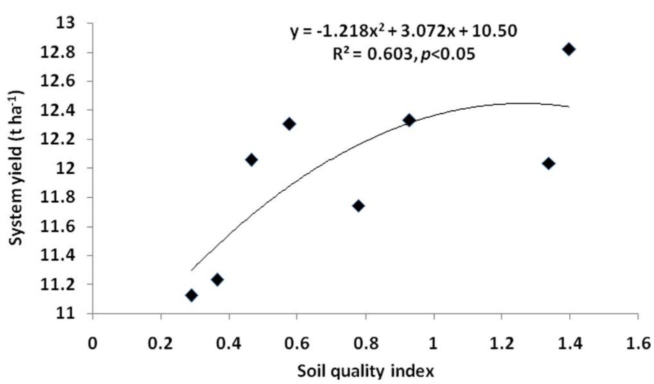

Fig. 3. Relationship between SQI and system yield.

contribution of each indicator towards SQI was 31, 38, 3 and 6% for MBC, APA, BD and micro-arthropod population, respectively (Fig. 4). The average contribution of MBC and APA to SQI was significantly higher in MW (50 and 48%) than RW (12 and 27%) system, ZT (36 and 40%) than CT (25 and 35%) and residue recycling (47% each) than residue removal (14 and 28%), respectively (Fig. 4). Micro-arthropod population contributed 11% towards SQI in RW system. MBC plays an important role in improving SQI. Higher MBC stimulated substantial alkaline phosphatase activity in soil. Soil microorganisms serve as the main impetus in organic matter transformations, particularly mineralization and immobilization of organic constituents. Nutrient availability, soil aggregation, soil tilth and decomposition of plant residues are governed by these transformations (Smith et al., 1993). Agronomic management practices strongly influence MBC in soil (Smith and Paul, 1990) thereby providing an indication of the capacity of soil to store and recycle nutrients. Gregorich et al. (1994) also found MBC as a sensitive indicator of change in organic matter levels in soil.

The individual effects of systems, tillage and residue on SQI were significantly different (Table 7). The SQI was higher by 90% in MW compared to RW, 22% in ZT compared to CT, and 100% with residue recycling compared to residue removal. The tillage × residue, system × tillage and system × residue interaction effect on soil quality index were found significant. Different management practices like tillage, crop rotation and crop residues affects soil biological, chemical and physical properties, which are indicators of soil quality (Blanco-Moure et al., 2016; Gajda et al., 2016). Improvement of SOC, enzymes activity, MBC, MBN as well as microorganisms population under higher crop residues retention and minimum soil disturbance might have resulted higher SQI values (Lima et al., 2013). Different soil quality indicators have been used to assess SQI and it was found that SQI is

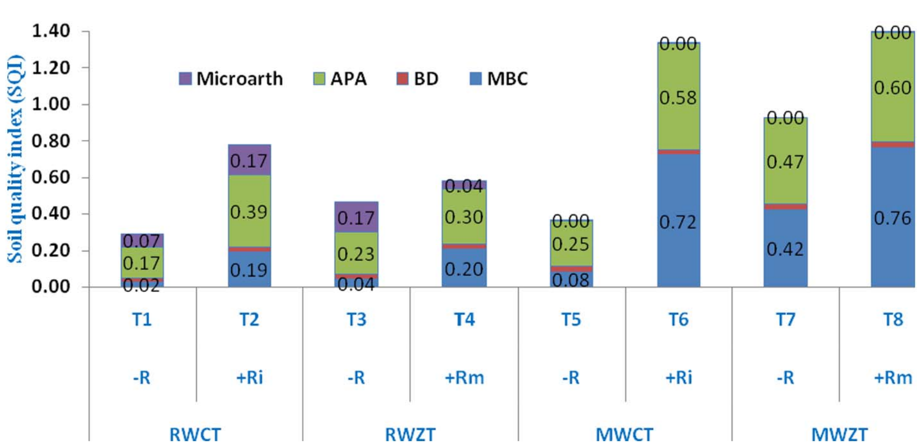

Fig. 4. The individual contribution of each of the key indicators to SQI under different CA-based practices.
Where RW- rice, wheat; MW- maize, wheat; CT- Conventional till; ZT- Zero till; R*i* - residue - incorporated; R*m*- residue mulched.
Microarth: Micro-arthropod population; APA: Alkaline phosphatase activity; BD: Bulk density; MBC: Microbial biomass carbon.

influenced by different agriculture management practices (Raiesi and Kabiri, 2016). Enzyme activities are widely used as soil quality indicator (Schloter et al., 2003). Soil fauna reflects general ecological changes in soil (Yan et al., 2012) and as a part of soil fauna microarthropod communities play an important role in the determination of soil quality (Aspetti et al., 2010) and decomposition of organic matter (Fujii and Takeda, 2017) in different cropping management systems. These are sensitive towards land and agriculture management practices (Parisi et al., 2005; Van Leeuwen et al., 2015).

3.10. System yield

Treatment 8 (MW/ZT + R*m*) produced the highest system yield (12.8 t ha^{-1}) which differed from other treatments except T4 (RW/ZT + R*m*; 12.3 t ha^{-1}) and T7 (MW/ZT − R; 12.3 t ha^{-1}) (Table 7). The contribution of ZT to increase in system yield was estimated to be 7.6% and that of residue was estimated to be 4.5%. Individual effect of system, residue and tillage on system yield was significant. Singh et al. (2016) also reported higher crop yields under ZT compared to CT in rice-wheat and maize-wheat systems.

4. Conclusions

Our results demonstrate a differential response of tillage and residue management in two cereal crop rotations. Rice-wheat rotation tends to have lower SQI ranging from 0.29 to 0.78 than maize-wheat ranging from 0.36 to 1.40 irrespective of tillage and residue treatments. But in both rotations, replacing conventional practices of tillage and crop management with no tillage and residue retention improve soil chemical, physical and biological properties. Maize–based cropping system with CA showed higher SQI than rice-based cropping system. Among the various treatments, MW/ZT + R*m* had the highest SQI (1.40). With respect to maintenance of higher yield, better soil quality and overall sustainability, this treatment showed maximum potential. Therefore, maize-wheat cropping system with ZT and residue retention (T8) not only help to preserve the precious natural resources but also substantially improved SQI and can be recommended to the farmers of IGP. Although overall, system yield was significantly correlated with SQI values, the treatment differences in SQI scores and system yield were not consistent. This may primarily be because of a relatively short-term nature of our study. Longer-term studies are essential to realize maximal effects of improvements in soil health and crop yields.

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Conflict of interest

The authors declare that they have no conflict of interest.

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