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Soil quality and carbon sequestration under conservation agriculture with balanced nutrition in intensive cereal-based system

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ABSTRACT

Conventional tillage practices and imbalanced use of inorganic fertilizers is well known to result in poor soil health. Alternative tillage and precision nutrient management are important strategies for tackling the issues of soil health deterioration, particularly in cereal-based intensive cropping systems. Therefore, we conducted a 4-year study with the objective of (a) monitoring the changes in soil physical, biological and chemical properties and crop productivity, (b) development of soil quality index-SQI, and monitor its' changes against system productivity as management goal, and (c) studying the changes in soil organic carbon-SOC in relation to annual C input. The experiment was laid out in a split-plot design with 3-tillage practices [zero tillage-ZT; permanent beds-PB; and conventional tillage-CT] and 4-nutrient management strategies [Control (unfertilized), farmers' fertilizer practice-FFP, recommended fertilizers doses-*Ad-hoc* and site specific nutrient management-SSNM] under a continuous maize (*Zea mays* L.) - wheat (*Triticum aestivum* L.)- mungbean (*Vigna radiata* L. Wilczek) rotation in a sandy loam soil (Typic Haplustept) of north-western Indo-Gangetic plains (NW-IGP) of India. The ZT/PB with SSNM/*Ad-hoc* nutrient management resulted in higher values of a) physical parameters *viz.*, water stable aggregates > 250 µm, saturated hydraulic conductivity (K_{sat}) and mean weight diameter-MWD, b) chemical parameters *viz.*, SOC, available N, P, and K, and c) biological parameters *viz.*, microbial biomass carbon and enzyme activities (fluorescein diacetate hydrolase, dehydrogenase, ß-glucosidase and alkaline phosphatase) compared with CT and unfertilized treatments. The CA practices recorded an increase in WSA (12–21%), MWD (14–29%), and K_{sat} (11–14%) compared with CT at the 0-0.15 m and 0.15–0.30 m soil depths, respectively. The PB-SSNM registered (44.1%) higher SOC content as compared to CT-unfertilized plots. Values for MBC, FDA and βGA declined in the order SSNM = *Ad-hoc* > FFP > Control. While, the DHA declined in the order SSNM > *Ad-hoc* = FFP > Control. Principal component analysis included MWD, SOC and available K in the minimum data set (MDS) as the soil quality indicators. Adoption of PB/ZT resulted ~22.5% higher SQI compared with CT. The SSNM plots improved SQI by ~19.3% and ~5.3% over unfertilized and FFP. The SSNM based CA practices attained a significantly higher annual C sequestration rate than other treatments. Therefore, adoption of CA with SSNM and *Ad-hoc* nutrient management in intensive cereal based systems of NW-IGP is essential for improving nutrient cycling, soil quality, crop productivity and C-sequestration potential.

1. Introduction

Soil degradation resulting from intensive conventional tillage and inadequate or imbalanced use of inorganic fertilizers in intensive production systems for more than four decades is of great concern in the north-western Indo-Gangetic Plains (NW-IGP) (Parihar et al., 2016a). Conservation agriculture (CA) based practices implying minimum tillage, permanent soil cover and crop diversification along with optimum

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use of inorganic fertilizers has revealed great potential as a sustainable production system without deteriorating soil health, and managing profitability at the same time (Sapkota et al., 2014). Jat et al. (2019a) reported significantly higher system productivity from a 10-year old CA-experiment under zero tillage (ZT) or permanent bed (PB) compared with conventional tilled (CT) system in eastern IGP. Nutrient management protocols customized for CA is very essential to tap the full beneficial potential of CA (Meena et al., 2018). Practising zero tillage (ZT) in flat and permanent raised beds (PB), combined with balanced fertilization often proved beneficial in sub-tropical Indian soils in several wheat-based cropping systems (Jat et al., 2013, 2019a; Jat et al., 2019b; Parihar et al., 2019; Sapkota et al., 2014). Improvising N management under CA led to improved crop yield, water use and N use efficiency (Jat et al., 2019a). Long-term ZT along with optimum nutrient and residue management enhances the soil SOC concentration and influences the distribution of SOC in the soil profile, in turn leading to favourable alterations in soil aggregation, hydraulic conductivity, porosity, moisture retention *etc.* (Bhattacharyya et al., 2019; Dey et al., 2016, 2020; Parihar et al., 2017a). A combination of CA and balanced nutrient management not only enhanced SOC concentration, but also improved the stability of SOC (Jat et al., 2019b; Parihar et al., 2019; Dey et al., 2020). More immediate effect of balanced nutrition in CA can be visible through improvement of microbial biomass carbon (MBC), soil microbial diversity, and enzymatic activities (Dey et al., 2016; Ghosh et al., 2019). The changes in these responsive parameters are an early indicator of the changes in other soil quality parameters and nutrient availability, which will manifest in later years (Jia et al., 2014). However, measurement and demonstration of soil quality indicators (physical, chemical and biological), and their interactions are very complex (Karlen et al., 2003). Soil quality, as defined by Doran et al. (1996), is the capacity of soil to perform various functions, *viz.*, to sustain biological productivity, maintain the air and water quality, and to promote plant, animal and human health within ecosystem and land use boundaries. Soil quality index (SQI) is often used to quantitatively measure the effect of any change of crop management practice on overall soil health (Andrews et al., 2002).

Despite the growing importance of CA in the tropical areas, the debates are still continuing around the profitability and yield /benefits of CA over conventional practices. Thus, development of SQI against cropping system productivity as a management goal, and monitoring the changes of SQI as an effect of different tillage, nutrient and residue management practices would surely offer a conclusive statement regarding feasibility and sustainability of CA in Indian tropical and subtropical cropping systems. The SQI is measured through changes in some chosen chemical, physical, and biological components of a soil, termed as indicators (Sharma et al., 2008, 2016). The choice of suitable indicators is the most crucial step for calculation of SQI. From the previous studies on SQI, it can be summarized that the indicators should (i) correlate well with ecosystem functions, (ii) integrate physical, chemical and biological processes and properties of soil, (iii) be easy to measure or observe, (iv) are sensitive to crop management variations, and components of existing soil data bases wherever possible (Doran and Parkin, 1996; Sharma et al., 2005). The soil quality indicators varied widely in the published literatures (Doran et al., 1996; Doran and Parkin, 1996; Andrews et al., 2002; Sharma et al., 2005, 2008, 2016). The indicators were highly site- and purpose specific. Till date most of the soil quality studies were undertaken in temperate soils. Parr et al. (1992) emphasized on soil physical parameters *viz.*, infiltration, aggregation stability and distribution, bulk density *etc*. as quality indicators, whereas, Biswas et al. (2017) suggested that, biological measurements, *viz.*, microbial biomass, respiration, and ergosterol concentrations, are very effective indicators for assessing long-term soil and crop management effects on soil quality. Recently, some studies were undertaken in Indian condition to monitor changes in SQI under CA systems (Bhaduri et al., 2014; Sharma et al., 2005, 2008, 2016). Based on prior knowledge of operational systems and purpose of analysis, researchers preferred non-linear (Bhaduri et al., 2014) or linear (Sharma et al., 2016) method of determination. The available N, mean weight diameter (MWD) and MBC turned out to be in minimum data set (MDS) in more than one instances (Sharma et al., 2005, 2008, 2016). Often ZT and application of optimum fertilizer N and organic manure both positively affected SQI (Sharma et al., 2005, 2016), whereas reports are there where ZT had no (Sharma et al., 2008) or negative (Sharma et al., 2005) effect on SQI.

Furthermore, it is a well-known fact that SOC can be greatly enhanced by CA, but its effect on other soil parameters and nutrient availability is yet still not much talked upon. The optimum nutrient management options under CA, especially in tropical and sub-tropical soils of IGP, are still a researchable issue. A few attempts made earlier were focussed on changes in SQI under CA, never covered the important cereal-based systems of IGP. Despite extensive research on precision nutrient management, precise information on the potential benefits of conservation agriculture (CA) and precision nutrient management (PNM) in combination on maintaining or enhancing soil physical, chemical and biological properties in the IGP region is lacking. In this backdrop, we conceptualized a research study to investigate and provide new scientific information on the effect of CA-based tillage and residue management, and precision nutrient management in a maize-wheat-mungbean rotation of NW-IGP on different aspects *viz.*, soil fertility, C-sequestration, nutrient cycling, soil health, yield benefits, soil quality and sustainability, *etc*. Our hypotheses were (a) The combination CA and PNM greatly enhances the soil physical, chemical and biological properties, and in turn soil quality, (b) The PNM under CA positively affects crop yields, and (c) Continuous crop residue addition at an accelerated rate in PNM-based CA leads to effective C sequestration. The objectives of the study were to (a) monitoring the changes in soil physical, biological and chemical properties and crop productivity, (b) development of SQI, and monitor its' changes against system productivity as management goal, and (c) studying the changes in SOC in relation to annual C input, as affected by tillage, residue and nutrient management options.

2. Materials and methods

2.1. Experimental site and design

The experiment was laid out in July 2012 at the research farm of Indian Council of Agricultural Research (ICAR)-Indian Institute of Maize Research, New Delhi, India (28°38′N, 77°11′E, 228.6 m elevation). The site represents a sub-tropical semi-arid climate, characterized by hot and dry summers, and a cold winters with a mean annual precipitation of ~652 mm. Taxonomically the soil represents a Typic Haplustept (Soil survey staff, 2014) of Gangetic alluvial origin, with a sandy loam texture consisting of 64.1% sand, 16.9% silt and 19% clay. The soil is very deep ($>$ 2 m), flat, well drained, non-saline (EC 0.32 dS m^{-1}) with an alkaline reaction (pH 7.9). The initial soil characteristics are described in detail in Table 1. A maize-wheat-mungbean (MWMb) rotation was being followed since 2012. Maize was sown during rainy season (July-October), wheat in winter season (November-April) and mungbean in spring season (May-June). The experimental design was a split-plot with 3-tillage practices and crop residue management [Zero tillage with residue retention (ZT); Permanent bed with residue retention (PB); and Conventional tillage with residue incorporation (CT)] as main plots and 4-nutrient management variants [Control (unfertilized); typical Farmers' Fertilizer Practice (FFP); recommended fertilizers dose (*Ad-hoc*); and Nutrient Expert® decision support tool-based fertilizer application (Pampolino et al., 2012), which represented site specific nutrient management (SSNM)] as sub plot treatments with 3-replications (36-plots).

Table 1
Initial status of soil properties (n = 3) ± SE at the experimental site prior to July 2012.

A. Soil Physical properties

Soil Properties	Depth (m)						
	0-0.10	0.10-0.20	0.20-0.30	0.30-0.40	0.40-0.50	0.50-0.60	0.60-0.70
Bulk density (g cm^{-3})	1.53 ± 0.02	1.64 ± 0.02	1.71 ± 0.03	1.73 ± 0.03	1.72 ± 0.02	1.72 ± 0.03	1.71 ± 0.01
Penetration resistance (kPa)	910 ± 23.1	1237 ± 40.4	1803 ± 46.2	2815 ± 86.6	2762 ± 71.0	2419 ± 69.3	2324 ± 63.5

B. Carbon and aggregation

Depth (m)	Soil organic carbon (g kg^{-1} of soil)	Water stable aggregate (%)	Mean weight diameter (mm)	Saturated Hydraulic conductivity (cm h^{-1})
0-0.15	4.97 ± 0.03	51.0 ± 1.00	0.825 ± 0.03	0.859 ± 0.01
0.15-0.30	4.40 ± 0.10	46.0 ± 0.58	0.720 ± 0.01	0.810 ± 0.02
0.30-0.45	3.87 ± 0.15	43.5 ± 0.88	0.580 ± 0.02	0.612 ± 0.02

C. Soil biological properties

Depth (m)	Microbial biomass carbon (µg C g^{-1} soil)	Fluorescein diacetate activity (µg Fluorescein^{-1}hr^{-1})	Dehydrogenase (µg TPF g^{-1}24 hr^{-1})	ß Glucosidase µg (p-NP g^{-1}24 hr^{-1})	Alkaline Phosphatase (µg p-NP g^{-1}24 hr^{-1})
0-0.30	335 ± 9.24	0.460 ± 0.02	27.6 ± 1.56	1.596 ± 0.03	38.0 ± 1.91

D. Soil chemical properties

Depth (m)	Available N (kgha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})	Soil Texture
0-0.15	162 ± 4.62	15.2 ± 0.75	169.2 ± 6.06	Sandy Loam
0.15-0.30	141 ± 1.73	12.4 ± 0.46	135.4 ± 3.23	Sandy Clay Loam
0.30-0.45	109 ± 1.15	6.4 ± 0.29	85.7 ± 2.25	Sandy Clay Loam

2.2. Soil and crop management

The experimental site was deep (0.30 m) tilled using a chisel plough followed by laser levelling prior to establishment of the experiment. The CT planting consisted of one deep tillage using a disc harrow. The ZT planting was done through ZT planter resulting in direct drilling of crop seeds. Permanent raised beds (PB) were established using bed/ridge former in the first year of experimentation itself and maintained for subsequent years, with re-shaping of beds once annually, while planting the crop using a raised bed multi-crop planter.

In the FFP, fertilizers were applied at the rate of 110:13.2:0 and 172:25.3:0 kg ha^{-1} of N: P: K for maize and wheat, respectively which was based on a survey consisting of 50 farmers' from the Delhi region. The *Ad-hoc* recommendations were based on the economic optima of nutrients for Delhi region as stated by ICAR. Those were 150:26.2:33.3 kg ha^{-1} and 120:26.2:33.3 kg ha^{-1} N: P: K for maize and wheat, respectively. The fertilizer doses for SSNM were worked out through Nutrient Expert®, an interactive decision support system developed by the International Plant Nutrition Institute (IPNI). Nutrient Expert® was developed using background data of nutrient omission plot trials conducted in maize and wheat at various locations in South Asia and the nutrient demand was estimated based on nutrient response and the uptake by the crop at a particular site. In this approach, the NPK recommendations are based on the relationships between nutrient uptake and grain yield, which can also be termed as internal nutrient efficiency and is predicted using the QUEFTS (quantitative evaluation of the fertility of tropical soils) model (Satyanarayana et al., 2013). The site specific nutrient doses were calculated by Nutrient Expert® based on plant nutrient demand for a targeted yield of a crop (maize 8.0 Mg ha^{-1} and wheat 5.0 Mg ha^{-1}), applied nutrient to previous crop, residue recycling, soil fertility status, and the economics of fertilizer input and prices of crop produce in the market. The SSNM recommendations based on Nutrient Expert® were 170:16.3:36.5 and 155:27.7:54 kg ha^{-1} of N: P: K (average of all tillage practices) for maize and wheat, respectively. One-third of recommended N and full dose of P and K was applied during final land preparation through diammonium phosphate (DAP), urea and muriate of potash (MOP). Remaining 2/3rd of N were applied in two equal splits through urea at eight leaves and tasseling stages in maize, and at crown root initiation and late jointing stages in wheat, respectively. A uniform rate of 100 kg DAP ha^{-1} was applied to mungbean as basal application. Approximately 30% of maize and wheat residues and 100% of mungbean residues were retained/incorporated annually in the plots amounting to 2.35-3.22 Mg ha^{-1}, 1.61-2.19 Mg ha^{-1} and 2.50-3.88 Mg ha^{-1}, respectively on dry weight basis. Each year the wheat and maize crop were harvested manually at a height of about 20 and 40 cm above ground, respectively. The 2, 4-D was sprayed @ 0.5 kg ha^{-1} to mungbean after two manual picking of pods, to kill those plants and whole of the residues were retained in the plots. A more detailed description of fertilizer, pesticide, crop residue and water management of the experiment is available in Parihar et al. (2017a, 2017b).

The ultimate criteria for comparing different treatment combination is system productivity converted to maize equivalent yield (MEY). Minimum support prices for maize, wheat and mungbean as fixed by government of India were used to convert these crops yield to equivalent yields of maize and then all were summed up to calculate the system productivity in terms of maize yield. Following Eq. (1) was used to estimate the MEY.

$$\text{MEY (Mg ha}^{-1}\text{)} = \text{Maize yield} + [(\text{WY} \times \text{Wp}) + (\text{MbY} \times \text{Mbp})] / \text{Mp} \tag{1}$$

Where, WY yield of wheat (Mg ha^{-1}); MbY yield of mungbean (Mg ha^{-1}); Wp is the wheat MSP (US\$ Mg^{-1}), Mbp is the mungbean MSP (US\$ Mg^{-1}) and Mp is the MSP of maize (US\$ Mg^{-1}).

2.3. Soil sampling

The soil samples were taken in 2012 (prior to establishing the experiment on 15th July 2012) and 2016 (during fourth year summer season on 10th June 2016) from fixed site treatments. Initial soil properties have been presented in Table 1. The samples were collected from three random spots in each replicated plot, mixed homogenously to make composite samples for analysis of different parameters. For analysis of microbial parameters, samples were collected from 0-0.30 m soil layer using a tube auger of 7 cm diameter, then stored moist in polyethylene bags at 4 °C until assaying for microbial biomass carbon and other soil enzyme activities. Prior to analysis, the soil samples were sieved using a 4 mm mesh sieve to eliminate stones, plant roots and large residue pieces. The soil samples for bulk density estimation were collected from seven depths (0–0.10, 0.10–0.20, 0.20–0.30, 0.30–0.40, 0.40–0.50, 0.50–0.60 and 0.60–0.70 m) in triplicates using a core sampler. Soil samples for aggregate analysis were collected from the 0-0.15, 0.15-0.30 and 0.30-0.45 m depths using a hand shovel. After drying in the shade, soil samples were crushed using the gentle stroke of a wooden hammer. For chemical analysis, soil samples were collected at the 0-0.15, 0.15-0.30 and 0.30-0.45 m depths in triplicate in each treatment by using a tube auger. After removing visible root debris, the soil samples were mixed, dried, ground and sieved (2-mm) for chemical analysis using standard methods.

2.4. Analytical methods

2.4.1. Soil chemical properties

Soil organic carbon in samples (0–0.15, 0.15–0.30 and 0.30–0.45 m) was determined in triplicate using an Elementar® dry combustion analyzer after sieving 50–70 mg air-dried soil through a 250 μm sieve and treating it with 2% HCl to remove carbonates. Air-dried soil samples were used for estimation of available N by alkaline $KMnO_4$ method (Subbiah and Asija, 1956), available P by Olsen's method (Olsen et al., 1954) and available K through 1 *M* NH_4OAc extraction (Schollenberger and Simon, 1945).

2.4.2. Soil physical properties

Soil bulk density was determined with a core sampler (Mishra and Ahmad, 1987). To measure saturated hydraulic conductivity, similar core samples were collected in triplicate from 0-0.15, 0.15-0.30 and 0.30-0.45 m soil depth, from each plot. After trimming the core of the extra soil on both sides, the undisturbed soil cores were saturated overnight by placing them in a water filled tray and a dummy ring was attached above it. The permeameter was put on stand and siphoning of water was done for 30 min by maintaining constant head of 2–3 cm on the top of the soil using siphon tubes with mariotte arrangement. The liquid flow was collected in a graduated cylinder and measured. The same process was repeated four times for each sample at 15 min intervals and the mean values were used for calculation of saturated hydraulic conductivity (K_{sat}) by constant head method (Parihar et al., 2016b) according to Eq.(2):

$$K_{sat} = \frac{Q * L}{A * t * (h + L)} \tag{2}$$

Where;

K_{sat} = Saturated hydraulic conductivity (cm min^{-1})
Q = Volume of water collected (cm^3)
L = Length of soil column (cm)
A = Cross sectional area of the permeameter (cm^2)
t = Time interval of collection (min)
h = Depth of the water above the soil (cm)

Soil strength or cone penetration resistance was measured using a hand-held penetrometer (Rimik CP40II penetrometer, Australia) fitted with a cone of 12.8 mm diameter, 130 mm^2 area, having maximum cone index of 5600 kPa. It recorded soil penetration resistance at 10 mm intervals down to 700 mm. Resistance data was taken under field capacity soil moisture and expressed in kilo Pascals (kPa).

The soil aggregate size distribution was studied through wet sieving using Yoder apparatus (Yoder, 1936). Fifty grams of air-dry soil (passed through 8 mm sieve but retained in a 4 mm sieve) was transferred to the upper most sieve in a set of sieves with diameters 4, 2, 1, 0.5, 0.25 and 0.125 mm. It was capillary rewetted through soaking for 10 min. Then the sieves were moved up and down in the water drum for 10 min with 3 cm amplitude and 30 cycles per minute frequency. Soils from each sieve and from drum were collected in beakers separately and oven-dried at 65–70 °C till constant weight was achieved. Thus, we obtained the distribution of aggregates into following classes of diameters, *i.e.,* (i) 0–125 μm, (ii) 125–250 μm, (iii) 250–500 μm, (iv) 500–1000 μm, (v) 1000–2000 μm, (vi) 2000–4000 μm and (vii) 4000–8000 μm. Water stable aggregates were expressed as the percentage of aggregates greater than 250 μm diameter. Mean weight diameter (MWD) of aggregates was estimated using the formula (Kemper and Rosenau, 1986), *i.e.* Eq. (3):

$$\mathrm{MWD\ (mm)} = \sum_{i=1}^{i=n} (X_i W_i) \tag{3}$$

where, W_i, is the proportion of aggregates mass (g) retained on each sieve in relation to total soil mass taken, X_i is the mean diameter of the sieve (mm).

2.4.3. Soil biological properties

Soil MBC was estimated using the chloroform fumigation-extraction method (Brookes et al., 1985). The optical density of the fumigated and non-fumigated extract was measured at 280 nm. The fluorescein released by the hydrolysis of fluorescein diacetate was used to determine the fluorescein diacetate activity (FDA) as described by Green et al. (2006). Dehydrogenase activity (DHA) was estimated by release of triphenyl formazan with reducing 2, 3, 5-triphenyl tetrazolium chloride (Casida et al., 1964). Alkaline phosphatase activity (APA) was assayed in soil suspended in modified universal buffer (pH 11), along with p-nitro phenyl phosphate (Tabatabai and Bremner, 1969). The ß-glucosidase activity (βGA) was assessed by measuring the *p*-nitrophenol released, after incubation of the soil samples with *p*-nitrophenyl β-D glucoside (0.025 *M*) for one hour at 37 °C; absorbance was measured at 490 nm (Eivazi and Tabatabai, 1988).

2.5. Soil carbon sequestration

The SOC stock (Mg ha^{-1}) for each soil depth (cm) was calculated on equivalent soil mass basis (ESM). To avoid bias due to treatment-induced differences in bulk density (BD in Mg m^{-3}), the "equivalent depth basis" correction *i.e.,* additional thickness (T_{add}) was computed based on the differences between soil mass and the equivalent soil mass and sub-superficial BD (Ellert and Bettany, 1995), and was added to the formula:

$$\text{TOC stock} = (\text{TOC concentration}) \times (\text{Soil depth} + T_{add}) \times \text{Bulk Density} \times 10000 \tag{4}$$

Carbon sequestration was calculated by subtracting the initial SOC stock from the final SOC stock:

$$Carbon\ sequestration\ (Mg\ ha^{-1}) = SOC_{\mathrm{final}} - SOC_{\mathrm{initial}} \tag{5}$$

The rate of sequestration or carbon sequestration potential (CSP) was calculated as:

$$CSP\ (Mg\ ha^{-1} year^{-1}) = \frac{(SOC_{\mathrm{final}} - SOC_{\mathrm{initial}})}{Number\ of\ years\ of\ experimentation} \tag{6}$$

2.6. Total C input to soil

Grain and straw/stover yields of maize, wheat and mungbean crops were recorded each year from the year of initiation of the experiment. Crop residue input on an annual basis was calculated accordingly. The average C contents of maize, wheat and mungbean residues were measured through Elementar® dry combustion analyzer. The cumulative annual C inputs over the years were thus estimated (Parihar et al., 2018).

2.7. Multivariate analysis and soil quality index

The principal component (PC) analysis was performed to screen minimum data set (MDS). The PCs having high eigen-values and variable with high loading score best represent the attributes of the system. We selected the PCs with eigen-value > 1 and those which described a minimum of 5% of cumulative variation. Again within each PC the variable with highest factor loading and those with 10% of the highest weight are retained in the MDS. To remove redundancy in variables in each PC, correlation approach was used (Andrews and Carroll, 2001). The variables in each PC having correlation coefficient > 0.75 between themselves were considered redundant and eliminated from MDS. In such case, only the variable with highest factor loading in each PC was retained. For development of SQI, the weightage of a variable was calculated as the ratio of percentage of the variation explained by the PC it belonged to, and the cumulative percent variation explained by all the PCs having eigen-value > 1. The score for the particular variable was computed by using more is better approach (Biswas et al., 2017). The soil quality index (SQI) was calculated as per the following equation:

$$\mathrm{SQI} = \sum\nolimits_{i=1}^{n} W_i \times S \tag{7}$$

where S = indicator score, W = PC weightage factor, i = variable number in MDS

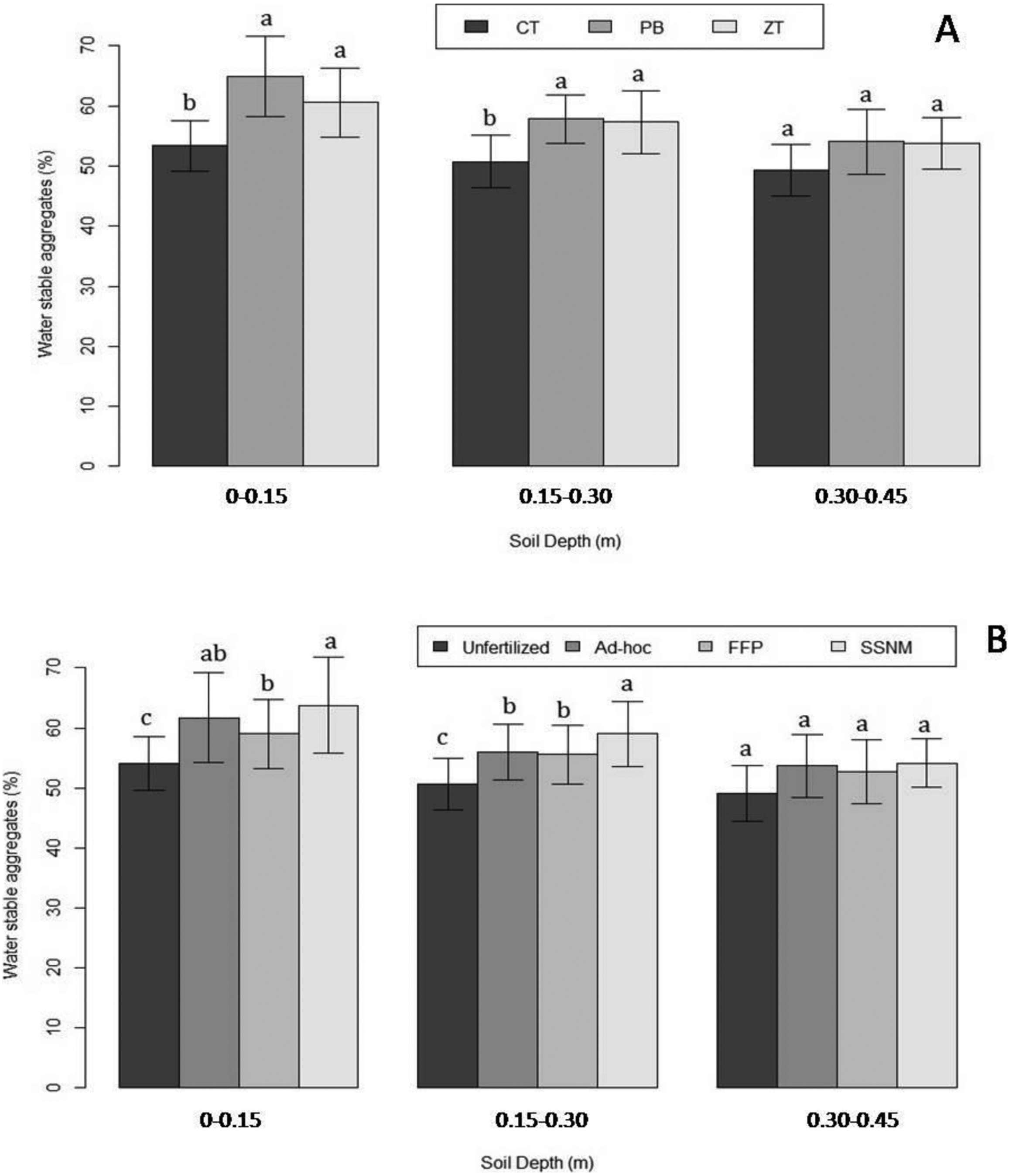

Fig. 1. Effect of tillage (A) and nutrient management (B) practices (after four years) on water stable aggregates (> 250 μm diameter) of a sandy loam soil under maize-wheat-mungbean system. The bars followed by a different letter within a depth are significantly different (at P < 0.05) according to least significant difference test. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, *Ad-hoc*: recommended dose of fertilizers, FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management. Error bars represents the standard deviation.

Further the system productivity was regressed on the computed SQI.

2.8. Statistical analysis

All data recorded for different soil properties and crop productivity were analysed by the agricolae package in R studio using sp.plot function for split plot design (Gomez and Gomez, 1984). If ANOVA was found significant, the LSD test was carried to know the significant difference between the mean of main and sub plot. Correlation analysis for soil biological (MBC, FDA, DHA, BGA, APA), chemical (SOC, Available N, Available P, Available K) and physical (WSA, MWD, HC, BD, PR) characteristics with SQI and MEY was performed using cor function. Plot function and ggplot2 package was used to draw the graphs. The prcomp() function was used to perform principal component analysis to select the minimum data set in R studio (R Core Team, 2019).

3. Results

3.1. Soil physical properties

There was no significant effect of tillage and nutrient management treatments on bulk density (BD) for the 0-0.70 m soil depths (Supplementary Fig. 1a and b). Different tillage practices had significant effect on penetration resistance (PR) at 0.10-0.50 m depths

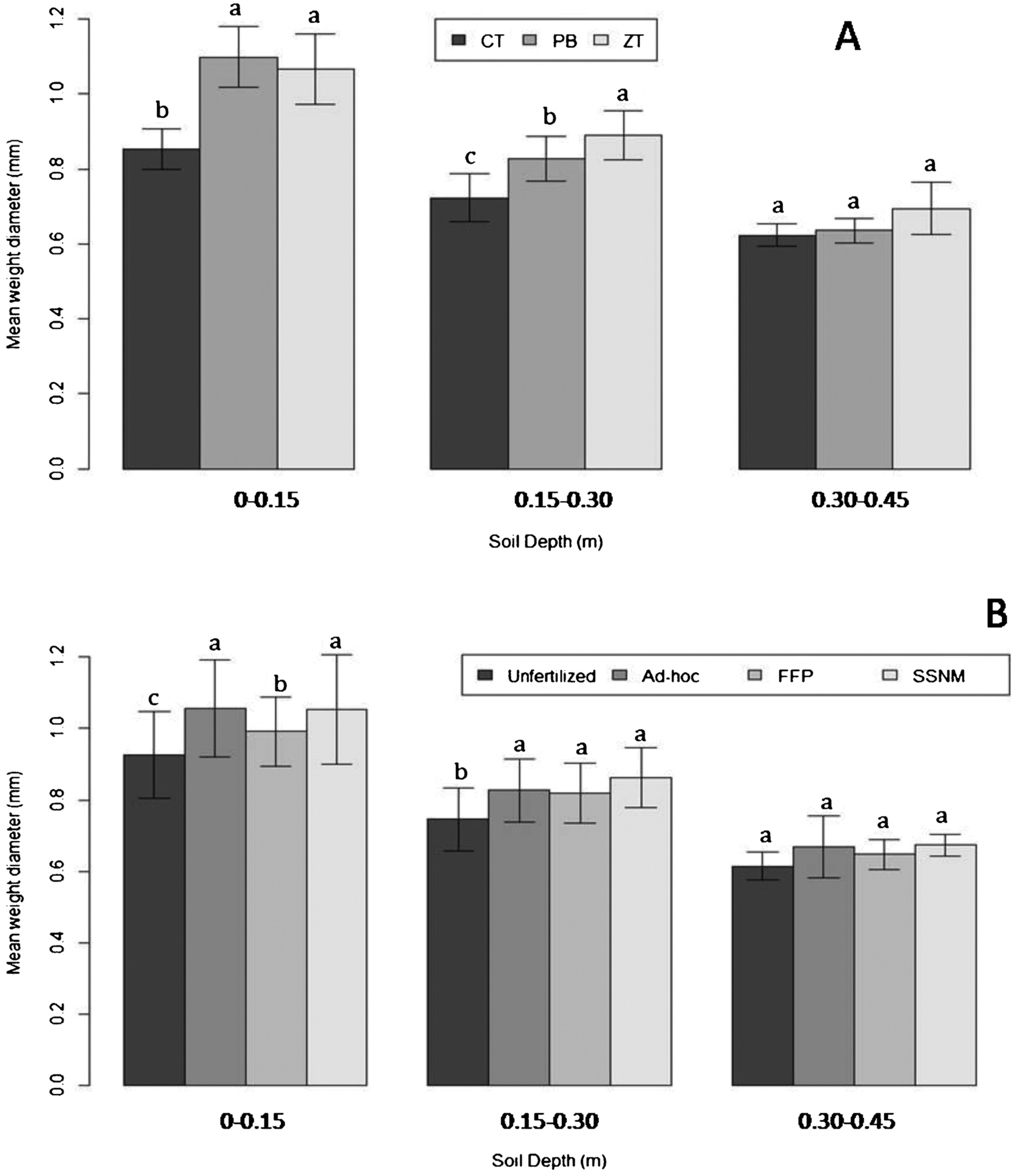

Fig. 2. Effect of tillage (A) and nutrient management (B) practices (after four years) on mean weight diameter of a sandy loam soil under maize-wheat-mungbean system. The bars followed by a different letter within a depth are significantly different (at $P < 0.05$) according to least significant difference test. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, *Ad-hoc*: recommended dose of fertilizers, FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management. Error bars represents the standard deviation.

only (Supplementary Fig. 2a and b, respectively). The PR was ~9 to 30% lower in PB and ZT compared with CT at the 0.10-0.50 m soil depth. The WSA (Fig. 1A), MWD (Fig. 2A) and K_{sat} (Fig. 3A) were significantly affected by ZT/PB practices in 0-0.15 and 0.15-0.30 m depths. The ZT and PB treatments recorded an increase in WSA (12–21%), MWD (14–29%), and K_{sat} (11–14%) compared with CT at the 0-0.15 m and 0.15-0.30 m soil depths, respectively. Similarly the WSA (Fig. 1B), MWD (Fig. 2B) and K_{sat} (Fig. 3B) at the 0–0.15 and 0.15–0.30 m soil depths in SSNM and *Ad-hoc* treatments were 10–18%, 11–16%, and 6–9% higher compared with unfertilized treatment, respectively, however the FFP was intermediate. There were no significant differences in the WSA ($P = 0.999$), MWD ($P = 0.882$) and K_{sat} ($P = 0.873$) at 0.30-0.45 m soil depth across tillage and nutrient management treatments. The tillage and nutrient management interaction effects were non-significant at all the soil depths for WSA, MWD and K_{sat} (data not presented).

3.2. Soil chemical properties

Irrespective of nutrient management options, PB and ZT registered significantly higher total SOC concentration in surface 0-0.15 m and 0.15-0.30 m soil layer, compared with CT (Table 2). On the other hand, among the nutrient management options, *Ad-hoc* and SSNM recorded significantly higher SOC in these soil layers compared with unfertilized and FFP plots. The tillage and nutrient management had significant ($P < 0.05$) interaction effect on SOC content of 0-0.15 m soil layer only

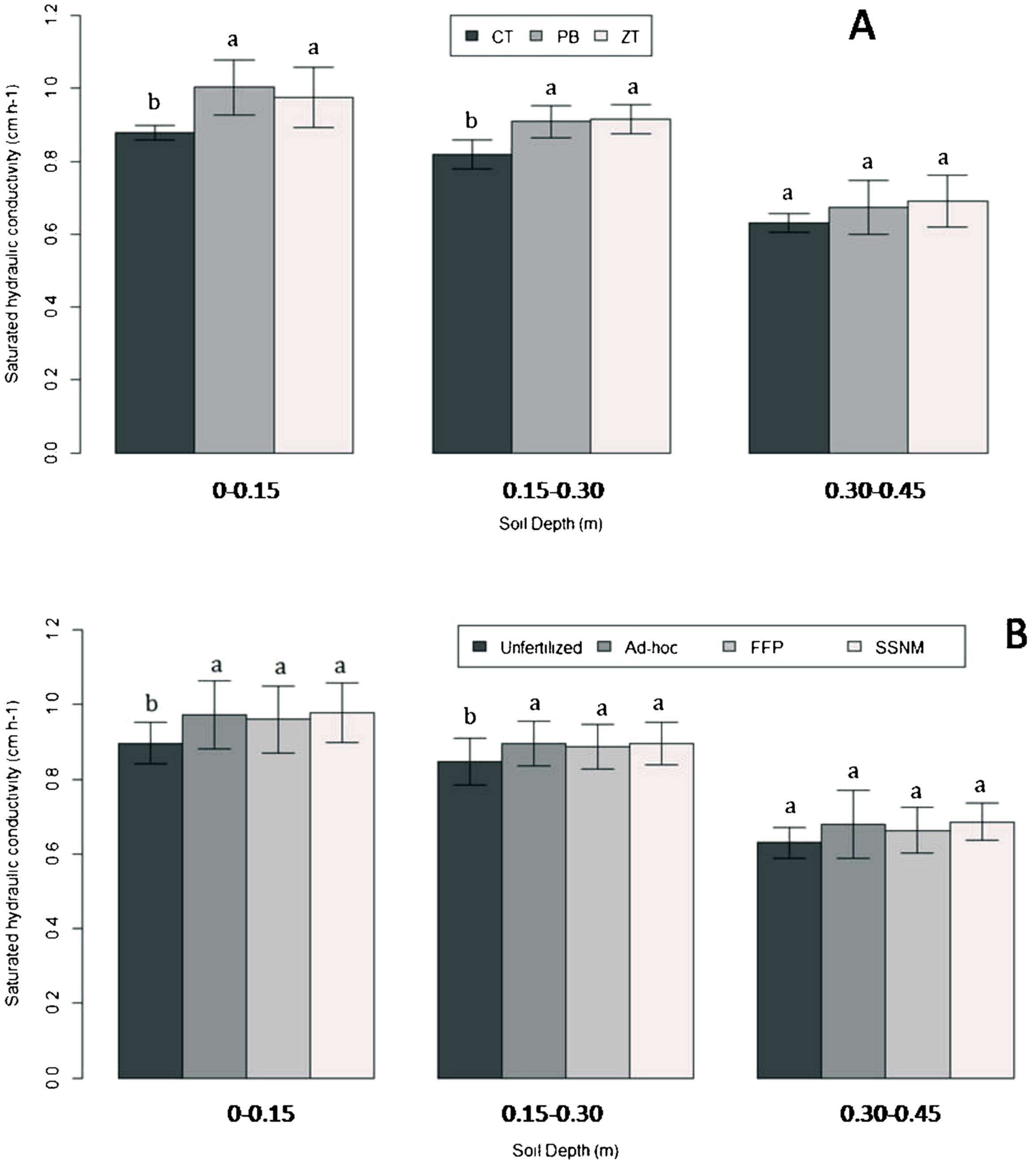

Fig. 3. Effect of tillage (A) and nutrient management (B) practices (after four years) on saturated hydraulic conductivity of a sandy loam soil under maize-wheat-mungbean system. The bars followed by a different letter within a depth are significantly different (at $P < 0.05$) according to least significant difference test. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, *Ad-hoc*: recommended dose of fertilizers, FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management. Error bars represents the standard deviation.

Table 2
Effect of tillage and nutrient management practices on total organic carbon content of a sandy loam soil after four years of maize-wheat-mungbean system.

Treatments*	Total soil organic carbon (g kg^{-1} of soil)		
	0-0.15 m	0.15-0.30 m	0.30-0.45 m
Tillage practices			
CT	5.11^{b}†	4.53^{b}	3.97^{a}
PB	6.18^{a}	5.24^{a}	4.11^{a}
ZT	6.05^{a}	5.32^{a}	4.20^{a}
Nutrient management			
Unfertilized	5.02^{b}	4.44^{b}	3.88^{a}
FFP	5.47^{b}	4.70^{b}	4.11^{a}
Ad-hoc	6.24^{a}	5.45^{a}	4.17^{a}
SSNM	6.40^{a}	5.54^{a}	4.22^{a}
P-value			
Tillage practices	0.0037	0.0052	0.3239
Nutrient management	< .0001	< .0001	0.0734
Tillage practices × Nutrient management	0.0008	0.7489	0.5058

* CT: Conventional tillage; PB: Permanent: Zero tillage; *Ad-hoc*: recommended dose of fertilizers FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management. †Values with in a column followed by the same letter are not significantly different at P ≤ 0.05.

(data not presented). However, the tillage and nutrient management interaction effect on SOC was not observed for 0.15-0.30 and 0.30-0.45 m soil layers. In 0-0.15 m soil depth, highest SOC content was found in PB-SSNM treatments and lowest SOC was in CT-Control. The PB-SSNM plots registered 44.1% higher SOC content as compared to CT-unfertilized for the above mentioned soil layer.

Treatments PB and ZT registered significantly higher amounts of available N, P, and K in 0-0.15 and 0.15-0.30 m soil layer, whereas there were no differences in N, P, or K availability at 0.30-0.45 m depth (Table 3). Similarly, nutrient management treatments also significantly affected the available N, P and K content at 0-0.30 m soil depth (Table 3), but not beyond. At 0-0.15 and 0.15-0.30 m depths, significantly higher available N (17–52%) and K (28–54%) were observed in SSNM and *Ad-hoc* compared to FFP and unfertilized treatments. Higher available N (14–21%) and P (41–42%) were also recorded in FFP compared to unfertilized treatment. However, available P was highest under SSNM at these depths, and the values were significantly higher than *Ad-hoc* treatments. The interaction of tillage and nutrient management was significant ($P < 0.05$) for available P at 0-0.15 and 0.15-0.30 m soil depths only (data not presented). The interaction effects were non-significant for available N and K at all the soil layers. The maximum available P content was recorded in PB-SSNM (27.7 kg ha^{-1}) and ZT-SSNM (21.8 kg ha^{-1}) treatments at 0-0.15 and 0.15-0.30 m, respectively. The lowest available P was recorded in CT-Control treatment for both soil depths.

3.3. Soil biological properties

The MBC and enzymatic activities were significantly enhanced under ZT and PB compared with CT. Irrespective of nutrient management the MBC was higher by 17% and 23% under PB and ZT, respectively in 0-0.30 m soil layer compared with CT. Under PB/ZT, the enzymatic activities *viz.*, DHA, FDA and βGA were 20–27% higher compared with CT treatments, whereas APA was improved by 8% and 10% upon adoption of PB and ZT, respectively in 0-0.30 m soil layer compared with CT (Table 4). On the other hand, the *Ad-hoc* and SSNM nutrient management strategies resulted in the highest levels of MBC and enzymatic activities. Values for MBC, FDA and βGA declined in the order SSNM = *Ad-hoc* > FFP > Control. The DHA declined in the order SSNM > *Ad-hoc* = FFP > Control. The APA was found ~11-13% higher under SSNM/*Ad-hoc* as compared with control plots. The interaction of tillage and nutrient management practices were non-significant ($P < 0.05$) for MBC and enzymatic activities (data not presented).

3.4. Crop productivity

Tillage and nutrient management practices had significant ($P < 0.05$) effect on maize-wheat-mungbean (MWMb) crop productivity. The grain yields of maize, wheat and mungbean were significantly higher under ZT and PB compared with CT. The increments in grain yields was varied from ~10% to 28% upon adoption of PB/ZT instead of CT (Supplementary Figs. 3a, 4a and 5a). The system productivity as measured in terms of maize equivalent yield (MEY) was highest in PB plots and lowest in CT plots. Plots under PB and ZT registered 20.3% and 17.2% higher 4-year pooled MEY compared to CT-Control, respectively. Irrespective of tillage regimes, grain/seed yields of maize, wheat and mungbean were significantly higher under fertilizer applied plots *viz.*, *Ad-hoc*, FFP and SSNM compared with unfertilized control plots (Supplementary Figs. 3b, 4b and 5b). The 4-year pooled MWMb system MEY was significantly higher under SSNM plots (13.7 Mg ha^{-1}) compared to other nutrient management plots (Fig. 4).

3.5. Soil quality index

For development of a unique SQI, physical, chemical and biological attributes of 0–30 cm layer of experimental soil was considered. Correlation analysis revealed significantly higher correlations ($P < 0.05$) between most of the soil attributes with system productivity

Table 3
Effect of tillage and nutrient management practices on available nutrients status of a sandy loam soil after four years of maize-wheat-mungbean system.

Treatments*	Available N (kg ha^{-1})			Available P (kg ha^{-1})			Available K (kg ha^{-1})		
	0-0.15 m	0.15-0.30 m	0.30-0.45 m	0-0.15 m	0.15-0.30 m	0.30-0.45 m	0-0.15 m	0.15-0.30 m	0.30-0.45 m
Tillage practices									
CT	169.1^{b}†	143.6^{b}	116.6^{a}	17.3^{b}	14.3^{b}	8.6^{a}	173.3^{b}	145.8^{b}	122.9^{a}
PB	200.1^{a}	166.3^{a}	123.1^{a}	23.7^{a}	17.4^{a}	8.9^{a}	203.4^{a}	164.2^{a}	131.6^{a}
ZT	194.1^{a}	171.0^{a}	127.8^{a}	22.2^{a}	18.0^{a}	9.4^{a}	198.7^{a}	167.5^{a}	133.2^{a}
Nutrient management									
Unfertilized	147.4^{c}	124.6^{c}	114.6^{a}	14.6^{d}	11.6^{c}	8.1^{a}	162.1^{b}	121.4^{b}	118.5^{a}
FFP	178.1^{b}	142.1^{b}	119.2^{a}	20.7^{c}	16.5^{b}	8.5^{a}	170.6^{b}	139.7^{b}	126.6^{a}
Ad-hoc	208.7^{a}	184.8^{a}	124.9^{a}	23.3^{b}	18.1^{b}	9.5^{a}	215.6^{a}	186.8^{a}	133.2^{a}
SSNM	216.9^{a}	189.7^{a}	131.4^{a}	25.6^{a}	19.9^{a}	9.8^{a}	218.8^{a}	188.8^{a}	138.7^{a}
P-value									
Tillage practices	0.0157	0.0109	0.1743	0.0038	0.0051	0.2438	0.0095	0.0292	0.0877
Nutrient management	< .0001	< .0001	0.0850	< .0001	< .0001	0.0594	< .0001	< .0001	0.0517
Tillage × Nutrient	0.4659	0.1257	0.8864	0.0013	0.0495	0.8628	0.9314	0.9202	0.1396

* CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, *Ad-hoc*: recommended dose of fertilizers, FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management. †Values with in a column followed by the same letter are not significantly different at P ≤ 0.05.

Table 4
Effect of tillage and nutrient management practices on microbial biomass and enzymatic activities of a sandy loam soil (0-0.30 m depth) after four years of maize-wheat-mungbean system.

Treatments*	MBC (μg C g^{-1} soil)	FDA (μg Fluorescein^{-1} soil hr^{-1})	Dehydrogenase (μg TPF g^{-1} soil 24 hr^{-1})	ß Glucosidase (μg p-NP g^{-1} soil 24 hr^{-1})	Alkaline Phosphatase (μg p-NP g^{-1} soil 24 hr^{-1})
Tillage practices					
CT	356.5^{b}†	0.488^{b}	28.7^{b}	1.837^{b}	41.0^{b}
PB	418.3^{a}	0.586^{a}	34.4^{a}	2.238^{a}	44.3^{ab}
ZT	439.6^{a}	0.594^{a}	35.7^{a}	2.334^{a}	45.3^{a}
Nutrient management					
Unfertilized	327.3^{c}	0.472^{c}	28.6^{c}	1.775^{c}	40.5^{c}
FFP	388.7^{b}	0.521^{b}	32.1^{b}	2.090^{b}	42.9^{bc}
Ad-hoc	440.3^{a}	0.605^{a}	34.3^{b}	2.281^{a}	45.0^{ab}
SSNM	462.8^{a}	0.627^{a}	36.8^{a}	2.399^{a}	45.6^{a}
P-value					
Tillage practices	0.0039	0.0049	0.0048	0.0027	0.0483
Nutrient management	< .0001	< .0001	< .0001	< .0001	0.0017
Tillage × Nutrient	0.3154	0.9145	0.9222	0.9987	0.2993

* MBC: microbial biomass carbon, FDA: activity of fluorescein diacetate, CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, *Ad-hoc*: recommended dose of fertilizers, FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management. †Values with in a column followed by the same letter are not significantly different at P ≤ 0.05.

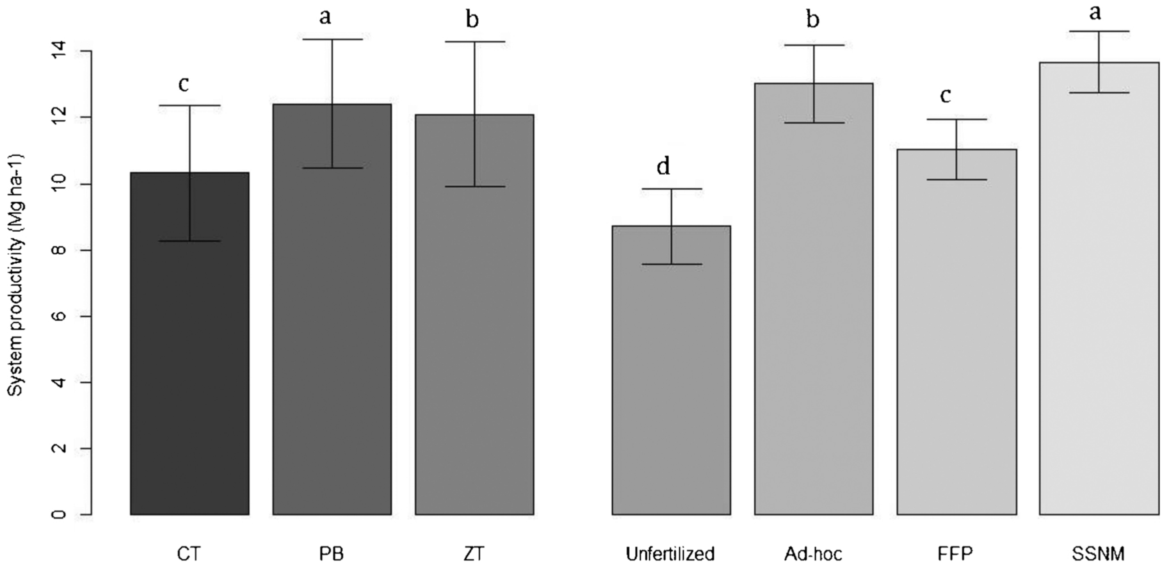

Fig. 4. Effect of tillage and nutrient management practices on 4-year mean system productivity (MEY) of maize-wheat-mungbean system. The bars followed by a different letter are significantly different (at P < 0.05) according to least significant difference test. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, *Ad-hoc*: recommended dose of fertilizers, FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management. MEY: Maize equivalent yield/system productivity. Error bars represents the standard deviation.

(MEY) (Fig. 5). These attributes were then chosen for PCA for creation of MDS. The PCA showed that 76.3% of the variance in data was explained by the first two principal components (PCs) (Table 5). Individually PC1 and PC2 explained 67.36% and 8.94% of the total variance in data. The MWD received highest factor loading weightage in PC1, and WSA, βGA, HC, available P, MBC, FDA and DHA were the other highly weighted attributes. These attributes had significantly higher correlations among themselves. Therefore, MWD was selected in MDS from PC1. The total SOC and available K received higher weightage in PC2 (Table 5). As these two parameters had low correlation (r = 0.401, P < 0.05) between them, both were retained for inclusion in MDS. The PCA screened indicators were normalized in a scale of 0 to 1 using linear scoring function. The weighted factors for PC1 and PC2 were 0.883 and 0.117. The following equation was developed as SQI:

SQI = 0.883 × MWD score + 0.117 × Total SOC score + 0.117 × Available K score (8)

The MDS components were validated through multiple regression equation developed between identified MDS indicators as independent variable and MEY as dependent variable. The following regression equation was developed, where MWD, total SOC and available K successfully contributed to explanation of the obtained yield (Eq. 9).

MEY = 11.04 × available K + 5358.1 × MWD + 16949 × TOC – 4729.6 R^2 = 0.86 (9)

The developed SQI was validated against 5-year pooled MEY (Fig. 6), which yielded scattered plot and linear trend line with R^2 value of 0.727. The SQI was significantly higher under PB/ZT compared with CT. On the other hand, nutrient management affected SQI in the following trend: SSNM > *Ad-hoc* = FFP > Unfertilized. The plots under SSNM registered 5.3% and 19.3% higher values of SQI compared with that of FFP and unfertilized plots (Fig. 7). The interaction effect of tillage and nutrient management was not significant on SQI (data not presented).

3.6. Carbon sequestration

The interaction effect of tillage and nutrient management practices was significant on total SOC only at surface 0-0.15 m layer. The treatment PB-SSNM had the highest SOC stock. Treatment

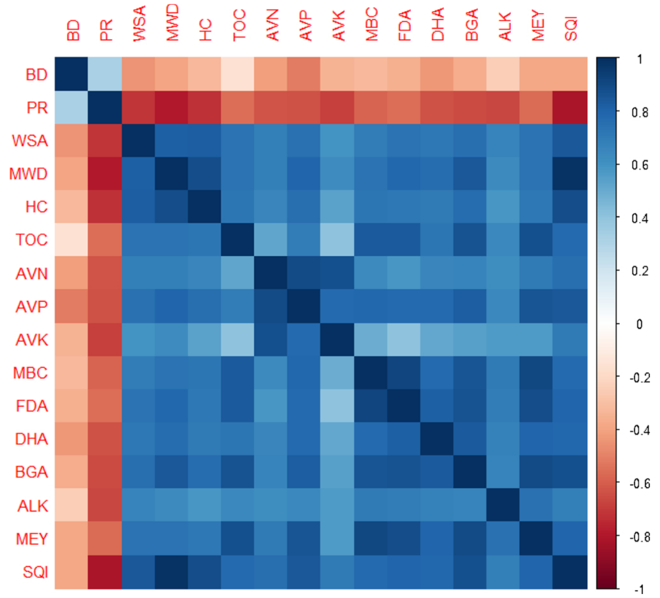

Fig. 5. Pearson correlation coefficient values (r) between various soil quality attributes of 0-0.3 m soil layer and maize equivalent yield (MEY).

Table 5
Principal component analysis of significant soil attributes of 0-0.30 m layer after four years of maize-wheat-mungbean system.

Soil attributes	PC1	PC2
Eigen value	3.07	1.12
Percentage of variance	67.36	8.94
Cumulative variance percentage	67.36	76.30
Eigen vectors		
Bulk density	−0.149	−0.416
Penetration resistance	−0.255	−0.148
Total water stable aggregate	0.286	0.064
Mean weight diameter	**0.299**	0.061
Hydraulic conductivity	0.276	0.001
Total soil organic C	0.262	**−0.430**
Available N	0.268	0.360
Available P	0.297	0.196
Available K	0.230	**0.464**
Microbial biomass C	0.285	−0.245
Fluorescein diacetate activity	0.284	−0.309
Dehydrogenase	0.279	−0.126
ß Glucosidase	0.297	−0.178
Alkaline Phosphatase	0.242	−0.163

combinations of PB/ZT along with *Ad-hoc*/SSNM recommendations had similar SOC stocks, with the values being 39–46% higher compared with CT-unfertilized (Fig. 8). The average C content of maize, wheat and mungbean residues were 41.4%, 38.7% and 42.5%, respectively. The annual C input to soil varied from 2.14 Mg ha^{-1} year^{-1} under CT-unfertilized to 3.41 Mg ha^{-1} year^{-1} under PB-SSNM (Fig. 8). The annual C inputs under CT-SSNM, PB-FFP, PB-*Ad-hoc*, PB-SSNM, ZT-FFP, ZT-*Ad-hoc* and ZT-SSNM were statistically similar. The CT-unfertilized plots registered least rate of annual C-sequestration (0.03 Mg ha^{-1} year^{-1}), which barely maintained the initial level of SOC. Despite significantly higher annual C input under CT-*Ad-hoc* (2.96 Mg ha^{-1} year^{-1}) and CT-SSNM (3.18 Mg ha^{-1} year^{-1}) than CT-unfertilized, annual C-sequestration under these plots was comparable. All the SSNM and *Ad-hoc* plots registered significantly higher annual C input compared with unfertilized plots. Low C input in PB-unfertilized and ZT-unfertilized plots resulted in very less annual C sequestration (0.05 Mg ha^{-1} year^{-1}), comparable to CT-unfertilized (Fig. 8). Highest annual C-sequestration registered under PB-SSNM (1.15 Mg ha^{-1} year^{-1}), followed by ZT-SSNM (1.10 Mg ha^{-1} year^{-1}), PB-*Ad-hoc* (1.06 Mg ha^{-1} year^{-1}) and ZT-*Ad-hoc* (0.96 Mg ha^{-1} year^{-1}) (Fig. 8). The plots under FFP, both under residue retention or incorporation (CT, PB and ZT), registered significant less C-sequestration compared with these above mentioned treatments, values often being statistically similar with that under unfertilized plots.

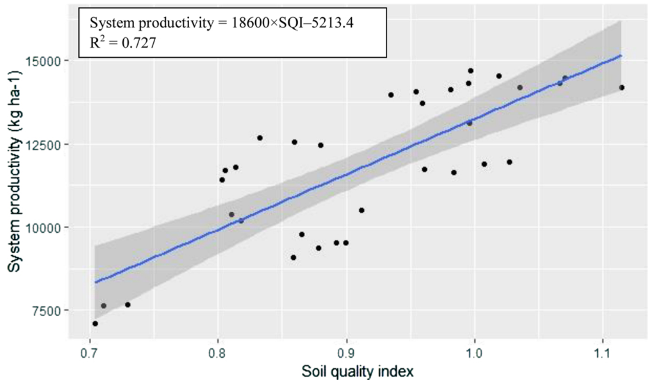

Fig. 6. Relationship between soil quality index with system productivity in terms of maize equivalent yield (MEY).

4. Discussion

4.1. Effect of tillage and residue management on nutrient availability, soil quality, carbon sequestration and crop productivity

Reduction in tillage under PB/ZT provided enough turnover time to form stable soil aggregates (Six et al., 2002). A reduction in the disruption of soil macroaggregates under PB/ZT causes slower macroaggregate turnover (Six et al., 1999, 2002), resulting in higher abundance of macroaggregates, thus causing higher WSA and MWD at 0-0.30 m soil depth (Figs. 1A and 2 A). Improved aggregation leads to continuity of soil pores and pore size distribution facilitating water infiltration resulting in greater K_{sat} (Fig. 3A) (Mishra et al., 2015). The improvement in soil physical properties in ZT and PB treatments are consistent with results reported elsewhere (Li et al., 2011; Dey et al., 2016, 2020; Bhattacharyya et al., 2019). By virtue of improved aggregation, CA-based systems provided better soil physical environment, or in other words enhanced protection for soil organic matter (SOM) (Bhattacharyya et al., 2019). Adoption of PB/ZT stabilized the SOC, whereas, in CT plot, despite similar amount of annual crop residue input, the SOC is not stable (Table 2 and Fig. 8). Typically fresh crop residues act as a continuous source of labile SOM in these plots, and they get encapsulated in the process of macroaggregate formation. Under CA-based reduced tillage, these SOC gets enough time to condense, undergo bio-chemical transformation towards chemical recalcitrance (Jat et al., 2019). Crop residues placed over surface decompose 1.5 to 3 times slower than the incorporated residues (Gupta and Ladha, 2010). An array of international literature support this finding in many different soil and climatic conditions, across the globe (Six et al., 2002; Dey et al., 2016, 2020; Jat et al., 2019b; Parihar et al., 2019). Parihar et al. (2019) reported enhanced stability along with low temperature sensitivity of SOC under residue retained PB/ZT plots, compared with residue incorporation in CT plots. Surface-retained residues protect the soil from raindrop impact, leading to less erosion, in turn enhancing stability of SOC (Dey et al., 2018). A stable thermal regime prevails under PB/ZT plots due to residue mulch on soil surface, which do not favour high rate of SOM decomposition. This is responsible for of huge build-up of total SOC over initial values under ZT/PB. Therefore, these CA-based plots registered significantly higher C sequestration potential in the long-run as compared with CT plots (Fig. 8).

Lower rate of SOM decomposition under PB/ZT leads to not only improved SOC, but also other nutrients associated with SOM. Enhanced

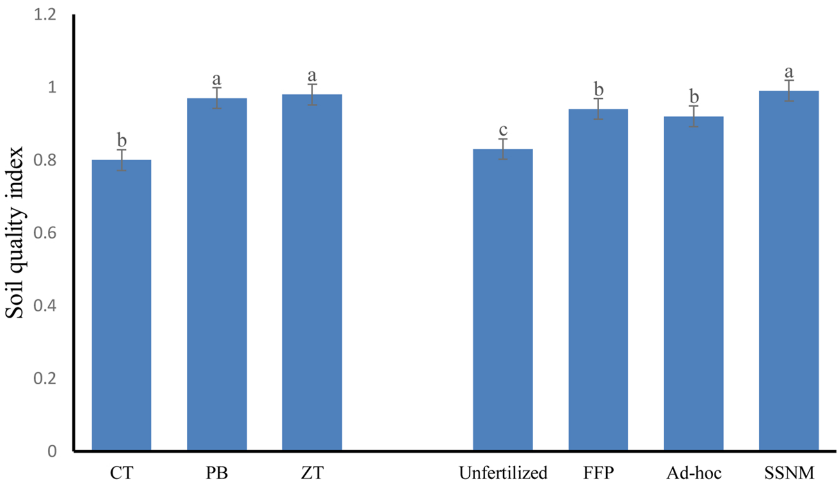

Fig. 7. Effect of tillage and nutrient management practices on soil quality index of 0–30 cm layer of maize-wheat-mungbean system. The bars followed by a different letter are significantly different (at $P < 0.05$) according to least significant difference test. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, *Ad-hoc*: recommended dose of fertilizers, FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management.

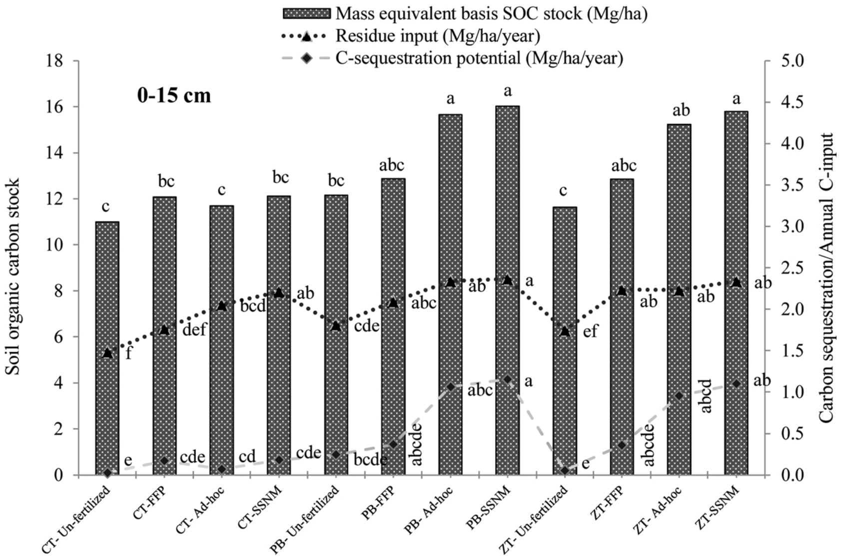

Fig. 8. Interactive effect of tillage and nutrient management practices on total soil organic carbon stock (on an equivalent mass basis), C-sequestration potential and annual C-inputs at 0-0.15 m soil depths after 4-year of experimentation under maize-wheat-mungbean system. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, *Ad-hoc*: recommended dose of fertilizers, FFP:Farmer fertilizer practices; SSNM: Site specific nutrient management. †bar followed by the same letter within a depth are not significantly different at $P \leq 0.05$.

SOM under PB/ZT acts as a buffer for N, P, K and other nutrients, thus replenishing the plant available pools against plant uptake and losses from soil (Table 3). Periodical addition of cereal residues with high C:N ratio along with *mungbean* residues with low C:N ratio stabilises the mineralization/immobilisation cycle of SOM (Meena et al., 2018). Tillage reduction stabilises soil N in intra-aggregate spaces (Bhattacharyya et al., 2019; Dey et al. (2016) reported a 9% increase of total N under CA-based rice-wheat system as compared to CT. Lower N mineralization and leaching losses were also reported under residue retention as compared with residue incorporation practices (Govaerts et al., 2007).

Abundance of SOM under CA-based plots prohibited adsorption, precipitation and fixation reaction of applied soluble P, by virtue of complexing/coating the adsorption surfaces and formation of soluble phosphate-humate complexes which enhances the lability and availability of soil P (Table 3) (Weil and Brady, 2016). Deep rooted crops can ‘mine’ the deep layer P and then deposit on surface in terms of crop residue. Under CT, remixing of surface applied residue is there, thus distributing the soil P again throughout the soil layers (Kumawat et al., 2018). On the contrary, PB/ZT accumulated labile pools of P in the surface soil, increasing P availability of surface soil (Table 3). Minimal soil mixing of applied P ensured less chances of fixation. On the other hand, crop residue left at the surface is a great source of organic P, which is mineralized overtime and in synchrony with crop needs, improves the P bioavailability (Table 3). Under ZT/PB, higher amounts of residue might also have contributed to soil non-exchangeable K, improving the buffering capacity of soil and in turn enhancing bioavailability of soil K (Table 3) (Meena et al., 2018). Govaerts et al. (2007) reported 1.65 and 1.43 times higher K concentrations in the 0–5 cm and 5–20 cm layers, respectively, on PB as compared with ZT. The cereal residue, especially wheat residues were rich in K, by virtue of high K uptake. When retained, they have added significant amount of K to the soil. Therefore, better soil aggregation *vis-à-vis* protection of aggregate associated SOM reduced mineralization of N, P and K from these aggregate associated fractions, further reducing losses from soil and ultimately enhancing availability of soil N, P and K (Table 3).

In the present MWMb system, the retained crop residue of mixed C:N ratio, was a perfect substrate for proliferation of microbial biomass and diversity. Under PB and ZT, surface retention of crop residue promoted microbial growth and diversity in the top 0–30 cm soil layer (Table 4). Well aggregated soil structure, improved K_{sat}, MWD and improved hydro-thermal conditions of surface soils under PB/ZT provided a suitable niche for a myriad of soil microorganisms to flourish (Spedding et al., 2004). Under CT plots, comparatively lesser availability of fresh crop residue on top soil due to intensive soil mixing through tillage operations reduces the soil biological activities (Dey et al., 2016). As a result, PB/ZT expressed significant positive effects on MBC and enzymatic activities (Table 4), which are consistent with several previous results (Spedding et al., 2004; Liu et al., 2014; Dey et al., 2016).

The variation in tillage and residue management had a great impact on soil aggregation process. Good aggregated soil often represents a healthy soil. The MWD being an indicator for soil aggregation status, is an apt SQI indicator, and properly represents soil physical health. The MWD registered significant positive correlations with soil chemical and biological quality indicators (Fig. 5). A good aggregation status of soil often promoted enhanced bio-availability of nutrients, diverse microbial population, optimum hydrothermal regime for plant and microbial growth, greater C sequestration potential *etc*. Along with MWD, total SOC and available K were selected as a soil health indicator. The experimental soils belonged to low C tropics of IGP, which makes improvement of total SOC a mandatory step to be followed for restoration and improvement of soil health, and improve the sustainability of the intensive cropping system. Being a central element to soil quality, total SOC registered significantly higher correlations with almost all other soil parameters, MEY and SQI (Fig. 5) (Sharma et al., 2016; Biswas et al., 2017). As evident from our research findings, PB/ZT significantly and positively affected all these parameters. Therefore, the PB/ZT registered significantly higher value of SQI compared with CT (Fig. 7).

The results regarding crop productivity clearly showed positive effects of PB and ZT, and residue retention on MEY (Fig. 4). In the MWMb system, yield of all the crops (maize, wheat and mungbean) enhanced over time through adoption of improved tillage practices. Abundant supply of crop residues as surface mulch helped in controlling weed, moderation of soil temperature, reduction in evaporation loss of soil water and improvement in soil biological activity. An improved soil health under these ZT/PB plots resulted higher crop production and over-all system productivity (Parihar et al., 2016; Parihar et al., 2017a; Parihar et al., 2017b). Our results corroborate with earlier studies from the same site and from other sites of South Asia which registered higher crop yields under ZT and PB compared to CT in maize-wheat systems (Gathala et al., 2013; Parihar et al., 2017a, b).

4.2. *Effect of nutrient management on nutrient availability, soil quality, carbon sequestration and crop productivity*

Application of nutrients enhanced soil physical parameters, compared with unfertilized plots (Figs. 1B, 2 B and 3 B). Crop demand based nutrient application through SSNM on CA-based plots, resulted in better utilisation and assimilation of applied nutrients, which in turn, promoted crop biomass production, both above and below ground (Sapkota et al., 2014; Parihar et al., 2017b). Reduction in tillage and optimal nutrient application had a positive effect on crop yields *vis-à-vis* crop biomass. Parihar et al. (2017a) also reported higher system yield in SSNM treatment compared to FFP, which might be due to optimum supply of nutrients as per crop demand and indigenous soil nutrient supplying capacity. As a result, the plots receiving nutrient according to *Ad-hoc* or SSNM under zero-till regimes (PB and ZT), generated high amount of fresh crop residues which were retained on surface instead of incorporation under CT. The MWMb system ensured residue of varying C:N ratio, different lability and a wide array of substrates for building up of SOM. Thus, the SSNM ensured both quantity and quality of annual C input to the soil under CA (Fig. 8), in turn improving soil aggregation, structure, WSA, MWD, K_{sat} *etc*. (Figs. 1B, 2 B and 3 B) (Bandyopadhyay et al., 2010). Balanced nutrient management helped to achieve the potential of CA to enhance soil physical properties to full extent. Better soil aggregation under SSNM helped in stabilisation of SOM in intra-aggregate spaces. Significant and positive correlation of SOC with soil physical properties like WSA ($r = 0.617$; $p = 0.003$), MWD ($r = 0.530$; $p = 0.007$) and HC ($r = 0.561$; $p = 0.005$) further strengthen this inference (Fig. 5). Therefore, SSNM or *Ad-hoc* based nutrient application promoted SOC stabilisation, thus enhancing SOC concentration in surface soil (Table 2), and over-all C-sequestration potential under CA (Fig. 8). Greater aggregation, enhanced intra-aggregate protection of associated SOC under PB/ZT enhanced the C-sequestration under *Ad-hoc* or SSNM fertilization regime (Six et al., 2002; Dey et al., 2016). On the other hand, lower crop yields were obtained under unfertilized control plots (Fig. 4) resulting in less incorporation/retention of crop biomass in soil, in turn registering least rate of annual C-sequestration.

Under Nutrient expert-based SSNM applications, efficient use of N, P and K fertilisers were promoted, synchronising crop demand and nutrient supply (Satyanarayana et al., 2013). In contention with earlier reports, our results also showed higher amounts of available N, P and K under efficient nutrient management practiced in SSNM plots (Satyanarayana et al., 2013; Meena et al., 2018) (Table 3). Higher abundance of substrates under *Ad-hoc*/SSNM plots results in an increase in microbial biomass and corresponding enzyme activities (Table 4) (Spedding et al., 2004). Better soil aggregation with enhanced K_{sat} (Figs. 1–4) under *Ad-hoc*/SSNM mediated the creation of favourable conditions for microbial growth in these plots. The combination of strong correlations between SOC and MBC, and MBC and DHA (indicative of general organic matter oxidation and microbial respiration) suggests that increased inputs of exogenous carbon (*i.e.,* plant residue) enhanced soil biological activity under PB/ZT and SSNM/*Ad-hoc* plots (Fig. 5). Higher crop residue or exogenous C input (Fig. 8), synchronisation of nutrient supply with crop demand, and enhanced microbial biomass and enzymatic activity (Table 4) are likely the primary mechanism driving short-term increases in nutrient availability under SSNM/*Ad-hoc* plots.

The nutrient management options in CA greatly impacted biomass production, and in turn C-input to soil. The SSNM/*Ad-hoc* plots under CA registered a well –aggregated soil, having higher values of MWD and SOC. The nutrient management options clearly manifested their effect on these two soil parameters, making these apt SQI indicators. These two SQI indicators represented soil physical and chemical health, respectively, and were highly correlated with other soil physical, chemical and biological parameters. On the other hand, cereal residues having higher K concentration supply K to soil through decomposition of crop stubbles/residue in CA (Meena et al., 2018). Thus, soil K supply was synchronized with crop demand under SSNM-based practices in the CA plots. Available K was selected as a SQI indicator by virtue of these profound effects of tillage, residue and nutrient management on it. The MWD, SOC and available K had significant correlation with SQI and MEY (Fig. 5). The SSNM plots, by virtue of enhancement of different soil properties, registered highest value of SQI (Fig. 7). The highest value of MEY under SSNM plots (Fig. 4), were in strong agreement with the SQI values under this system.

5. Conclusions

Results indicated that implementation of CA-based practices that include reduced tillage and precise nutrient management strategies can rapidly improve soil fertility, quality and C-sequestration potential as well as crop productivity in sandy loam soils of the NW-IGP, therefore proving the hypotheses. The CA reported to achieve annual C-sequestration rate as high as ~ 1.15 Mg ha^{-1} year^{-1} under PB-SSNM, which indicated better stabilisation of SOC under CA-based precision nutrient management. The study proves the superiority of SSNM-based CA over conventional practices through a multi-factorial approach, and also substantiates the fact that CA-specific nutrient management protocols are essential to utilise the full benefit of CA over conventional practices. The nutrient management should be considered as the fourth component of CA along with tillage, crop residue and crop rotation management. In current scenario, CA, if managed well through SSNM protocols presents a win-win situation in the intensively cropped (3 crops a year) agriculture of IGP. First, better crop productivity is achieved, which is critical to nations food security. Second, soil health is retained or rather improved which ensures sustainability of the production system. Third, under CA soil C-sequestration potential is enhanced so it can be prompted for better soil health. All three outcomes from the present study will be the key to achieve the sustainable development goals.

Declaration of Competing Interest

There is no conflict of interest among the authors.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2020.104653.

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