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*Rainfed Inceptisol soils, despite their agricultural potential, pose serious problems, including soil erosion, low fertility, nutrient imbalance, and low soil organic matter, and ultimately lead to poor soil quality. To address these constraints, two long-term experiments were initiated to study conservation agricultural practices, comprising conventional and low tillage as well as conjunctive use of organic and inorganic sources of nutrients in Inceptisol soils of Agra center of the All-India Coordinated Research Project for Dryland Agriculture (AICRPDA). The first experiment included tillage and nutrient-management practices, whereas the second studied only conjunctive nutrient-management practices. Both used pearl millet (*Pennisetum americanum* *(L.) Linn) as test crop. These experiments were adopted for soil quality assessment studies at 4 and 8 years after their completion, respectively, at the Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad, India. Soil quality assessment was done by identifying the key indicators using principal component analysis (PCA), linear scoring technique (LST), soil quality indices (SQI), and relative soil quality indices (RSQI). Results revealed that most of the soil quality parameters were significantly influenced by the management treatments in both the experiments. In experiment 1, soil quality indices varied from 0.86 to 1.08 across the treatments. Tillage as well as the nutrient-management treatments played a significant role in influencing the SQI. Among the tillage practices, low tillage with one interculture + weedicide application resulted in a greater soil quality index (0.98) followed by conventional tillage + one interculture (0.94), which was at par with low tillage + one interculture (0.93). Among the nutrient-management treatments, application of 100% organic sources of*

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nutrients gave the greatest SQI of 1.05, whereas the other two practices of 50% nitrogen (N) (organic) + 50% (inorganic source) (0.92) and 100% N (inorganic source) (0.88) were statistically at par with each other. The various parameters that emerged as key soil quality indicators along with their percentage contributions toward SQI were organic carbon (17%), exchangeable calcium (Ca) (10%), available zinc (Zn) (9%), available copper (Cu) (6%), dehydrogenase assay (6%), microbial biomass carbon (25%) and mean weight diameter of soil aggregates (27%). In experiment 2, SQI varied from 2.33 to 3.47, and 50% urea + 50% farmyard manure (FYM) showed the greatest SQI of 3.47, which was at par with 100% RDF + 25 kg zinc sulfate ($ZnSO_4$) (3.20). Under this set of treatments, the key soil quality indicators and their contributions to SQI were organic carbon (19%), available N (20%), exchangeable Ca (3%), available Zn (4%) and Cu (17%), labile carbon (20%), and mean weight diameter of soil aggregates (17%). The quantitative relationship established in this study between mean pearl millet yields (Y) and RSQI irrespective of the management treatments for both the experiments together could be quite useful to predict the yield quantitatively with respect to a given change in soil quality for these rainfed Inceptisols. The methodology used in this study is not only useful to these Inceptisols but can also be used for varying soil types, climate, and associated conditions elsewhere in the world.

Keywords conjunctive nutrient use, linear scoring technique, management practices, pearl millet, principal component analysis, rainfed, soil quality indicators and indices

Introduction

The Inceptisol soils, known as the young mineral soils, constitute the largest soil order, occupying almost 15% of the global ice-free land area and supporting approximately 20% of the world's population. In India, these soils are mostly spread throughout the Indo-Gangetic Plain and along the lower courses of the country's major rivers (especially the deltas along the east coast) (ISSS 2009). Though these soils have good agricultural potential, they pose serious problems, including soil erosion, poor fertility, nutrient imbalances, and low soil organic matter, which become constraints to sustaining productivity on a long-term basis. Recently, Manna et al. (2006) reported a decline in yield of rice, wheat, and jute crops grown in these soils due to gradual depletion of nutrients, variations in soil organic matter, and structural degradation. Some of the important factors that may contribute to accelerated exhaustion of nutrients from the soils could be intensive cultivation using high nitrogen (N), phosphorus (P), and potassium (K) fertilizers, limited use of organic manures, and less recycling of crop residues (Sharma et al. 2004; Sharma and Chaudhary 2007). Besides these factors, inappropriate cultural practices may also render a fertile and productive soil unproductive and degraded at an alarming rate, consequently reducing its productive potential. According to Lal (1993), intensive tillage may lead to a range of degradative processes, including a decline in soil structure, accelerated erosion, depletion of soil organic matter (SOM) and fertility, and disruption in cycles of water, organic carbon, and plant nutrients. Such degradative effects are more pronounced especially in stressed agroecology such as hot semi-arid rainfed conditions (Suri 2007), where the soils encounter diverse constraints on account of physical, chemical, and biological soil health, ultimately resulting in poor functional capacity, poor soil quality (AICRPDA 2003; Das and Chatterjee 1982; ISSS 2009), and poor productivity. Such productivity-linked soil constraints can be mitigated by following the techniques of conservation farming practices comprising low or no tillage, covering the soil with mulch using crop residues or other suitable materials, and conjunctive use of organic and inorganic sources of nutrients. Earlier reports from temperate and other regions reveal that conservation farming practices may help in conserving water, preventing erosion, maintaining organic-matter content at reasonable level, improving fertility and overall soil quality, and sustaining economic productivity (Lal 1997; Smith and Elliott 1990; Unger 1990).

Studying the impact of these conservation agricultural practices on cropping system sustainability and the soil quality on a long-term basis would be of immense value (Mandal et al. 2007). To achieve the sustainability of the systems, especially those highly susceptible to degradation, use of monitoring tools that promptly and realistically reflect the changes imposed on soil function by different crops and management practices becomes an important aspect (Freidman et al. 2001). Soil quality assessment is one such important tool. Over the past decade, increasing interest in soil quality and its evaluation has been observed in the literature (Amado et al. 2007; Andrews, Karlen, and Cambardella 2004; Doran and Parkin 1996; Karlen et al. 1997). As stated by Karlen et al. (1997), *soil quality* is the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation. To make wise decisions that would improve crop production and maintain environmental sustainability, comprehensive evaluation of soil quality is very much essential (Qi et al. 2009). Owing to the complex functional state, the quality of the soil cannot be measured directly but could be inferred from the measurable soil properties termed as the *soil quality indicators* (Acton and Padbury 1993). Single variables cannot fully reflect the changes in soil quality, and hence, a minimum dataset of soil quality indicators that integrate the main soil functions need to be considered (Doran and Parkin 1996). Some of the variables such as soil organic matter, microbial biomass, and soil aggregation have been frequently cited as potential variables (Saggar, Yeates, and Shepherd 2001; Leibig, Tanaka, and Wienhold 2004; Amado et al. 2007). Monitoring of such potential variables helps in the early identification of unsustainable agricultural practices especially in soils with low resistance to degradation factors and low resilience. Recently, Sharma et al. (2005, 2008a, 2008b) have conducted such studies on soil quality improvement and assessment in moisture-stressed Alfisols of semi-arid tropics and Oxisols of subhumid regions. However, the information pertaining to management of rainfed Inceptisols is meager. Hence, the present study was conducted with the objectives to (i) study the impact of tillage and conjunctive use of nutrients on soil quality parameters, (ii) identify the key soil quality indicators and their relative contribution towards soil quality, (iii) identify the best tillage and nutrient-management practices from the view point of improving soil quality, and (iv) establish a predictable quantitative relationship between long-term crop yield and soil quality under pearlmillet system in rainfed semi-arid Inceptisol soils.

Materials and Methods

Site Description

Out of the network centers of All-India Coordinated Research Project for Dryland Agriculture (AICRPDA), under the technical and administrative jurisdiction of Central Research Institute for Dryland Agriculture (CRIDA), Agra center, situated at 27° 10′ N latitude and 78° 05′ E longitude in Uttar Pradesh on the Indo-Gangetic Plains, was selected for the present study. This center conducts the lead research on dryland agriculture for the Agra region. This region is climatically arid to hot semi-arid with an annual rainfall of 669 mm and is characterized by intermittent drought twice in five years. The length of growing period in this region generally varies from 90–120 days. The soils are deep loamy alluvium-derived soils (occasionally saline and sodic phases) with medium available water capacity (AWC; 5–6 cm). In general, these soils are neutral in reaction with desirable level of electrical conductivity and have low organic carbon and medium phosphate and potash contents (AICRPDA 2006).

Experimental Details

Two long-term experiments, one focusing on tillage in combination with nutrient-management practices and another focusing on conjunctive nutrient-use practices, were initiated at the experimental station to study their influence on soil quality parameters. The first experiment was initiated during 2000 in a split-plot design with three main treatments and three subtreatments in three replications using pearl millet (*Pennisetum americanum* (L.) Leeke) as test crop. The main treatments were composed of three tillage practices: T1, conventional tillage (CT); T2, low tillage + one interculture (LT1); and T3, low tillage + one interculture + weedicide (LT2), whereas the subtreatments included three nutrient-management treatments: T1, 100% N (organic); T2, 50% N (organic) + 50% N (inorganic); and T3, 100% N (inorganic). Hence, the nine treatments in all were as follows: T1, CT + IC + 100% N (organic source/compost); T2, CT + IC + 50% N (organic + 50% inorganic source); T3, CT + IC + 100% N (inorganic source); T4, LT + IC + 100% N (organic source/compost); T5, LT + IC + 50% N (organic + 50% inorganic source); T6, LT + IC + 100% N (inorganic source); T7, LT + weedicide + IC + 100% N (organic source/compost); T8, LT + weedicide + IC + 50% N (organic) + 50 % inorganic source); and T9, LT + weedicide + IC + 100% N (inorganic source). Tillage was as follows: conventional tillage (CT) had summer plowing + three harrowings (disk harrow) + two intercultures at 20 and 40 days after seeding (DAS); low tillage 1 (LT 1) had two harrowings (disk harrow) + two intercultures at 20 and 40 DAS; and low tillage 2 (LT 2) had two harrowings (disk harrow) + one interculture at 20 DAS + herbicide application. The inorganic source of nitrogen (N) was urea and the organic source was farmyard manure (FYM). A uniform dose of phosphorus (P) as phosphorus pentoxide (P_2O_5) was applied through single superphosphate (SSP) at the time of sowing. The term *interculture* used here essentially means the operations done during the crop growing season to remove weeds, break crust, and loosen the soil and for fertilizer placement. The second experiment was initiated during 1997 with eight conjunctive nutrient-use treatments (combined use of organic and inorganic sources of nutrients) in a randomized block design with four replications using pearl millet as the test crop. Out of these eight treatments, only the five most relevant treatments were chosen for the present soil quality assessment study: T1, control; T2, 50% urea + 50% crop residue; T3, 50% urea + 50% FYM; T4, 100% RDF + 25 kg $ZnSO_4$, and T5, farmers' method.

Soil Sampling and Analysis

Soil samples were collected during 2005 from the plow layer (0.0–0.15 m depth) from both the experimental sites after the harvest of 2004 kharif (rainy season) crop. These samples were partitioned and passed through standard prescribed sieves for further use in a different kind of analysis. Soil samples that passed through the 8-mm sieve and were retained on the 4.75-mm sieve were used for aggregate analysis, while the sample that passed through the 0.2-mm sieve was used for estimating organic carbon (OC) as well as labile carbon (LC). For the rest of the soil quality parameters such as chemical [pH, electrical conductivity (EC), available N, available P, available K, exchangeable calcium (Ca), exchangeable magnesium (Mg), available sulfur (S), and micronutrients such as available zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), and boron (B)] and biological [microbial biomass carbon (MBC) and dehydrogenase assay (DHA)] parameters, soil samples that passed through 2-mm sieves were used. The standard protocols adopted for estimating different 19 soil quality parameters were as follows: Soil pH and EC were measured in a 1:2 soil/water suspension (Rhoades 1982), organic carbon by wet oxidation with sulfuric acid (H_2SO_4) + potassium dichromate ($K_2Cr_2O_7$) (Walkley and Black 1934), available N by alkaline-$KMnO_4$ oxidizable N method (Subbaiah and Asija 1956), available P by 0.5 M sodium bicarbonate ($NaHCO_3$) extraction method (Olsen et al. 1954), available K (Hanway and Heidal 1952) and exchangeable Ca and Mg using neutral normal ammonium acetate method, diethylenetriaminepentaacetic acid (DTPA)–extractable Zn, Fe, Cu, and Mn by DTPA reagent [0.005 M DTPA + 0.1 M triethanolamine (TEA) + 0.01 M calcium chloride ($CaCl_{2.}2H_2O$); pH 7.3] using inductively coupled plasma spectrophotometer (ICP-OES, GBC Australian model) (Lindsay and Norvell 1978), extractable boron (B) by DTPA-sorbitol extraction (Miller, Vaughan, and Kutoby-Amacher 2001), bulk density (BD) by Keen's box method, aggregate stability using the wet sieve technique (Yoder 1936), mean weight diameter (MWD) (Van Bevel 1949), microbial biomass carbon (MBC) by fumigation–incubation (Jenkinson and Powlson 1976), dehydrogenase activity by the triphenyl tetrazolium chloride method (TTC) (Lenhard 1956), and labile carbon (C) by the potassium permanganate ($KMnO_4$) method using 0.01 M $KMnO_4$ instead of 0.02 M originally suggested by Weil et al. (2003).

Soil Quality Assessment Methodology

To assess soil quality, the data obtained for 19 chemical, physical, and biological soil quality parameters were statistically tested for their level of significance using the split plot design in the case of experiment 1 and randomized block design in the case of experiment 2. After the statistical analysis, the parameters that were found to be significant were subjected to principal component analysis (PCA) (Andrews et al. 2002a, 2002b; Doran and Parkin 1994) using SPSS software (version 12.0, SPSS Inc., Chicago, Ill., USA). The PCA was done to reduce the dimensionality (number of variables) of the dataset and to retain most of the original variability in the data. The principal components (PC) that received eigenvalues ≥ 1 (Brejda et al. 2000a, 2000b) and explained at least 5% of the variation in the data (Wander and Bollero 1999) and variables that had high factor loading were considered as the best representative of system attributes. Within each PC, only highly weighted factors (having absolute values within 10% of the greatest factor loading) were retained for the minimum data set (MDS). Further, to reduce the spurious groupings among the highly weighted variables within each principal component, intercorrelations were worked out (Andrews et al. 2002a). Based on the intercorrelation values, variables were labelled as well-correlated variables when the 'r' value was >0.70. Among the well-correlated variables, only one variable was considered for the MDS. However, in some cases as an exception, more than one variable were also retained for the MDS depending upon the important role of the variables in regulating the soil functions. When the correlations were not significant between the highly weighted variables, reflecting their independent functioning, then all the variables were considered important and retained for the MDS. As a check of how well the MDS represented the management system goals, multiple regressions were also performed considering the indicators retained in the MDS as independent variables and the functional goals such as long-term average yields of pearlmillet crop as dependent variable. The variables qualified under these series of steps were termed as the *key indicators* and were considered for computation of soil quality index (SQI) after suitable transformation and scoring.

As suggested by Andrews et al. (2002a), all the observations of each identified key MDS indicator were transformed using linear scoring technique. To assign the scores, indicators were arranged in order depending on whether a greater value was considered "good" or "bad" in terms of soil function. In the cases of "more is better" indicators, each observation was divided by the greatest observed value such that the greatest observed value received a score of 1. For "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 1. After transformation using linear scoring, 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 eigenvectors > 1, gave the weighted factors for indicators chosen under a given PC. After performing these steps, to obtain soil quality index (SQI), the weighted MDS indicator scores for each observation were summed up using the following function:

$$\mathrm{SQI} = \sum_{i=1}^{n} (\mathrm{Wi} \times \mathrm{Si})$$

In this relation, Si is the score for the subscripted variable and Wi is the weighing factor obtained from the PCA. Here the assumption is that greater 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 greatest SQI value. The numerical values thus obtained clearly reflect the relative performance of the management treatments, and hence were termed as the *relative soil quality indices* (RSQI). Further, the percentage contributions of each final key indicator toward SQI were also calculated and plotted in a radar chart. The radar charts are a very effective way to display multivariate observations and to identify which variables are dominant for a given observation. In this graph, each ray represents one variable and the length of each ray is proportional to the size of the variable (in the present study, the percentage contributions).

Statistical Analyses

Analysis of variance (ANOVA) for two experiments was performed using the Drysoft design package. Randomized block design and split-plot design were used for the first and second experiments respectively and the differences were compared by least significant difference (LSD) test to a significance level of $P < 0.05$ (Snedecor, Cochran, and Cox 1989). Principal component analysis was performed using SPSS 12 version. To establish quantitative predictive relationship between pearl millet crop yield and soil quality, simple regression function was developed by using means of 4-year pearl millet crop yields and relative soil quality indices values, which were obtained by transforming the SQI values to the scale of 1.

Results and Discussion

Influence of Various Soil and Nutrient-Management Treatments on Soil Quality Parameters

Experiment 1. The results on the influence of tillage and nutrient-management practices on various physical, chemical, and biological soil quality parameters are presented in Tables 1 and 2. Soil reaction of the experimental plots was neutral to slightly alkaline with pH varying from 7.2 to 7.8 and electrical conductivity from 0.26 to 0.37 dS m^{-1}. Both of these parameters were not affected by the tillage and the nutrient-management treatments practiced over a period of 5 years. Organic C, which varied from 3.59 to 4.84 g kg^{-1} across the treatments, was significantly influenced by both tillage as well as nutrient-management treatments, but their interaction effects were not significant. Conventional tillage + one interculture recorded the significantly greatest organic C content (4.67 g kg^{-1}) followed by the practice of low tillage + one interculture (4.21 g kg^{-1}), which are 20% and 8% greater, respectively. The reason for the relatively greater content of organic matter under conventional tillage compared to reduced tillage could not be understood. On the other hand, application of nutrients through 100% organics maintained significantly greater (11%) organic C content (4.59 g kg^{-1}) over the conjunctive use of 50% N (organics) + 50% N (inorganics) (4.10 g kg^{-1}) and 100% inorganics (4.10 g kg^{-1}). Though the treatments showed a significant impact, the absolute quantity of organic C in these soils remained low when compared to the critical limits earlier suggested for Indian conditions (<5.0 g kg^{-1}) (Tandon 2005). A similar trend of low organic C status was previously reported by Khresat (2005) and Sharma et al. (2004) in rainfed Inceptisol soils. Available N ranging from 115.7 to 136.0 kg ha^{-1} was significantly influenced by nutrient-management treatments while the tillage practices did not show any effect. The treatments of 100% organics (127.1 kg ha^{-1}) as well as 100% inorganics (133.3 kg ha^{-1}) were almost at par in maintaining soil available N. Available P content across the treatments varied from 27.1 to 42.7 kg P ha^{-1} but was not significantly influenced either by tillage or by the nutrient-management practices. Available K varied from 189.7 to 329.0 kg ha^{-1} across the management practices and was significantly influenced by the tillage practices but not by the nutrient-management treatments. Of the tillage practices, conventional tillage + one interculture maintained greater available K (308.5 kg ha^{-1}).

Among the secondary nutrients, exchangeable Ca varied from 3.38 to 5.02 cmol kg^{-1}, exchangeable Mg from 2.48 to 3.35 cmol kg^{-1}, and available S from 24.6 to 39.5 kg ha^{-1} across the treatments. It was observed that tillage showed significant influence only on exchangeable Ca but not on exchangeable Mg and available S. The nutrient-management practices showed significant influence only on available S, where application of nutrients through 100% organic sources recorded significantly greatest available S (38.7 kg ha^{-1}). Tillage practices did not show any significant influence on any of the micronutrients whereas the nutrient-management treatments significantly influenced all the micronutrients except available B. The interaction effect of both tillage and nutrient-management treatments was observed only on available Cu and B. Of all the nutrient-management practices followed, application of nutrients through 50% N (organic) + 50% inorganic sources recorded significantly greatest available Zn (1.91 μg g^{-1}), Fe (15.9 μg g^{-1}), Cu (0.87 μg g^{-1}), and Mn (15.6 μg g^{-1}).

Biological variables have been highlighted as potential indictors of soil quality as they are frequently more sensitive to management than physical and or chemical properties (Bandick and Dick 1999; Mijangos et al. 2006; Saffigna et al. 1989). Hence, monitoring of the biological variables provide an early identification of unsustainable agricultural

Table 1
Effect of tillage and nutrient management practices on physicochemical and chemical soil quality parameters under pearl millet system in Inceptisols of Agra

No.	Name of the treatments	pH	EC (dS m^{-1})	OC (g kg^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (cmol kg^{-1})	Mg (cmol kg^{-1})	S (kg ha^{-1})	Zn (µg g^{-1})	Fe (µg g^{-1})	Cu (µg g^{-1})	Mn (µg g^{-1})	B (µg g^{-1})
1	CT + IC + 100% N (organic source/compost)	7.4	0.31	4.84	131.1	30.8	269.1	5.02	3.04	39.5	1.55	16.5	0.91	10.5	0.58
2	CT + IC + 50% N (organic) + 50% inorganic source)	7.8	0.37	4.74	118.6	33.8	329.0	3.89	2.48	24.7	1.77	18.2	0.69	16.9	0.66
3	CT + IC + 100% N (inorganic source)	7.8	0.32	4.44	127.5	37.9	327.4	4.09	3.04	35.5	1.31	14.7	0.63	11.8	0.51
4	LT + IC + 100% N (organic source/compost)	7.4	0.29	4.70	132.8	34.8	267.1	3.56	3.35	38.7	1.56	13.3	0.63	12.5	0.62
5	LT + IC + 50% N (organic) + 50% inorganic source)	7.4	0.27	3.72	115.7	31.7	189.7	3.38	3.10	24.6	1.99	15.1	0.61	13.5	0.53
6	LT + IC + 100% N (inorganic source)	7.2	0.28	4.20	124.6	27.1	246.1	4.11	2.78	34.5	1.47	12.2	0.88	10.8	0.53
7	LT + weedicide + IC + 100% N (organic source/compost)	7.6	0.27	4.23	136.0	29.7	216.6	4.95	2.72	37.8	1.83	13.5	0.46	10.0	0.56
8	LT + weedicide + IC + 50% N (organic) + 50% inorganic source)	7.7	0.29	3.83	124.6	33.2	270.9	4.43	3.23	28.5	1.98	14.3	1.31	16.3	0.38
9	LT + weedicide + IC + 100% N (inorganic source)	7.6	0.26	3.59	129.1	42.7	278.2	4.25	3.08	24.8	1.32	14.7	0.94	13.4	0.59
	LSD ($P = 0.05$)														
	Between two main treatment means	NS	NS	0.37	NS	NS	25.0	0.38	NS	NS	NS	NS	NS	NS	NS
	Between two subtreatment means	NS	NS	0.34	9.14	NS	NS	NS	NS	3.33	0.38	1.62	0.16	2.95	NS
	Between two subtreatment means at same main treatments	NS	NS	NS	NS	7.85	NS	NS	0.54	5.76	NS	NS	0.27	NS	0.11
	Between two main treatment means at same or different subtreatments	NS	NS	NS	NS	7.89	NS	NS	0.50	7.13	NS	NS	0.26	NS	0.13

Notes. CT, conventional tillage; LT, low tillage; IC, interculture; NS, nonsignificant; and LSD, least significant difference.

Table 2

Effects of tillage and nutrient-management practices on biological and physical soil quality parameters under pearl millet system in Inceptisols of Agra

No.	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)
1	CT + IC + 100% N (organic source/compost)	7.68	61.5	262.7	1.20	0.29
2	CT + IC + 50% N (organic) + 50% inorganic source)	5.56	42.2	241.6	1.21	0.23
3	CT + IC + 100% N (inorganic source)	4.35	44.7	234.0	1.28	0.25
4	LT + IC + 100% N (organic source/compost)	7.31	60.2	282.8	1.26	0.30
5	LT + IC + 50% N (organic) + 50% inorganic source)	6.91	48.2	259.1	1.28	0.24
6	LT + IC + 100% N (inorganic source)	5.19	50.4	237.9	1.25	0.23
7	LT + weedicide + IC + 100% N (organic source/compost)	8.35	58.5	248.3	1.25	0.32
8	LT + weedicide + IC + 50% N (organic) + 50 % inorganic source)	7.20	49.2	247.5	1.28	0.26
9	LT + weedicide + IC + 100% N (inorganic source)	6.77	50.8	233.3	1.35	0.24
	LSD ($P = 0.05$)					
	Between two main treatment means	0.89	NS	NS	0.04	NS
	Between two subtreatment means	0.63	6.33	15.9	0.04	0.03
	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

Notes. CT, conventional tillage; LT, low tillage; IC, interculture; NS, nonsignificant; and LSD, least significant difference.

practices. This would be particularly relevant to soils with low resistance to degradation factors and low resilience. Of the three biological soil quality parameters assessed in the present study, only the dehydrogenase activity has been significantly influenced by the tillage practices, whereas the significant effect of nutrient-management treatments was observed on all the three parameters. Practice of low tillage + one interculture + weedicide recorded more DHA of 7.44 μg TPF h^{-1} g^{-1} compared to other tillage practices. Among the nutrient-management treatments, application of nutrients through 100% organic sources recorded the significantly greatest dehydrogenase activity (7.78 μg TPF $h^{-1}g^{-1}$), microbial biomass C (60.1 μg g^{-1} of soil), and labile C (275.7 μg g^{-1} of soil). According to Pancholy and Rice (1973), greater dehydrogenase activity in soil might be due to the more easily decomposable components of crop residues, owing to the greater metabolism of soil microorganisms. When the physical parameters of soil quality were considered, tillage treatments showed a significant influence only on soil bulk density, whereas the nutrient-management treatments significantly influenced both bulk density as well as mean weight diameter of the soil aggregates. Soil bulk density varied from 1.20 to 1.35 Mg m^{-3} across the management treatments and was found significantly low under practice of conventional tillage + one interculture (1.23 Mg m^{-3}). It was interesting to observe that soils which received nutrients through 100% organic sources maintained the significantly lowest bulk density (1.23 Mg m^{-3}) and greatest mean weight diameter of soil aggregates (0.31 mm).

Experiment 2. In the second experiment, the influence of the long-term conjunctive nutrient-management treatments on various physical, chemical, and biological soil quality parameters were studied after 8 years of the experiment. The data presented in Tables 3 and 4 indicated that except for pH and EC, all the soil quality parameters were significantly influenced by the management treatments. Soil pH of this experimental site was neutral to slightly alkaline, varying from 7.0 to 7.5, and the electrical conductivity varied from 0.23 to 0.30 dS m^{-1} across the management treatments. Organic C and available N, ranging from 2.91 to 4.23 g kg^{-1} and 122.78 to 150.9 kg ha^{-1}, respectively, were found to be low with reference to the critical limits suggested for these soils (Tandon 2005), whereas available P and available K were observed to be in the medium range, varying from 10.6 to 26.6 kg ha^{-1} and 177.4 to 274.2 kg ha^{-1}, respectively, across the management treatments. Of all the conjunctive nutrient-management treatments, application of 50% urea + 50% FYM maintained the greatest organic C content (4.23 g kg^{-1}), available N (150.9 kg ha^{-1}), available P (26.6 kg ha^{-1}), and available K (274.2 kg ha^{-1}). Exchangeable Ca and Mg varied from 3.99 to 5.14 cmol kg^{-1} and 1.53 to 2.45 c-mol kg^{-1} respectively across the management treatments. The plots that received 100% RDF + 25 kg $ZnSO_4$ recorded significantly greater available S (32.2 kg ha^{-1}), which was almost at par with 50% urea + 50% FYM (29.1 kg ha^{-1}), whereas the lowest amount of S was observed in the control plot (20.8 kg ha^{-1}). Among the micronutrients, available Zn, Fe, Cu, and Mn contents were high in these soils, whereas available B was in medium range. Even in case of micronutrients, the conjunctive application of 50% urea + 50% FYM recorded significantly greatest available Fe (14.3 μg g^{-1}), available Cu (2.40 μg g^{-1}), and available B (0.52 μg g^{-1}). The conjunctive nutrient-management treatments had a significant influence on biological as well as physical soil quality parameters. Dehydrogenase activity varied from 4.54 to 7.69 μg TPF h^{-1}g^{-1}, microbial biomass C from 34.2 to 53.4 μg g^{-1} of soil, and labile carbon from 227.6 to 323.1 μg g^{-1} of soil across the management treatments. Under both the experiments, microbial biomass C as well as labile C were significantly influenced by the management treatments and remained low in these soils. Zou et al. (2005) also reported that young soils such as Inceptisols and Entisols had lower levels of microbial biomass C and labile organic C than older soils such as Ultisols and Oxisols. They also indicated that organic C levels in young soils were more labile than those in older soils with greater potential turnover rates and shorter potential turnover time for the young soils, suggesting that older soils either contain a high proportion of old organic materials or have high levels of organo-mineral association. The physical soil quality parameters such as bulk density varied from 1.19 to 1.33 Mg m^{-3} while the mean weight diameter of soil aggregates ranged from 0.21 to 0.35 mm across the management treatments. Among the treatments, it was observed that application of 50% urea + 50% crop residue as well as 50% urea + 50% FYM maintained the greatest soil biological and physical soil quality.

Influence on Key Indicators and Soil Quality Indices

The main aim was to assess the impact of these management treatments on soil quality and also to identify the key indicators that influence on overall soil quality in

Table 3
Influence of conjunctive nutrient-management treatments on physicochemical and chemical soil quality parameters under pearl millet system in Inceptisols of Agra

No.	Name of the treatments	pH	EC (dS m^{-1})	OC (g kg^{-1})	N (Kg ha^{-1})	P (Kg ha^{-1})	K (Kg ha^{-1})	Ca (Cmol kg^{-1})	Mg (Cmol kg^{-1})	S (kg ha^{-1})	Zn (µg g^{-1})	Fe (µg g^{-1})	Cu (µg g^{-1})	Mn (µg g^{-1})	B (µg g^{-1})
1	T1: control	7.0	0.25	2.91	122.8	10.6	177.4	3.99	1.53	20.8	1.34	8.14	1.18	9.51	0.36
2	T2: 50% urea + 50% crop residue	7.5	0.30	3.50	140.6	16.2	274.1	5.14	1.57	27.0	1.42	12.2	1.78	13.2	0.52
3	T3: 50% urea + 50% FYM	7.0	0.26	4.23	150.9	26.6	274.2	4.67	2.44	29.1	1.79	14.3	2.40	14.6	0.52
4	T4: 100% RDF + 25 kg $ZnSO_4$	7.4	0.23	3.84	140.4	16.4	241.5	5.02	2.45	32.2	3.32	13.0	2.25	14.2	0.46
5	T5: farmers' method	7.5	0.24	3.44	135.7	14.2	207.7	4.06	2.45	24.5	2.29	12.7	1.48	16.8	0.38
	LSD ($P = 0.05$)	NS	NS	0.76	14.7	4.11	46.6	0.82	0.37	5.05	0.65	3.66	0.62	2.82	0.12

Notes. FYM, farmyard manure; and RDF, recommended dose of fertilizer.

Table 4

Influence of conjunctive nutrient-management treatments on biological and physical soil quality parameters under pearl millet system in Inceptisols of Agra

No.	Name of the treatments	DHA (μg TPF h^{-1} g^{-1})	MBC (μg g^{-1} of soil)	LC (μg g^{-1} of soil)	BD (Mg m^{-3})	MWD (mm)
1	T1: control	4.54	34.2	227.6	1.33	0.21
2	T2: 50% urea + 50% crop residue	7.69	51.5	306.1	1.19	0.30
3	T3: 50% urea + 50% FYM	7.61	53.4	323.1	1.21	0.35
4	T4: 100% RDF + 25 kg $ZnSO_4$	7.17	41.4	285.7	1.28	0.27
5	T5: farmers' method	7.01	42.9	280.6	1.32	0.24
	LSD ($P = 0.05$)	1.27	7.27	28.3	0.07	0.07

Notes. FYM, farmyard manure; and RDF, recommended dose of fertilizer.

these Inceptisols. Hence, after assessing the soil quality variables, the variables that are statistically significant were subjected to principal component analysis (PCA) and linear scoring techniques to identify the key indicators and to compute the overall soil quality indices.

Experiment 1. In the first experiment where the influences of tillage as well as the nutrient-management treatments were studied, it was observed that out of 19 soil quality parameters, only two parameters, pH and EC, were not significantly influenced either by tillage or by the nutrient-management treatments, and these were dropped from the PCA. In the PCA of 17 variables, six PCs had eigenvalues >1 and explained 74.3% variance in the data set (Table 5). In PC1, only two variables, MBC and MWD, were qualified as the highly weighted variables. In the rest of the PCs, only single variables of organic carbon in PC2, available Zn in PC3, exchangeable Ca in PC4, available Cu in PC5, and dehydrogenase assay (DHA) in PC6 were found to be highly weighted and were retained for the minimum data set (MDS). The correlation matrix (Table 6) run for the variables qualified under PC1 revealed a significant correlation (0.696**) but both the variables under PC1 were retained for the MDS considering the important role they play in soil quality. Hence, the parameters retained finally for the minimum data set were organic C, exchangeable Ca, available Zn, available Cu, dehydrogenase assay, microbial biomass C, and mean weight diameter and these were labeled as the key indicators for pearl millet system under Inceptisols of the Agra region.

To establish a quantitative relationship between the final key soil quality indicators and the crop yields, linear regressions were worked out using the seven final parameters retained in the data set and the average yields of pearl millet. Using the enter method (all variables simultaneously), a significant model has emerged which accounted for 82.3% of variance ($R^2 = 0.82$) in the data set. The most significant variables at $P < 0.05$ along with their β coefficients were exchangeable Ca (0.799; $P < 0.000$), available Cu (0.668; $P < 0.006$), DHA (–0.732; $P < 0.008$), MBC (0.644; $P < 0.043$), and MWD (–0.616; $P < 0.012$). These variables with large standardized β coefficients reflected significant influence on pearl millet yields whereas organic C and available Zn with relatively small β coefficient values reflected lower contributions to the pearl millet yield with a unit change. The

Table 5
Results of principal component analysis (PCA) of soil quality parameters as influenced by different tillage and nutrient-management treatments under pearl millet system

Parameter	PC1	PC2	PC3	PC4	PC5	PC6
Total eigenvalues	4.083	2.574	2.020	1.558	1.315	1.082
Percentage of variance (%)	24.019	15.141	11.887	9.166	7.734	6.363
Cumulative percentage (%)	24.019	39.159	51.047	60.213	67.947	74.310
Eigenvectors						
OC	0.310	**0.784**	−0.206	0.049	0.120	−0.177
N	0.624	−0.135	0.563	−0.007	0.042	0.052
P	−0.326	−0.059	0.550	0.370	0.136	0.325
K	−0.276	0.491	0.425	−0.044	0.425	−0.234
Ca	0.416	0.089	0.271	**−0.647**	0.189	0.409
Mg	0.251	−0.377	0.246	0.502	0.337	−0.389
S	0.741	0.296	0.071	−0.223	−0.060	−0.245
Zn	−0.040	−0.209	**−0.745**	−0.111	0.066	−0.018
Fe	−0.311	0.575	−0.125	0.273	0.358	0.324
Cu	−0.182	−0.391	0.066	−0.326	**0.605**	−0.102
Mn	−0.547	0.058	−0.311	0.030	0.483	0.200
B	0.135	0.635	0.155	0.355	−0.281	0.289
DHA	0.547	−0.420	−0.339	0.149	0.078	**0.470**
MBC	**0.873**	−0.149	0.041	0.075	0.132	0.018
BD	−0.391	−0.571	0.290	0.249	−0.161	0.090
MWD	**0.812**	−0.023	0.009	0.063	0.224	0.174
LC	0.554	0.000	−0.378	0.532	0.187	−0.100

Table 6
Pearson's correlation matrix for highly weighted variables under PCs with high factor loading

PC1	MBC	MWD
MBC	1.00	0.696**
MWD	0.696**	1.00
Correlation sum	1.696	1.696

**Correlation is significant at $P = 0.01$ level.

relationship of the key indicators with mean pearl millet yield can be explained by the following equation:

$$\begin{aligned}\mathrm{Yld}_{\mathrm{Pearl\ millet}} = {} & 102.4 + 107.5\,(\mathrm{OC}) + 348.5\,(\mathrm{Ex.\ Ca})^{*} - 85.9\,(\mathrm{Zn}) + 977.7\,(\mathrm{Cu})^{*} \\ & - 134.0\,(\mathrm{DHA})^{*} + 20.7\,(\mathrm{MBC})^{*} \\ & - 3777.7\,(\mathrm{MWD})^{*} \qquad (\mathrm{R}^2 = 0.82)(P = 0.05)\end{aligned}$$

Soil quality index calculation is a core issue in the process of soil quality evaluation though it is an indirect approach based on integrated evaluation of quality indicators and

Table 7
Soil quality indices and relative soil quality indices of the long-term tillage and nutrient-management treatments under pearl millet system in Inceptisols of Agra

	Treatment	SQI	RSQI
1	CT + IC + 100% N (organic source/compost)	1.08	0.90
2	CT + IC + 50% N (organic) + 50 % inorganic source)	0.88	0.74
3	CT + IC + 100% N (inorganic source)	0.86	0.72
4	LT + IC + 100% N (organic source/compost)	1.02	0.85
5	LT + IC + 50% N (organic) + 50% inorganic source)	0.88	0.74
6	LT + IC + 100% N (inorganic source)	0.89	0.74
7	LT + weedicide + IC + 100% N (organic source/compost)	1.05	0.88
8	LT + weedicide + IC + 50% N (organic) + 50% inorganic source)	0.99	0.83
9	LT + weedicide + IC + 100% N (inorganic source)	0.90	0.75
	LSD ($P = 0.05$)		
	Between two main treatment means	0.04	NS
	Between two subtreatment means	0.06	0.05
	Between two subtreatment means at same main treatments	NS	NS
	Between two main treatment means at same or different subtreatments	NS	NS

Notes. CT, conventional tillage; LT, low tillage; IC, interculture; NS, nonsignificant; and LSD, least square difference.

their weights. Soil quality indices computed using these seven key soil quality indicators varied from 0.86 to 1.08 across the tillage and nutrient-management treatments practiced for pearl millet system (Table 7 and Figure 1). For simple understanding, the soil quality indices were reduced to a scale of one and termed *relative soil quality indices* (RSQI), which varied between 0.72 to 0.90. It was observed that tillage as well as the nutrient-management treatments played a significant role in influencing the soil quality indices,

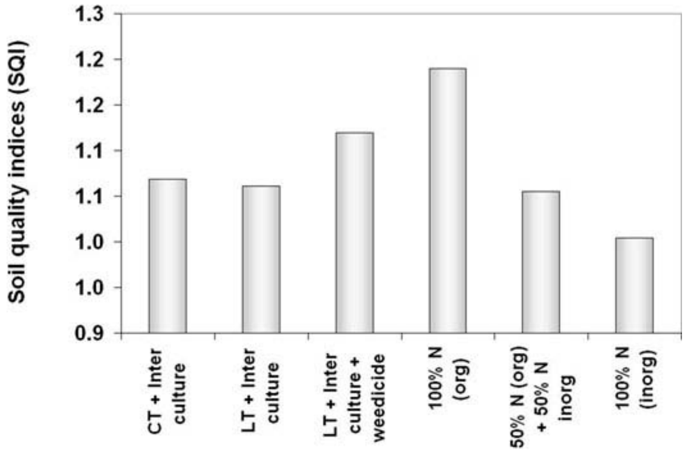

Figure 1. Average effects of tillage and nutrient-management treatments on soil quality indices under pearl millet system in Inceptisols of Agra.

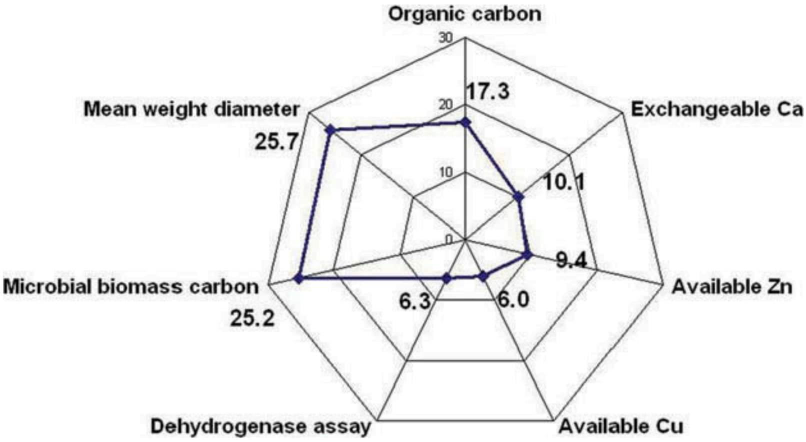

Figure 2. Percentage contributions of key soil quality indicators toward soil quality indices (SQI) as influenced by tillage and nutrient-management treatments under pearl millet system in Inceptisols of Agra.

whereas their interaction effects were not so conspicuous. When averaged over the nutrient-management treatments, practice of low tillage + one interculture + weedicide resulted in greater soil quality index of 0.98 followed by practice of conventional tillage + one interculture (0.94), which was at par with the practice of low tillage + one interculture (0.93). Among the nutrient-management treatments, it was interesting to note that application of nutrients solely through 100% organic sources maintained the greatest soil quality with SQI value of 1.05, whereas the remaining two nutrient-management treatments, 50% N (organic) + 50% (inorganic source) as well as 100% N (inorganic source) with SQI values of 0.92 and 0.88, maintained soil quality at par with each other respectively. When we studied the simultaneous influence of tillage and nutrient-management treatments (interactions) on soil quality, we observed that, despite being statistically nonsignificant, the relative order of performance of these treatments in influencing soil quality as indicated by SQI values was CT + IC + 100% N (organic source/compost) (1.08) > LT + weedicide + IC + 100% N (organic source/compost) (1.05) > LT + IC + 100% N (organic source/compost) (1.02) > LT + weedicide + IC + 50% N (organic) + 50 % inorganic source) (0.99) > LT + weedicide + IC + 100% N (inorganic source) (0.90) > LT + IC + 100% N (inorganic source) (0.89) > CT + IC + 50% N (organic) + 50% inorganic source) (0.88) = LT + IC + 50% N (organic) + 50% inorganic source) (0.88) > CT + IC + 100% N (inorganic source) (0.86). In this experiment, the average percentage contributions of key indicators toward soil quality indices were organic C (17%), exchangeable Ca (10%), available Zn (9%), available Cu (6%), dehydrogenase assay (6%), microbial biomass carbon (25%), and mean weight diameter (27%).

Experiment 2. In the second experiment, the long-term influence of conjunctive nutrient-management treatments on 19 soil quality parameters has been studied in pearl millet system. It was observed that out of 19 soil quality variables, only two variables (viz., pH and EC) were not significantly influenced by the management treatments and were dropped from the PCA. In the PCA of 17 variables, three PCs had eigenvalues >1 and explained 79.0% variance in the data set (Table 8). In PC1, five variables [viz., organic C, available

Table 8
Results of principal component analysis (PCA) of soil quality parameters as influenced by different conjunctive nutrient-management treatments under pearl millet system in Inceptisols of Agra

No.	PC1	PC2	PC3
Total eigenvalues	9.393	2.665	1.368
Percentage of variance (%)	55.253	15.678	8.047
Cumulative percentage (%)	55.253	70.930	78.977
Eigenvectors			
OC	**0.825**	0.074	0.247
N	**0.850**	0.131	−0.256
P	0.816	−0.129	−0.127
K	0.813	−0.180	0.055
Ca	0.651	−0.287	**0.543**
Mg	0.513	**0.795**	−0.031
S	0.736	0.200	0.465
Zn	0.297	**0.816**	0.293
Fe	0.778	0.323	−0.197
Cu	**0.821**	0.230	0.104
Mn	0.559	0.525	−0.432
B	0.716	−0.440	0.356
DHA	0.812	0.041	−0.022
MBC	0.767	−0.323	−0.445
LC	**0.912**	−0.160	−0.173
BD	−0.650	0.603	0.178
MWD	**0.861**	−0.228	−0.009

N, available Cu, labile C, and mean weight diameter (MWD)] were qualified as the highly weighted variables. In PC2, exchangeable Mg and available Zn were the highly weighted variables whereas in PC3, only exchangeable Ca was the highly weighted variable. The correlation matrix (Table 9) run for the variables qualified under PC1 revealed a quite significant correlation among all the five variables. However, considering their importance, we thought it appropriate to retain all the five variables (viz., organic C, available N, available Cu, labile C, and MWD). In PC2, the correlation analysis between the variables qualified revealed a significant correlation and hence available Zn was retained for final MDS while exchangeable Mg was dropped from the final MDS. Hence, the final parameters that were retained for the final MDS were organic C, available N, exchangeable Ca, available Zn and Cu, labile C, and mean weight diameter and were termed as the key indicators for pearl millet system under Inceptisols of Agra. As was done in experiment 1, to establish a quantitative relationship between the key soil quality indicators and average pearl millet yields, linear regressions were worked out using the seven final key soil quality indicators and the average pearl millet yields, All the variables were entered simultaneously and a significant model has emerged that accounts for 70.0% variance ($R^2 = 0.70$)* in the data set. The relationship between crop yield and key soil quality indicators could be explained as follows:

Table 9
Pearson's correlation matrix for highly weighted variables under PC's with high factor loading

PC1	OC	N	Cu	LC	MWD
OC	1.00	0.574*	0.685**	0.779**	0.703**
N	0.574*	1.00	0.787**	0.733**	0.759**
Cu	0.685**	0.787**	1.00	0.669**	0.679**
LC	0.779**	0.733**	0.669**	1.00	0.750**
MWD	0.703**	0.759**	0.679**	0.750**	1.00
Correlation sum	**3.741**	**3.853**	**3.820**	**3.931**	**3.891**
PC2	**Mg**	**Zn**			
Mg	1.00	0.735**			
Zn	0.735**	1.00			
Correlation sum	1.735	1.735			

*Correlation is significant at $P = 0.05$ level.
**Correlation is significant at $P = 0.01$ level.

$$\begin{aligned} \text{Yld}_{\text{Pearl millet}} = & -532.7 + 13.5\,(\text{OC}) - 3.62\,(\text{available N}) + 263.0\,\text{exc. Ca.} \\ & + 194.8\,(\text{available Zn}) + 315.8\,(\text{available Cu}) + 2.45\,(\text{LC}) \\ & - 1271.0\,(\text{MWD}) \quad (\text{R}^2 = 0.70)^*(P = 0.05) \end{aligned}$$

When soil quality indices (SQI) were computed using these seven key indicators, SQI values varied from 2.33 to 3.47 across the conjunctive nutrient-management treatments (Figure 3). In this case also, the SQI values were reduced to a scale of 0–1 termed as *relative soil quality indices* (RSQI), which varied from 0.64 to 0.95. Among all the treatments

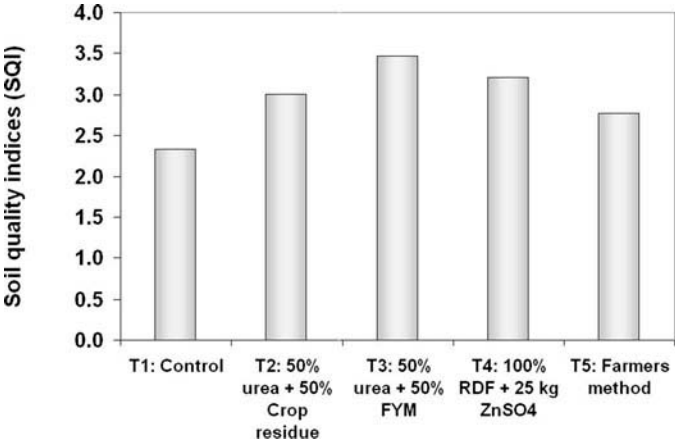

Figure 3. Soil quality indices as influenced by long-term use of conjunctive nutrient-management treatments under pearl millet system in Inceptisols of Agra.

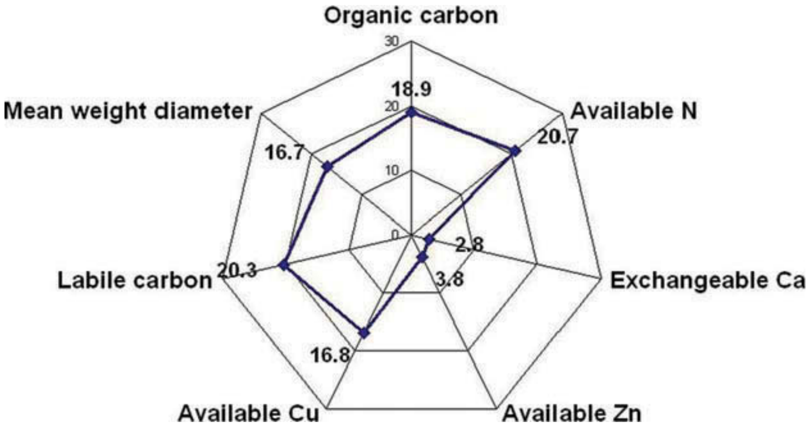

Figure 4. Percentage contributions of key soil quality indicators towards soil quality indices in long-term conjunctive nutrient-management treatments under pearl millet system in Inceptisols of Agra.

practiced, the application of 50% urea + 50% FYM showed the greatest SQI of 3.47, which was at par with 100% RDF + 25 kg zinc sulfate ($ZnSO_4$) (3.20). Irrespective of their statistical significance, the relative order of performance of the conjunctive nutrient-management treatments in influencing soil quality in terms of SQI was T3, 50% urea + 50% FYM (3.47) > T4, 100% RDF + 25 kg $ZnSO_4$ (3.20) > T2, 50% urea + 50% crop residue (3.01) > T5, farmers' method (2.77) > T1, control (2.33). The average percentage contributions of the key indicators to soil quality indices were organic carbon (19%), available N (20%), exchangeable Ca (3%), available Zn (4%) and Cu (17%), labile carbon (20%), and mean weight diameter (17%) (Figure 4).

Relevance of the Identified Key Soil Quality Indicators on Soil Functions

When the findings of both the experiments were considered together, the set of soil quality parameters that emerged as the key indicators for these rainfed Inceptisol soils were organic C, available N, exchangeable Ca, available Zn and Cu (chemical indicators); labile C, dehydrogenase assay, and microbial biomass C (biological indicators); and mean weight diameter (physical indicator). The importance of identifying key indicators for a given set of soil and climatic and crop conditions lies in the fact that these indicators help the land managers to take effective steps to improve soil quality for greater productivity. For Inceptisols, which are coarse textured and generally low in organic matter, buildup and maintenance of soil organic C becomes a challenging task. As evident from these results, use of organic sources of nutrients along with the inorganic sources can help in building up of the soil organic C if practiced on a long-term basis. Soil organic matter has a great deal of control on many of the key soil functions (Doran and Parkin 1994). It acts as a main source and sink of nutrients such as C, N, and partly of P and S, affects the micronutrient availability in soils (Frank, Ishida, and Suda 1976; Sharma and Chaudhary 2007) and is essential for maintaining good soil structure especially in low clay content soils as in the case of the present Inceptisols under study by helping in forming and stabilizing soil aggregates (Dalal and Mayer 1986). If intensive agriculture is practiced in these soils, there is every possibility of decrease in organic-matter content, which ultimately leads to loss in soil productivity (Hussain et al. 1999) because it correlates with a number of important physical, chemical, and microbiological properties. Hence**,** organic matter and organic matter–dependent properties become the most promising indicators for use in a soil quality assessment (Wander and Drinkwater 2000). Another important key indicator identified for these soils was available N. In the present study, despite the combined use of organic and inorganic sources of nutrients, available soil N trailed to the level much lower than the critical limit suggested for Indian conditions (<280 kg N ha^{-1}). Hence, any management practices that focus on improving this indicator become very crucial for ensuring greater crop yields. It is well established that micronutrients play an essential role in balanced plant nutrition and also for the growth and development of crops (Talukdar, Basumatary, and Dutta 2009). In this study, available Cu and Zn have emerged as the key indicators for these Inceptisol soils. The availability of micronutrients is usually influenced by the physicochemical properties of the soil as well as their distribution in soil (Sharma and Chaudhary 2007). To understand the inherent capacity of soil to supply these nutrients to plants, knowledge of the status of micronutrients and their interrelationship with soil characteristics is very helpful. Some studies revealed that organic C has a positive effect on available Zn, Cu, Mn, and Fe (Follett and Lindsay 1970; Karim, Sedberry, and Miller 1976; Katyal et al. 1991). Besides soil characteristics, land-use pattern also plays a vital role in governing the nutrient dynamics and fertility of soils (Venkatesh et al. 2003). Because of continuous cultivation, soils under a particular land-use system may directly or indirectly modify the DTPA-extractable micronutrient content and their availability to crops apart from affecting the soil physicochemical properties. So, periodical assessment of these key soil properties along with micronutrient status under different land-use systems may have significant importance to ensure appropriate fertility management (Talukdar, Basumatary, and Dutta 2009).

Apart from the chemical soil quality parameters, soil biological parameters such as labile carbon, dehydrogenase assay, and microbial biomass C emerged as the key indicators for these soils. In fact, these parameters serve as the potential early, sensitive indicators of soil degradation and contamination. According to Nortcliff (2002), biological attributes are very dynamic and exceptionally sensitive to changes in soil conditions, which make them preferential for short-term evaluations. These biological processes or indicators, apart from mediating the nutrient cycling (Mandal et al., 2007), are very closely related to the cycling of soil organic matter (SOM), which is a key component of soil quality (Beyer et al. 1993; Barrios et al. 2006). Microbial biomass C is a very dynamic and sensitive indicator of a long-term decline in total soil organic matter (Powlson, Brookes, and Christensen 1987; Cameron et al. 1998; Grace and Sharma 2010) fluctuating with weather, crop, input, and season (Garcia and Rice 1994). Another important key indicator that emerged in our study was the dehydrogenase activity. It is thought to reflect the total range of oxidative activity of soil microflora and consequently may be considered to be a good indicator of microbial activity (Nannperi, Grego, and Ceccanti 1990). The increase in dehydrogenase activity and microbial biomass would be in proportion to the addition of number and amount of nutrients (Manjaiah and Singh 2001; Masto et al. 2006). Soil labile organic C, another key indicator identified for the Inceptisol soils under study, is most active fraction of soil organic C with rapid turnover rates and would change substantially as a result of disturbance and management (Coleman, Crossley, and Hendrix 1996; Harrison, Broecker, and Bonani 1993; Zou et al. 2005). In view of the foregoing discussion, the relevance of MBC and LC in the Inceptisols under this study becomes very high because these soils, besides being low in soil fertility, are also poor in biological soil functions.

The only physical parameter that has emerged as the key soil quality indicator for these Inceptisols is the mean weight diameter. It measures the aggregate stability, which refers to the resistance of soil aggregates to breakdown by water and mechanical force

(Kay 1990). According to Tate (1995), aggregates play major roles in several aspects of soil health: the movement and storage of water, soil aeration, physical protection of SOM, prevention of erosion, root development, and microbial community activity. Measuring aggregate stability gives valuable data about soil structural degradation, which is often caused by loss of organic matter (Chen, Hseu, and Tsai 1998). The key indicator, mean weight diameter of soil aggregates, which ranged from 0.21 to 0.35 mm in these soils, was considerably low despite the management practices involving conjunctive use of organics and inorganic sources of nutrients. This clearly indicates the need for persistent efforts in soil structure management in these Inceptisols on a long-term basis.

Quantitative Relationship between Crop Yields and Relative Soil Quality Indices

The quantitative relationship between average pearl millet crop yields (mean of 4 years) (data not reported here) and relative soil quality indices (RSQI) irrespective of the management treatments for both the experiments together are presented in Figure 5. In most of the past studies, relationships of yields have been established with individual soil quality indicators for want of appropriate procedure to integrate the indicators to SQI and RSQI. In this study, we were interested to find out general quantitative relationship to predict the changes in yield with unit change in RSQI. For simplicity, we considered the 4-year mean pearl millet crop yields of both the experiments and their corresponding RSQI values to work out the relationships. The predictive function goes as follows:

$$\mathrm{Y} = -372.5 + 2449\mathrm{x} \qquad (\mathrm{R}^2 = 0.435)$$

where Y is the average pearl millet yield (kg ha^{-1}) and x is the relative soil quality index, which can vary from 0–1. To illustrate, if the RSQI value is 0.81, the pearl millet yield would be 1611 kg ha^{-1} against the observed value of 2059 kg ha^{-1}, thereby predicting about 78.6% of the observed value. It is interesting to note here that in both the experiments, average pearl millet yields (4-year mean) as influenced by the management treatments varied from 1055 to 2147 kg ha^{-1}. Thus, the relationship is useful to

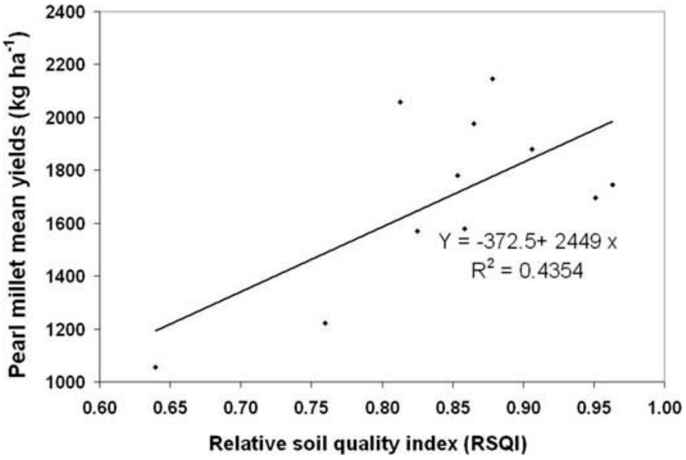

Figure 5. Predictive relationship between average pearl millet crop yield and relative soil quality indices (RSQI) irrespective of the management treatments.

compute the yield quantitatively with respect to the changes in soil quality for these rainfed Inceptisols. The same analogy can be used for similar soil types, climate, and cropping systems elsewhere.

Conclusions

The present study has clearly established that reduction in the intensity of tillage and supplementing nutrients, especially N, through organics either alone or in combination with inorganic fertilizer in the ratio of 1:1 on an N basis, played significant roles in positively influencing overall soil quality, which was measured by identifying the key soil quality indicators and computing the SQI. These rainfed Inceptisols, which are predominantly constrained by susceptibility to soil erosion, low fertility, nutrient imbalance, and miserably low soil organic matter, can be managed and rejuvenated for greater productivity, if the identified key indicators (viz., organic C, available N, exchangeable Ca, available Zn and Cu, labile C, dehydrogenase assay, microbial biomass C, and mean weight diameter of soil aggregates) are periodically assessed and monitored. If these indicators are adequately managed, the major soil functions such as nutrient release, availability characteristics, water retention and transmission characteristics, and desirable biological soil functions can be improved, which in turn will not only improve and sustain the soil quality but also the crop productivity on long-term basis. The prediction relationship developed between pearl millet crop yield and relative soil quality indices irrespective of management level in this study can be used to predict the changes in yield in response to given change in soil quality and vice versa. The methodology used in the study for identification of key indicators and assessment of soil quality is of state of the art and has a wider scope for use under diversity of climatic, edaphic, and crop conditions across the world. The present methodology is very effective in assessing the aggrading or degrading effects of different management practices on soil quality and screening the best practices for the benefit of land managers. However, to increase the further scope of this method for classifying the soils into different absolute soil quality classes, one has to include the inherent soil quality indicators/variables in addition to the presently used dynamic (management-sensitive) indicators. The authors believe that the information generated and presented in this article could be of good use to the future researchers, land managers, students, nongovernmental organizations, and federal and state agricultural departments in different tropical and subtropical regions not only in India but also across the world.

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