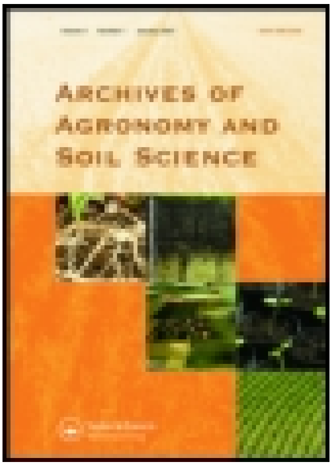

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Combined effect of tillage and organic fertilization on soil quality key indicators and indices in alluvial soils of Indo-Gangetic Plains under rainfed maize–wheat system

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Inceptisols in the submountainous region of Indo-Gangetic Plains in India are known as low productive areas due to several constraints like decline in soil organic matter and fertility, deterioration of soil physical and biological properties. The present study was conducted with tillage as main treatments and integrated nutrient management as subtreatments to improve soil quality and to identify the key indicators of soil quality after 5 years of experimentation in maize–wheat cropping system at Ballowal Saunkhri. Conventional tillage (CT) + interculture (IC) maintained significantly higher soil quality indices (SQI) of 1.12 which was at par with 50% CT + IC + chemical weed control (CWC) (1.08). Application of nitrogen (N) through 50% (organic) + 50% (inorganic) maintained higher soil quality with SQI of 1.10 followed by application of 100% N through organics (1.08). The results indicated that reduction in the intensity of tillage to 50% with interculture practices and combined use of organic and inorganic fertilizers maintained higher soil quality in these degraded Inceptisols. The methods of principal component analysis and computation of SQI adopted will be highly useful to future researchers, land managers, and students at locations across the world having similar climatic and edaphic conditions.

Keywords: soil quality; key indicators; maize–wheat; Inceptisols; conjunctive nutrient management

Introduction

Alluvial soils (mostly Inceptisols) occupy 95.8 million hectares or 29.13% of total geographical area of India. They are spread throughout the Indo-Gangetic Plain and along the country's major rivers (especially in deltas along the east coast). These soils are agriculturally very important and contribute significantly toward food production within the country. However, Inceptisols in the submountainous region of Punjab, where the primary crops are rainfed maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.), have shown decreased productivity due to several soil-related constraints (Pal et al. 2009). Manna et al. (2006) reported that yield decrease in these soils could be primarily attributed to a gradual depletion of nutrients, decreased soil organic matter (SOM) content, and structural degradation. Several other authors reported that, in general, accelerated depletion of micronutrient and

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secondary nutrient, intensive cultivation using high analysis inorganic fertilizers, decreased use of organic manures, and virtually no recycling of crop residue decreased the productivity of crops in rainfed regions (Sharma et al. 2004; Sharma & Chaudhary 2007). Suri (2007) emphasized that such degradative effects are more pronounced in stressed tropical and subtropical environments resulting in decline in productivity.

Increasing the SOM in rainfed regions is quite difficult and can only be achieved if application of organic inputs (farm yard manure (FYM), compost, poultry manure, green manuring, etc.) exceed the decomposition rates (Singh et al. 2004). This supported earlier studies conducted by Parr et al. (1990) which focused on recycling on-farm wastes to maintain or improve fertility of the soil as well as by Lal (1993) who emphasized that intensive tillage can lead to a range of degradative processes. Singh and Kaur (2012) reported several agricultural problems associated with current rice (*Oryza sativa* L.)–wheat production system in the Indo-Gangetic Plains. These include reduced SOM, depleted water resources, lower water quality, increased ground water pollution, reduced productivity, higher production costs, and greater environmental pollution. As a result, sustainability of the rice–wheat system as currently practiced is under great threat. Therefore, to achieve higher sustainable productivity, efforts must be focused on reversing soil resource degradation by the way of reducing tillage intensity, recycling of crop residues, and returning organic materials to the soil. Several authors have stressed that by adopting conservation tillage, and recycling of organic materials soil quality can be improved thus resulting in greater SOM, reduced erosion, increased infiltration, increased water stable aggregates, and greater microbial biomass carbon when compared to conventional soil management practices and tillage systems.

Until the late 1980s and early 1990s, the concept of soil quality focused primarily on soil fertility from the view point of a production agronomist. Gradually, the focus changed to yield and chemical properties (Malhi et al. 2000; Noble & Hurney 2000), soil fertility and yield (Mohammad & Mohammad 1999), and yield alone (Suresh et al. 1999; Subbarao et al. 2000), physical properties (Unger et al. 1998), carbon pools (Campbell et al. 1998), chemical soil quality (Eck & Stewart 1998), etc. To quantify the long-term management effects on the soil function, the soil quality assessment approach required a paradigm shift (Dalal & Moloney 2000; Andrews & Carroll 2001). Doran and Parkin (1994) were among the first which defined soil quality as the 'capacity of the soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health'. Several authors have discussed how soil quality can be inferred by measuring changes in attributes of soil or ecosystem, referred to as indicators. These indicators may directly monitor the soil, or the outcomes influenced by the soil, such as increased biomass, improved water use efficiency, and better aeration.

Soil quality indicators can also be used to evaluate sustainability of land-use and soil management practices in agro ecosystems (Shukla et al. 2006). Dalal and Moloney (2000) reported that indicators which directly monitor soil quality could be grouped in visual, chemical, physical, or biological categories. Mairura et al. (2007) reported the integration of scientific and farmer evaluations of soil quality and emphasized the indicators such as crop yield and performance, soil color and texture, which distinguished between productive and nonproductive soils. Parr et al. (1992) suggested that increased infiltration, aeration, macropores, aggregate distribution and their stability, SOM, bulk density (BD), soil resistance, erosion, and nutrient runoff are important indicators for improved soil quality. Total soil nitrogen (N), available phosphorus (P), dehydrogenase activity (DHA), and mean weight diameter (MWD) of soil aggregates were identified as the key indicators for alluvial soils (Chaudhury et al. 2005). Assessment of soil-test properties from time to time has also been emphasized for evaluating the chemical aspects of soil quality (Arshad & Coen 1992; Karlen et al. 1992). Wang and Gong (1998) and Shukla et al. (2006) reported that the indicators used or selected by different researchers in different regions may not be the same because soil quality assessment is purpose and site-specific.

Doran and Parkin (1996) and Doran et al. (1996) cautioned that in selecting indicators, it is important to ensure that they: (1) correlate well with natural processes in the ecosystem; (2) integrate soil physical, chemical, and biological properties and processes, and serve as basic inputs required for estimation of soil properties or functions which are more difficult to measure directly; (3) are relatively easy to use under field conditions, so that both specialists and producers can use them to assess soil quality; (4) are sensitive to changes in management and climate; and (5) are components of existing soil databases wherever possible.

After identification, combining the indicators in a meaningful way to a single value index may assess soil quality more precisely (Jaenicke & Lengnick 1999; Bucher 2002). This would help in measuring the level of improving or declining soil condition (Wienhold et al. 2004). A valid soil quality indicator would also help in interpretation of data from different soil measurements and show whether the management and land-use are having the desired results for productivity, environmental protection, and health (Granatstein & Bezdicek 1992). Most of the systematic research efforts on the assessment of soil quality have been done in temperate regions (Hussain et al. 1999; Andrews et al. 2002; Shukla et al. 2006). The information is much more limited for fragile, tropical agro-ecosystems (Palm et al. 1996; Ericksen & McSweeney 1999), which are prone to deterioration of land, soil, and water resources. Some research initiatives have been made on systematic assessment of soil quality on the Indian subcontinent in (1) a semi-arid tropical Alfisol (Sharma et al. 2005), (2) irrigated Inceptisols (Masto et al. 2007), (3) an irrigated rice–wheat system on Vertisols (Mohanty et al. 2007), and (4) the lowlands of Assam under a rice-based system (Singh 2007). In most of those studies, a wide spectrum of methods and varying sets of indicators were used under irrigated conditions with high cropping intensities and high levels of management.

As previously stated, maize and wheat are two important rainfed crops which are grown in rotation on rainfed Inceptisols in Punjab. The current low yields for these two crops have been attributed to several soil-related productivity constraints including low organic matter and fertility, poor physical and biological soil quality, and suboptimal soil functions associated with those conditions (AICRPDA 2003). To address this problem, our goal was to develop some appropriate tillage practices and strategies for increasing SOM so that soil quality and related soil functions could be improved.

Therefore, our objectives were to (1) identify soil quality key indicators for submountainous Inceptisols of Indo-Gangetic Plains, Punjab; (2) assess long-term effects of current soil management practices on these indicators; (3) identify improved soil management practices; and (4) rank those practices using a soil quality index approach with regard to their impact on rainfed maize and wheat production systems.

Materials and methods

Experimental design

The study was conducted at Hoshiarpur Centre of All India Coordinated Research Project for Dryland Agriculture (AICRPDA), in the Punjab region of India which is geographically located between 31° 6′ 5″ N latitude, 76° 23′ 26″ E longitude, and at an altitude of 346 m. The experiment was started during the *kharif* (June to September) season of 2000 with nine treatment combinations consisting of three tillage practices: (1) conventional tillage (CT) with always two ploughings, preparatory cultivations, and plankings along with interculture (IC) (weeding with hand hoe in maize and manual weeding in wheat), (2) 50% CT with always one ploughing, preparatory cultivation, and planking plus IC, and (3) 50% CT + IC + chemical weed control (CWC) as main plots and three N sources: (1) 100% of the recommended N through organic source (FYM), (2) 50% of the recommended N through organic source + 50% through inorganic sources, and (3) 100% of the recommended N through inorganic sources) as subplots (48 m^2), in a split-plot design with three replications each year. The nine treatment combinations will be referred to as:

T1 = CT + IC + 100% N (organic source/FYM),
T2 = CT + IC + 50% N (organic) + 50% inorganic source),
T3 = CT + IC + 100% N (inorganic source),
T4 = 50% CT + IC + 100% N (organic source/FYM),
T5 = 50% CT + IC + 50% N (organic) + 50% N (inorganic source),
T6 = 50% CT + IC + 100% N (inorganic source)
T7 = 50% CT + IC + CWC + 100% N (organic source/FYM),
T8 = 50% CT + IC + CWC + 50% N (organic) + 50% N (inorganic source), and
T9 = 50% CT + IC + CWC + 100% N (inorganic source).

Each treatment was applied to both crops (maize and wheat) every year. In addition to the treatments, standard agronomic practices for the region were used for the maize (cultivar Prakash hybrid) and wheat (cultivar PBW 175) rotation. The normal recommended doses of fertilizers are 80 kg N (through urea), 40 kg P_2O_5 (through single super phosphate), and 20 K_2O kg ha^{-1} (through muriate of potash) for maize and 80 kg N, 40 P_2O_5, and 25 K_2O kg ha^{-1} for wheat. Entire quantity of P and potassium (K) and half dose of N (depending on the source as per treatments) were drilled basally. Remaining half N was top-dressed 30 days after sowing (DAS) in all the treatment plots. The composition of the organic source of nutrients (FYM) was: 6.0 g kg^{-1} N and 3.2 g kg^{-1} P. The amount of FYM added by spreading for 100% and 50% organic N was 12 and 6 Mg ha^{-1}, respectively. Intercultural operations as hand hoeing at 20–25 DAS was done to keep the weeds under check. In CWC treatments, preemergence application of atrazine at 1.25 kg ha^{-1} was done within 2 days of sowing. Maize crop was always sown during the last week of June and was harvested in first week of October. Wheat crop was always sown in first week of November and harvested in second week of April.

Soil analyses

After harvesting the fifth year's crop (maize), soil samples were collected from plough layer (0 to 0.15 m depth), air-dried, ground, partitioned, and passed through standard size sieves prior to further analyses. Soil samples passed through an 8-mm sieve and retained on the 4.75-mm sieve were used for aggregate analysis, while samples passing through a 0.2-mm sieve were saved for estimating organic carbon (OC) and labile carbon (LC). For the remaining SQI soil samples passed through a 2-mm sieve was used for analysis. Soil pH was measured in 1:2 soil water suspensions where 10 g of soil was taken and stirred intermittently for 30 min with 20 ml water and measured with a pH meter (pH Analyzer

LI 612, Elico Limited, Sanathnagar, Hyderabad) (McLean 1982). Electrical conductivity (EC) was estimated in 1:2 soil water suspension using an EC meter (VSI-04 model, VSI Electronics Private Limited, Mohali, Punjab, India) (Rhoades 1982). Soil organic carbon (SOC) was determined by the modified Walkley–Black wet digestion method (Walkley & Black 1934). Available N was estimated by alkaline-$KMnO_4$ method (Subbaiah and Asija 1956). Bicarbonate-extractable P was extracted with 0.5 M sodium hydrogen carbonate ($NaHCO_3^-$) (pH of 8.5) and quantified colorimetrically (Olsen et al. 1954). Available K was extracted with 1 M neutral ammonium acetate solution and analyzed using an inductively coupled plasma spectrophotometer (ICP-OES, GBC, Australia) (Hanway & Heidal 1952). Exchangeable Ca and Mg were determined by analyzing the 1 M ammonium acetate extract on an atomic absorption spectrophotometer (GBC AAS 906 AA, Australia) (Lanyon & Heald 1982). Sulfur (S) was extracted with 0.15% $CaCl_2$ reagent (Williams & Steinbergs 1959) and was estimated turbidimetrically with a blue (340 nm) filter in the spectrophotometer (Elico mini 171 model, Elico Limited, Hyderabad). The micronutrients (Zn, Fe, Cu, and Mn) were estimated using the method suggested by Lindsay and Norvell (1978) with inductively coupled plasma spectrophotometer (model ICP-OES XP, Australia) while, boron (B) was estimated using diethylene tri amine penta acetate (DTPA)-sorbitol extraction method (Miller et al. 2000).

BD was measured by soil core method (Blake & Hartge 1986). The distribution of water stable aggregates was determined by wet sieving technique using sieves of 4.75, 2, 1, 0.5, 0.25, and 0.1 mm sizes (Yoder 1936) and MWD was computed after oven drying (Van Bavel 1950). DHA was measured by triphenyl tetrazolium chloride method (TTC) (Lenhard 1956). The results are given in mg triphenylformazan formed per hour per gram soil. Soil microbial biomass carbon (SMBC) was determined using the chloroform fumigation incubation technique (Jenkinson & Powlson 1976). Immediately after collection, the portion of the 2-mm sieved samples was preserved in a horizontal refrigerator at 4–5°C. Before analyzing SMBC, these samples were taken out of the refrigerator and primed in biochemical oxygen demand (BOD) incubator at field capacity (15% w/w) moisture regime for 10 days at 25°C ± 1°C. Microbial biomass carbon (MBC) was calculated according to Equation (1):

$$\mathrm{MBC}\left(\mu\mathrm{g\ g}^{-1}\ \mathrm{of\ soil}\right) = (\mathrm{EC_F} - \mathrm{EC_{UF}})/\mathrm{K_{EC}} \quad (1)$$

where EC_F is the total weight of extractable carbon in the fumigated sample, EC_{UF} is the total weight of the extractable carbon in unfumigated samples and K_{EC} = 0.25 ± 0.05 represents the efficiency of extraction of microbial biomass carbon.

Soil labile carbon (SLC), which is also considered as one of the important biological soil quality indicators, was estimated using the method suggested by Weil et al. (2003) with slight modification. In this method, moist fresh air-dried soil was equilibrated with 20 ml 0.01 M $KMnO_4$ solution for 15 min. The soil-solution suspension was centrifuged at 1008 × g for 5 min. The absorbance was measured at 550 nm using Mini Spectrophotometer (Model SL 171 of Elico Limited, Hyderabad.).

Data screening for assessment of soil quality indices (SQI)

The data set containing 19 soil quality parameters was statistically analyzed using the split plot design. Parameters that were found significant were subjected to principal component analysis (PCA) using SPSS software (Version 12.0). The principal components (PC), which received eigen values ≥1 (Brejda et al. 2000) and explained at least 5% of the data variation (Wander & Bollero 1999) and variables which had high factor loading, were considered to best representative the system attributes. Within each PC, only highly weighted factors (having absolute values within 10% of the highest factor loading) were considered for the minimum data set (MDS). Those variables were labeled as the 'key indicators' and were considered for computation of SQI after suitable transformation and scoring. The values of each indicator were transformed using linear scoring technique (Andrews et al. 2002). To assign the scores, indicators were arranged in an order depending on whether a higher value was considered 'good' or 'bad' in terms of influencing the soil function. For the 'more is better' category of indicators, each observation was divided by the highest observed value such that the highest observed value received a score of one. For the 'less is better' indicators, the lowest observed value (in the numerator) was divided by each observation (in the denominator) such that the lowest observed value received a score of one. After transformation using linear scoring procedure, the MDS indicators for each observation were weighted using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage when divided by the total percentage of variation explained by all PCs with eigen vectors >1 gave the weighted factors for indicators chosen under a given PC. After performing these steps to obtain SQI, the weighted MDS indicator scores for n observations (no. of indicators qualified from PCA) were summed up according to Equation (2):

$$\mathrm{SQI} = \sum_{i=1}^{n} (\mathrm{W}_i \times \mathrm{S}_i) \tag{2}$$

where S_i is the score for the subscripted variable obtained by linear scoring method and W_i is the weighing factor obtained by dividing the individual percent variance of a given PC with cumulative variability of all the PCs. It was assumed that higher index scores meant better soil quality or greater performance of soil function. For better understanding and relative comparison of the long-term performance of the conjunctive nutrient use treatments, the SQI values were reduced to a scale of 0–1 by dividing all the SQI values with the highest SQI value. The numerical values obtained clearly reflect the relative performance of the management treatments, and hence were termed as the 'relative soil quality indices' (RSQI). Further, the percent contributions of each of the final key indicators toward s SQI were also calculated and plotted in a pie chart.

Statistical Analyses

Statistical analysis of data was done through analysis of variance (two-way ANOVA) in 'Drysoft' design package developed by Central Research Institute for Dryland Agriculture, Santoshnagar, Hyderabad. As the experiment was conducted in split plot design; hence, data analysis was also in the same design and the differences were compared by Least Significant Difference (LSD) test at a probability level of $P < 0.05$ (Snedecor & Cochran 1989). The sources of variance in the statistical analysis were tillage systems, integrated nutrient management treatments, tillage × integrated nutrient interactions and replications. PCA was done using SPSS version 12.

Results and discussion

Soil parameter

Soils within all experimental plots were alkaline with pH values ranging from 7.5 to 8.6 (Table 1). The tillage practices had no significant effect on soil pH, but the fertilizer treatments and their interactions (tillage × fertilizer) had significant effect. Among the nine treatments, T6 resulted in the lowest pH of 7.5, while T5 resulted in the highest pH of 8.6.

SOC, an important and crucial parameter for these marginal (low) fertility soils, varied between 5.0 and 7.9 g kg^{-1} and was significantly influenced by both tillage and nutrient management treatments. Comparing the tillage treatments, the average OC value for the three CT + IC treatments ((T1 + T2 + T3)/3) (7.6 g kg^{-1}) was significantly higher followed by 50% CT + IC + CWC (7.09 g kg^{-1}). On an average, combined use of organic and inorganic fertilizers recorded significantly higher amount of SOC (7.0 g kg^{-1}) compared to 100% N (inorganic source) (6.6 g kg^{-1}) and 100% N (organic source/FYM) (6.5 g kg^{-1}). Similarly Hati et al. (2006) found that integrated use of organic and inorganic source of nutrients increased SOC. In the present study, substantial increase in SOC was observed by continuous addition of organic materials along with mineral fertilizers. Of all the treatment combinations studied, T3 recorded significantly highest amount of SOC of 7.9 g kg^{-1} which was at par with T8 (7.7 g kg^{-1}).

Available N is considered as another very important parameter in these soils which varied from 57.2 to 72.4 mg kg^{-1} across the treatments (Table 1). Despite, improved management treatments, these values were considerably low compared to the critical limits suggested for Indian conditions (125 mg kg^{-1} N) (Subbaiah & Asija 1956). When averaged over three nutrient management treatments, the combination of CT and IC and 50% CT and IC recorded 6.8% and 4.9% higher N compared to CT + IC + CWC. Unlike tillage treatments, fertilizer

Table 1. Effect of tillage and fertilizer treatments on soil pH, EC, SOC, and macronutrients under maize–wheat cropping sequence in Inceptisols of Ballowal Saunkhri, India.

Name of the treatments	pH	EC (dS m^{-1})	OC (g kg^{-1})	N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})
T1	7.9	0.19	7.6	72.1	16.9	106.1
T2	7.9	0.19	7.3	57.2	11.6	90.6
T3	8.4	0.19	7.9	70.3	14.6	79.6
T4	7.6	0.16	5.0	72.4	17.3	73.5
T5	8.6	0.17	5.9	58.2	14.9	77.1
T6	7.5	0.17	5.2	65.5	12.7	80.0
T7	8.2	0.19	6.9	57.3	20.6	104.3
T8	8.3	0.17	7.7	69.2	17.9	89.7
T9	8.2	0.16	6.6	60.3	13.3	81.7
Between two main treatment means	NS	0.02	0.5	NS	NS	4.4
Between two subtreatment means	0.27	NS	0.4	3.2	2.4	8.7
Between two subtreatment means at same main treatments	0.46	NS	0.7	5.6	NS	15.0
Between two main treatment means at same or different subtreatments	0.48	NS	0.7	7.8	NS	12.7

Notes: T1 = CT + IC + 100% N (organic source/FYM), T2 = CT + IC + 50% N (organic) + 50% inorganic source), T3 = CT + IC + 100% N (inorganic source), T4 = 50% CT + IC + 100% N (organic source/FYM), T5 = 50% CT + IC + 50% N (organic) + 50% N (inorganic source), T6 = 50% CT + IC + 100% N (inorganic source), T7 = 50% CT + IC + CWC + 100% N (organic source/FYM), T8 = 50% CT + IC + CWC + 50% N (organic) + 50% N (inorganic source), and T9 = 50% CT + IC + CWC + 100% N (inorganic source).CT, conventional tillage; IC, interculture; CWC, chemical weed control; N, nitrogen.

treatments showed a significant effect on available N. Among all the treatments, T4 recorded the highest available N content of 72.4 kg ha^{-1}. This indicated that reduction in tillage by 50% and application of 100% N through organic source played significant role in improving available N. This could be attributed to the reason that addition of organic source of nutrients in combination with reduction in tillage might have resulted in a greater multiplication of soil microbes that convert organically bound N to inorganic form (Sahrawat 2005).

Application of 100% organic fertilizer resulted in higher available P (18.2 mg kg^{-1}) followed by combined use of organic and inorganic sources of nutrients (16.25 mg kg^{-1}). Besides addition of P through organic manures, the increase in available P in the present study may also be attributed to the decomposition of organic matter and mineralization of organic P. Available K in the soils varied from 73.5 to 106.1 mg kg^{-1} (Table 1) across the treatments. Tillage and the fertilizer treatments and their interactions had a significant influence on the available K status. When averaged over three nutrient management treatments, the combination of CT and IC recorded the highest available K content of 92 mg kg^{-1} (Table 1). However, when averaged over tillage treatments, highest available K was recorded in application of 100% organic fertilizer (94.6 mg kg^{-1}).

Similar to K, exchangeable Ca content in the soils was significantly influenced by the tillage and fertilizer treatments individually. Exchangeable Ca in the soils ranged from 6.1 to 8.6 cmol kg^{-1} across the treatments (Table 2). On an average, 50% CT + IC and application of 100% inorganic fertilizer resulted in higher exchangeable Ca in the soils. Exchangeable Mg and available S in the soils ranged between 0.5 to 1.1 cmol kg^{-1} and 4.9 to 7.4 mg kg^{-1}, respectively, (Table 2) which was significantly influenced by tillage practices alone.

Iron (Fe) and manganese (Mn) were significantly influenced by the tillage treatments individually. DTPA extractable Fe and Mn ranged between 4.1 to 6.6 µg g^{-1} and 6.3 to 11.5 µg g^{-1}, respectively, across the treatments. On an average, CT + IC recorded significantly highest DTPA extractable Fe and Mn in the soils. Available copper (Cu) and DTPA-sorbitol extractable B in the soils varied between 0.3 to 0.45 and 1.2 to 1.3 µg g^{-1},

Table 2. Effect of tillage and fertilizer on secondary and micronutrients contents under maize–wheat cropping sequence in Inceptisols of Ballowal Saunkhri, India.

Name of the treatments	Ca	Mg	S	Zn	Fe	Cu	Mn	B
	(cmol kg^{-1})		(mg kg^{-1})	(µg g^{-1})				
T1	6.9	0.8	7.4	0.8	5.9	0.4	9.9	1.2
T2	6.8	0.8	6.8	0.9	5.7	0.4	10.7	1.2
T3	8.5	0.7	6.2	0.9	6.6	0.5	11.5	1.2
T4	8.1	0.9	5.0	0.9	4.2	0.4	7.8	1.1
T5	6.5	0.7	7.6	0.7	4.9	0.4	8.8	1.2
T6	8.4	0.7	6.2	0.5	4.4	0.3	6.3	1.2
T7	6.4	0.7	5.0	0.9	5.5	0.4	10.1	1.3
T8	6.2	1.1	6.6	0.67	4.7	0.4	8.2	1.2
T9	6.1	0.5	6.4	0.7	4.8	0.4	9.0	1.1
Between two main treatment means	0.95	NS	NS	NS	0.7	0.05	1.7	NS
Between two subtreatment means	0.76	0.1	0.8	NS	NS	NS	NS	0.04
Between two subtreatment means at same main treatments	NS	0.2	1.4	NS	NS	0.05	NS	NS
Between two main treatment means at same or different subtreatments	NS	0.15	1.3	NS	NS	0.06	NS	NS

Note: Abbreviations see Table 1.

Table 3. Effect of tillage and fertilizer treatments on physical and biological soil parameters under maize–wheat cropping sequence in Inceptisols of Ballowal Saunkhri, India.

Name of the treatments	DHA (μg TPF hr^{-1} g^{-1})	MBC (μg g^{-1} of soil)	LC (μg g^{-1} of soil)	BD (Mg m^{-3})	MWD (mm)
T1	3.3	151.1	371.1	1.5	0.35
T2	3.6	155.8	370.7	1.4	0.30
T3	3.0	119.7	353.9	1.5	0.37
T4	2.5	124.1	360.5	1.5	0.26
T5	2.6	152.9	358.3	1.4	0.26
T6	2.7	129.9	337.6	1.5	0.25
T7	3.7	129.8	363.0	1.4	0.27
T8	3.2	120.4	350.6	1.5	0.32
T9	3.1	122.3	336.6	1.5	0.26
Between two main treatment means	NS	NS	NS	NS	0.04
Between two subtreatment means	NS	NS	16.6	NS	NS
Between two subtreatment means at same main treatments	NS	NS	NS	NS	NS
Between two main treatment means at same or different subtreatments	NS	NS	NS	NS	NS

Note: Abbreviations see Table 1. DHA, dehydrogenase activity; MBC, microbial biomass carbon; LC, labile carbon; BD, bulk density; MWD, mean weight diameter.

respectively, (Table 3). Among the biological soil quality parameters, LC was significantly influenced by fertilizer treatments alone and it varied from 337 to 371 μg g^{-1}. In general, it was quite interesting to observe that organic source of nutrients played an important role in improving the availability of major nutrients such as N, P, K, and S.

BD of the soils varied from 1.4 to 1.5 Mg m^{-3} (Table 3) and was not significantly influenced by any of the soil management treatments. MWD of the soil varied from 0.3 to 0.4 mm across the treatments, which was significantly influenced by the tillage practices alone. When averaged over the three nutrient management treatments, the combination of CT and IC recorded significantly highest MWD of 0.3 mm.

Results of principal component analysis

Key indicators of soil quality

Data pertaining to 19 SQI were statistically analyzed and it was observed that out of 19 soil quality parameters, available Zn, DHA, MBC, and BD were insignificant and hence were dropped from further PCA. Following a strict criteria, only significant variables were considered for PCA. In the PCA of the remaining 15 variables, five PCs had eigen values >1 and explained 76.4% variance in the data set (Table 4). In PC1, PC3, and PC5, three variables (only one variable in each) viz. SOC, available N, and EC were qualified as the highly weighted variables, respectively, and were retained for the final MDS. In each of the PC2 and PC4, two variables were qualified as highly weighted variables. In PC2, available P and exchangeable Mg were found highly weighted with correlation value of 0.449* which was less than 0.70 and hence were retained in the final MDS (Table 5). Even in PC4, pH and available S being the highly weighted variables had a correlation value of 0.428* (*significant at P = 0.05) and were retained for the final MDS. Hence, variables which were qualified in all the PCs were retained in the MDS and no variable was eliminated. Finally, the variables retained in MDS were viz. pH, EC, SOC, available

Table 4. Principal component analysis of soil quality parameters as influenced by different soil management treatments under maize–wheat cropping sequence in Inceptisols of Ballowal Saunkhri, Hoshiarpur, India.

	PC1	PC2	PC3	PC4	PC5
Total eigen values	4.582	2.264	1.978	1.560	1.083
% of variance	30.544	15.096	13.186	10.401	7.217
Cumulative %	20.544	45.640	58.826	69.228	76.444
Eigen vectors					
pH	0.413	−0.371	−0.021	**0.587**	−0.268
EC	0.572	−0.045	0.018	−0.200	**0.704**
SOC	**0.872**	−0.082	0.124	0.220	0.090
Available N	−0.072	0.276	**0.795**	0.015	0.091
Available P	0.434	**0.696**	−0.354	0.077	−0.298
Available K	0.697	0.284	−0.339	0.072	0.308
Exchangeable Ca	−0.155	0.390	0.586	−0.388	0.054
Exchangeable Mg	0.163	**0.676**	0.267	0.338	0.148
Available S	0.169	−0.503	0.211	**0.636**	0.249
Available Fe	0.775	−0.344	0.066	−0.406	0.027
Available Cu	0.763	−0.084	0.312	−0.188	−0.298
Available Mn	0.708	−0.330	−0.037	−0.426	−0.261
Available B	0.533	0.313	−0.513	−0.056	0.111
SLC	0.342	0.529	0.010	0.207	−0.175
MWD	0.693	0.031	0.514	0.136	−0.166

Note: Bold values indicate high factor loading which qualifies the soil quality indicators within each PCs.

Table 5. Pearson's correlation matrix for highly weighted variables under PC's with high factor loading.

Variables under PCs	Available P	Exchangeable Mg
PC1		
P	1.00	0.449*
Mg	0.449*	1.00
Correlation sum	1.449	1.449
	pH	S
PC2		
pH	1.00	0.428*
S	0.428*	1.00
Correlation sum	1.428	1.428

Note: *Correlation is significant at P = 0.05 level.

N, available P, exchangeable Mg, and available S and these were termed as the key indicators for different soil management treatments under maize–wheat cropping sequence in Inceptisols of Ballowal Saunkhri, Hoshiarpur.

Soil quality indices (SQI)

SQI (pH, EC, SOC, available N, available P, exchangeable Mg, and available S) varied from 0.96 to 1.19 across the tillage and fertilizer treatments (Table 6). The SQI, when reduced to a scale of one, termed as RSQI varied between 0.80 and 0.99. The tillage and fertilizer treatments as well as their interaction effects had significant influence on SQI.

Table 6. Soil quality indices (SQI) and relative soil quality indices (RSQI) under different soil management treatments in maize–wheat cropping sequence in Inceptisols of Ballowal Saunkhri, India.

Name of the treatments	SQI	RSQI
T1	1.16	0.96
T2	1.09	0.91
T3	1.11	0.92
T4	1.01	0.83
T5	1.00	0.83
T6	0.96	0.80
T7	1.07	0.89
T8	1.19	0.99
T9	0.96	0.80
Between two main treatment means	0.05	0.04
Between two subtreatment means	0.04	0.03
Between two subtreatment means at same main treatments	0.07	0.06
Between two main treatment means at same or different subtreatments	0.07	0.06

Note: Abbreviations see Table 1.

Among the tillage treatments CT + IC maintained significantly highest soil quality of 1.12 which was at par with 50% CT + IC + CWC (1.08). Among the tillage treatments, application of nutrients through 50% N (organic fertilizer) + 50% N (inorganic fertilizer) maintained higher soil quality with SQI of 1.10 followed by application of 100% organic fertilizer (1.08). Of all the treatment combinations, T8 maintained the highest soil quality with SQI value of 1.19 which was at par with T1 (1.16). Sharma et al. (2005) achieved significantly higher SQI with the incorporation of organic along with inorganic fertilizer. The average percent contribution of key indicators toward SQI was in the order of SOC (31%) > available N (14%) > pH (12%) > available P (14%) > exchangeable Mg (13%) > available S (10%) > EC (6%) (Figure 1).

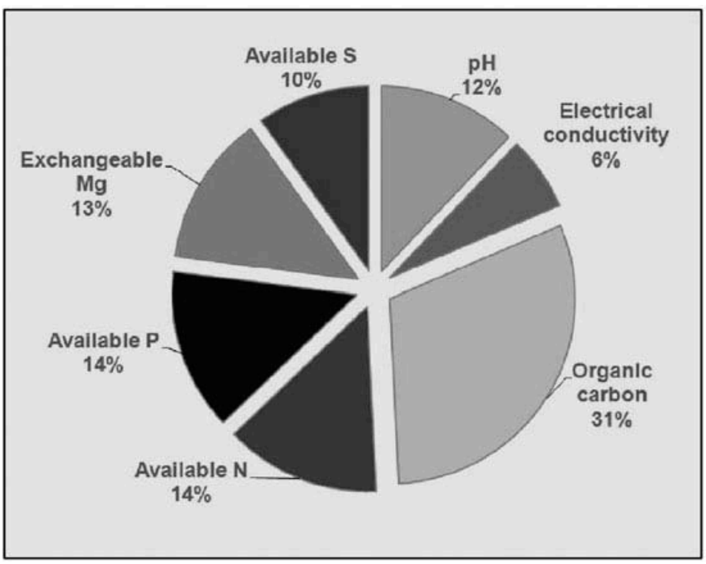

Figure 1. Percent contributions of key soil quality indicators toward SQI under different soil management treatments in maize–wheat cropping sequence at Ballowal Saunkhri, India.

Conclusion

In the present study, based on the 19 soil quality indicators, pH, EC, SOC, available N, available P, exchangeable Mg, and available S were identified as the key indicators of soil quality for submountainous Inceptisols. Significantly higher SQI was observed with practice of CT along with IC and 50% CT + IC + CWC. Similarly, combined use of organic and inorganic fertilization also resulted in higher SQI compared to inorganics alone. Overall, from the present study it was concluded that reduction in tillage along with IC, CWC, and combined use of organic and inorganic fertilizers maintained the highest SQI. This study indicates an appropriate practice that could be adopted in Inceptisols of Indo-Gangetic Plains for maintaining higher soil quality. The methodology and results of the present study could be of great importance in improving and assessing soil quality not only in the study locations, but also in other climatically and edaphically identical regions across the world.

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