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Evaluation of long-term soil management practices using key indicators and soil quality indices in a semi-arid tropical Alfisol

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Abstract. Alfisol soils of rainfed semi-arid tropics (SAT) are degrading due to several physical, chemical, and biological constraints. Appropriate soil-nutrient management practices may help to check further soil degradation. A long-term experiment comprising tillage and conjunctive nutrient use treatments under a sorghum (*Sorghum bicolor* (L.) Moench)–mung bean (*Vigna radiata* (L.) Wilkzec) system was conducted during 1998–05 on SAT Alfisols (Typic Haplustalf) at the Central Research Institute for Dryland Agriculture, Hyderabad. The study evaluated soil and nutrient management treatments for their long-term influence on soil quality using key indicators and soil quality indices (SQI). Of the 21 soil quality parameters considered for study, easily oxidisable N ($KMnO_4$ oxidisable-N), DTPA extractable Zn and Cu, microbial biomass carbon (MBC), mean weight diameter (MWD) of soil aggregates, and hydraulic conductivity (HC) played a major role in influencing the soil quality and were designated as the key indicators of 'soil quality' for this system. The SQI obtained by the integration of key indicators varied from 0.66 (unamended control) to 0.83 (4 Mg compost + 20 kg N as urea) under conventional tillage (CT), and from 0.66 (control) to 0.89 (4 Mg compost + 2 Mg gliricidia loppings) under reduced tillage (RT). Tillage did not influence the SQI, whereas the conjunctive nutrient-use treatments had a significant effect. On an average, under both CT and RT, the sole organic treatment improved the soil quality by 31.8% over the control. The conjunctive nutrient-use treatments improved soil quality by 24.2–27.2%, and the sole inorganic treatment by 18.2% over the control. Statistically, the treatments improved soil quality in the following order: 4 Mg compost + 2 Mg gliricidia loppings > 2 Mg Gliricidia loppings + 20 kg N as urea = 4 Mg compost + 20 kg N as urea > 40 kg N as urea. The percentage contribution of the key indicators towards the SQI was: MBC (28.5%), available N (28.6%), DTPA-Zn (25.3%), DTPA-Cu (8.6%), HC (6.1%), and MWD (2.9%). The functions predicting the changes in yield and sustainability yield index with a given change in SQI were also determined.

Additional keywords: semi-arid tropics, soil quality indicators, sorghum-mung bean, sustainability yield index.

Introduction

Alfisols of semi-arid tropical regions of the world have been degraded in terms of soil quality primarily due to loss of topsoil by wind and water erosion, depletion of organic carbon, and losses of nutrients (ICRISAT 1987). Tillage is a major factor dictating loss of soil organic matter (Rasmussen *et al*. 1989), and in order to maintain a high level of soil organic matter to enhance soil tilth, fertility, and productivity, there has been a growing awareness among researchers to identify suitable soil management practices depending upon climatic and edaphic conditions. These management practices may ensure the protection of soil from erosion, reduction in the loss of nutrients through runoff, improvement in soil fertility, sustainability in production, and maintenance of overall soil quality in the tropics. In most long-term experiments initiated world-wide to identify suitable soil-management treatments, the main research focus until the end of the 20th Century was to monitor increases in yields and individual changes in predominant soil parameters. For example, research focussed on yield and chemical properties (Malhi *et al*. 2000; Noble and Hurney 2000), soil fertility and yield (Mohammad and Mohammad 1999), yield (Suresh *et al*. 1999; Subbarao *et al*. 2000), physical properties (Unger *et al*. 1998), carbon pools (Campbell *et al*. 1998), chemical soil quality (Eck and Stewart 1998), etc. In order to quantitatively assess the effects of the long-term management systems or practices on the capacity of the soils to function, the soil quality assessment approach has been a paradigm shift (Dalal and Moloney 2000; Andrews and Carroll 2001).

Soil quality has been defined as the 'capacity of the soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health' (Doran and Parkin 1994). In the past soil quality was understood as the inherent capacity of the soil to supply essential plant nutrients. Later, it was viewed as an abstract characteristic of soils that could not be defined because of its dependence on external factors such as land-use and soil management practices, ecosystem and environmental interaction, socioeconomic and political priorities, and so on (Doran *et al*. 1996).

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Soil quality cannot be measured directly, but must be inferred from measuring changes in its attributes or attributes of the ecosystem, referred to as indicators. These indicators may directly monitor the soil, or monitor the outcomes that are affected by the soil, such as increases in biomass, improved water use efficiency, and aeration. Soil quality indicators can also be used to evaluate sustainability of land-use and soil management practices in agroecosystems (Shukla *et al*. 2006). The indicators which directly monitor soil quality are grouped into 4 categories as visual, chemical, physical, and biological indicators (Dalal and Moloney 2000). Nortcliff (2002) stated that there are potentially many soil properties which might serve as indicators of soil quality, and research is required to identify the most suitable. He also emphasised that the methods used in determining these indicators must be fully defined, otherwise the comparison of different sets of data may be of little value. Mairura *et al*. (2007) reported the integration of scientific and farmers' evaluation of soil quality indicators and emphasised that the indicators for distinguishing productive and non-productive soils include crop yields and performance, soil colour, and its texture. Parr *et al*. (1992) suggested that increased infiltration, aeration, macropores, aggregate distribution and their stability, and soil organic matter, and decreased bulk density, soil resistance, erosion, and nutrient runoff are some of the important indicators for improved soil quality. Further, Chaudhury *et al*. (2005) identified total soil N, available P, dehydrogenase activity and mean weight diameter (MWD) of aggregates as the key indicators for Alluvial soils. Karlen *et al*. (1992) suggested biological measurements, viz. microbial biomass, respiration, and ergosterol concentrations, as very effective indicators for assessing long-term soil and crop management effects on soil quality. Assessment of soil-test properties from time to time has also been emphasised for evaluating the chemical aspects of soil quality (Arshad and Coen 1992; Karlen *et al*. 1992). 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 (Wang and Gong 1998; Shukla *et al*. 2006). However, when selecting indicators, it is important to ensure that they: (*i*) correlate well with natural processes in the ecosystem (this also increases their utility in process-oriented modelling); (*ii*) integrate soil physical, chemical, and biological properties and processes, and serve as basic inputs needed for estimation of soil properties or functions which are more difficult to measure directly; (*iii*) be relatively easy to use under field conditions, so that both specialists and producers can use them to assess soil quality; (*iv*) be sensitive to variations in management and climate; and (*v*) be components of existing soil databases wherever possible (Doran and Parkin 1996; Doran *et al*. 1996; Chen 1998).

Interpreting soil quality merely by monitoring changes in individual soil quality indicators may not give complete information about soil quality. The recent approach in assessing soil quality includes normalisation of the data from measurements and conversion to a numeric value that is more than a static descriptor, called a 'soil quality index' (SQI), which can be used to compare various management practices or to assess management-induced changes over time. Therefore, combining them in a meaningful way to a single index may assess soil quality more precisely (Jaenicke and Lengnick 1999; Bucher 2002) to be used to gauge the level of improving or declining soil condition (Wienhold *et al*. 2004). A valid SQI would also help with interpretation of data from different soil measurements and show whether management and land-use are having the desired results for productivity, environmental protection, and health (Granatstein and Bezdicek 1992). Masto *et al*. (2007) stated that the soil quality concept provides a tool to help quantify the combined biological, chemical, and physical response of soil to crop management practices. But the best way to assess soil quality is to link these indicators (soil properties) with soil functions (Doran and Parkin 1994; Karlen *et al*. 1996).

Recently, however, with the intensification in agriculture, most of the systematic research efforts on the assessment of soil quality have been in temperate regions (Hussain *et al*. 1999; Andrews *et al*. 2002*a*; Shukla *et al*. 2006). Information is much more limited in the fragile agro-ecosystems of the tropics (Palm *et al*. 1996; Ericksen and McSweeney 2000), which suffer more in terms of climatic and edaphic constraints and soil quality degradation. Some research initiatives have been made on systematic assessment of soil quality on the Indian subcontinent in (*i*) a semi-arid tropical Alfisol (Sharma *et al*. 2005), (*ii*) irrigated Inceptisols (Masto *et al*. 2007), (*iii*) an irrigated rice–wheat system on Vertisols (Mohanty *et al*. 2007), and (*iv*) the lowlands of Assam under a rice-based system (Singh 2007). In most of these studies, a wide spectrum of methodologies and varying sets of indicators have been used under irrigated conditions with high cropping intensities and higher levels of management. Little research effort has been made on systematic soil quality assessment in cereal–legume systems under conservation tillage using low-cost conjunctive nutrient-use treatments comprising farm-based organics in a rainfed semi-arid tropical Alfisol.

An 8-year-old, long-term, on-going experiment comprising conservation tillage and conjunctive nutrient-use treatments under a sorghum (*Sorghum bicolor* (L.) Moench)–mung bean (*Vigna radiata* (L.) Wilkzec) system was evaluated for soil quality. The main objectives of the study were (*i*) to identify the key soil quality indicators for Alfisols under a sorghum–mung bean system, (*ii*) to compute the SQI by integrating key indicators in corroboration with the functional goals, and iii) to evaluate the soil and nutrient management treatments for their long-term influence on soil quality using key indicators and SQI.

Materials and methods

A long-term experiment was initiated during 1998 at Hayathnagar Research Farm of the Central Research Institute for Dryland Agriculture, Hyderabad, situated at 17°18′N, 78°36′E at an elevation of 515 m above mean sea level. This region is semi-arid tropical with hot summers and mild winters and a mean annual temperature of 26°C. The mean maximum temperature from March to May varies from 36 to 39°C. Mean minimum temperature during December to February ranges from 14 to 17°C. Mean annual rainfall is 746 mm and accounts for approximately 42% of annual potential evapotranspiration (1754 mm). Nearly 70% of the total precipitation is received during the south-west monsoon season (June–September). The experimental soils belong to Hayathnagar series (Typic Haplustalf) and are slightly acidic to neutral in reaction (pH 6.5) with sandy loam texture and increasing clay content to 18% in the lower horizons. The soils are low in available N (145 kg/ha), and medium in available P (13.0 kg/ha) and available K (157 kg/ha). The initial organic carbon content of the soils was 5.2g/kg. The experiment was laid out in a split-plot design with 2 tillages (conventional (CT) and reduced (RT)) as main treatments and 5 low-cost, farm-based conjunctive nutrient-use treatments as sub-treatments laid out in 16 by 4 m plots with 3 replicates. Sorghum and mung bean were used as test crops. CT consisted of 2 ploughings (carried out by tyned cultivator) before planting + one plough planting + harrowing + operation for topdressing (this includes summer tillage/off season tillage); RT comprised plough planting + operation for topdressing of N using light implements such as a pick axe.

Five conjunctive nutrient-use treatments equivalent to 40 kg N/ha applied to the sorghum crop were: control (no N) (T_1), 40 kg N as urea (T_2), 4 Mg compost + 20 kg N as urea (T_3), 2 Mg gliricidia (*Gliricidia maculata*) loppings + 20 kg N as urea (T_4), and 4 Mg compost + 2 Mg gliricidia loppings (T_5). The mung bean crop received the same treatments but the doses were reduced to half to supply N equivalent to 20 kg N/ha. Compost (N content 5 g/kg) was spread before sowing the crops. Sorghum received fertiliser N as urea in 2 equal splits, one half as basal at the time of sowing and another half 30–35 days after sowing (DAS), while mung bean received N in a single split as basal dose. Fresh loppings of gliricidia (a nitrogen-fixing tree containing 33.3 g N/kg dry-weight basis in leaves and twigs) were applied at 30–35 DAS as per the treatments along with second split of N. Recommended rate of P (13.0 kg P/ha) as single superphosphate was broadcast equally to both sorghum and mung bean crops uniformly before sowing. As the soils fall under the medium category of available K, its application is not recommended for this region and hence it was not applied to the crops. Crop yield data were recorded for each year from 1998 to 2005 except for 2003 when the crop failed due to severe drought. The crop yield data were analysed statistically by using split-plot design (Snedecor and Cochran 1989). The sustainable yield index (SYI) was computed as follows:

$$SYI = (Y - \sigma)/Y_{max}$$

where Y is the average yield of the treatments across the years, σ is the treatment standard deviation, and Y_{max} is the maximum observed yield over years in the experiment (Singh *et al.* 1990). In this paper, the yield and SYI data were used only as functional goals in the process of identification of key indicators and computation of soil quality.

Soil sampling and analyses

Soil samples were drawn from 0–0.20 m depth after the eighth cropping season (during 2005) of the study. The soils were analysed for pH and electrical conductivity (EC) (Rhoades 1982), organic carbon (SOC) by the Walkley-Black procedure (Anderson and Ingram 1996), available N (Subbaiah and Asija 1956), available P (Olsen *et al.* 1954), and available K and exchangeable Ca and Mg (Hanway and Heidel 1952), available S was determined after extracting with 0.15% $CaCl_2$ (Williams and Steinbergs 1959). Micronutrient cations (Zn, Fe, Cu, Mn) (Lindsay and Norvell 1978) and concentrations were measured using inductively coupled plasma spectrophotometer, model ICP-OES simultaneous system, GBC-Australia. Boron was estimated using DTPA-Sorbitol extraction (Miller *et al.* 2000).

Bulk density (BD) was measured by soil core method (Blake and Hartge 1986) and hydraulic conductivity (HC) by constant head method (Klute 1965). The distribution of aggregate sizes was determined using the wet sieving technique (Yoder 1936) and MWD was computed (van Bevel 1949). MWD was calculated using the equation:

$$MWD = \sum_{i=1}^{n} (X_i \times W_i)$$

where X_i is the average diameter of each particle class (mm), and W_i is the proportion by weight of the given size fraction of aggregate relating to X_i.

Microbial biomass C and N (MBC, MBN) were estimated using the chloroform fumigation incubation technique (Jenkinson and Powlson 1976; Jenkinson and Ladd 1981). Dehydrogenase activity (DHA) in the soils was measured by triphenyl tetrazolium chloride method (Lenhard 1956). Labile carbon (LC), also considered an important biological soil quality indicator, was estimated using the method suggested by Weil *et al.* (2003) with slight modification.

Computation of soil quality index

The data obtained on the soil quality parameters were subjected to analysis of variance (ANOVA) using a split-plot design for testing their level of significance. To identify the minimum dataset, various successive steps of data analysis were followed, primarily employing the principal component analysis (PCA) technique (Doran and Parkin 1994; Andrews *et al.* 2002*a*) using SPSS (Version 9.0). Principal components (PC) for a dataset are defined as linear combinations of variables that account for maximum variance within the set by describing vectors of closet fit to the *n* observation in *p*-dimensional space, subject to being orthogonal to one another. PCA is a mathematical procedure that transforms several (possibly) correlated variables into a (smaller) number of uncorrelated variables (PC). The objective of PCA is to reduce the dimensionality of the parameter dataset and to identify new meaningful underlying variables, knowing that the PC are dependent on the units used to measure the original variables as well as on the range of values they assume. The first PC accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible.

In brief, the various successive steps of analysis followed to identify key indicators and to compute SQI included the following: (*i*) fixing or defining the goals, (*ii*) testing the level of significance for various soil indicators as influenced by various management treatments, (*iii*) PCA to select representative minimum dataset (MDS), (*iv*) correlation analysis among soil variables to reduce spurious grouping among highly weighted variables within each PC, (*v*) multiple regression using the final MDS components as the independent variables and each goal attribute as a dependent variable, and (*vii*) scoring of the MDS indicators based on their performance of soil function and computation of SQI.

Results and discussion

Effect on soil and nutrient management treatments on soil parameters

The data on 21 soil quality parameters, physical (BD, MWD of aggregates, HC), chemical (pH, EC, SOC, available N, P, K, exchangeable Ca and Mg, available S, DTPA-extractable micronutrients Zn, Fe, Cu, Mn, and B), and biological (DHA, MBC, LC, MBN) are presented in Table 1.

Tillage had significant influence on soil pH, available S, DTPA-extractable Mn, and HC, while the conjunctive nutrient-use treatments significantly influenced all chemical physical and biological parameters except pH and Ca. The interactive effect of tillage and nutrient management treatments was, however, significant only for available P and K, DTPA-extractable Zn and Fe, DHA, and LC contents of the soils. Among the nutrient-use treatments, the sole organic treatment (4 Mg compost + 2 Mg gliricidia loppings) increased the SOC by 21.6%, available N by 24.5%, DHA activity by 56.1%, MBC by 38.8%, LC by 20.3%, and MBN by 38.8% over the unamended control.

As most of the soil quality parameters except exchangeable Ca were significantly influenced by the soil-nutrient management treatments, we considered all of the variables for PCA (Table 2). Since these soils were slightly acidic to neutral in reaction constituting 1 : 1 layer silicates (kaolinites with cation exchange capacity 14 cmol/kg), they would release exchangeable Ca into the soil solution at only 20–40% Ca saturation of the exchange complex (Prasad and Power 1999). Hence, exchangeable Ca was considered important to regulate its supply in soil solution and was also considered for PCA. As per the criteria set by Brejda *et al*. (2000), in the present study, the PC with eigen values $\geq$1 and which explained at least 5% of the variation in the data (Wander and Bollero 1999) were considered. The PC with higher eigen values and variables which had high factor loading were considered as best representative of system attributes. The amount of variability explained by PC1, PC2, PC3 PC4, and PC5 was 41, 14, 13, 10, and 5%, respectively. However, the cumulative variance was 81.65%. Within each PC, only highly weighted factors (having absolute values within 10% of the highest factor loading) were retained for MDS. When more than one factor was retained under a single PC, multivariate correlation coefficients were used to determine if the variables could be considered redundant and therefore eliminated from the MDS (Andrews *et al*. 2002*a*). From the group of variables which were well correlated ($r > 0.70$) with one another, only one variable was considered for the MDS. However, flexibility criteria were also followed in rare circumstances depending upon the importance of the variables. The remaining variables were eliminated from the dataset. If the highly weighted variables were not correlated, each was considered important and was retained in the MDS.

In PC1, the 4 variables qualified for the next step were: available N, DTPA-Zn, MBC, and MBN. However, all of these variables were found well correlated ($r > 0.70$) in the inter-correlation study as per the criteria suggested by Andrews *et al*. (2002*a*) (Table 3). Since semi-arid tropical soils suffer from poor fertility, especially available N and Zn, they were considered important from the view point of soil fertility and were retained. Further, based on well-correlated criteria, MBC and MBN were considered as representative indicators of each other and only MBC was retained being an important biological soil quality indicator. Finally in PC1, available N, Zn, and MBC were retained for the MDS.

In PC2, among the 3 variables (pH, EC, Ca) that qualified, pH and Ca, though not well correlated ($r > 0.7$) were found to have significant correlation. As the soil reaction was slightly acidic to near neutral, pH was not found to be a major constraint and hence was dropped from the MDS. Considering the importance of Ca in plant nutrition in these soils, among this group of variables, only Ca was retained for the MDS and the rest of the variables were eliminated. Similar to PC2, in PC3, Cu and Mn, though not well correlated ($r < 0.70$), were significantly correlated with each other, among which only one variable was needed to be retained. As the Mn content in these Alfisols was well above the critical limit set for plant availability (>2.5 μg/g), it was considered redundant, and Cu, which was $\leq$1 μg/g, was retained for the final MDS. In PC4, among the significantly correlated variables, i.e. available P and HC, only HC was retained, as it is one of the representative variables of physical properties of Alfisols, which suffer from crusting and hard setting tendencies and low water retention. As the available P content in soil was adequate (>25 kg/ha), it was eliminated from the MDS. In PC5, only 1 variable, i.e. MWD of the soil aggregates, was found to qualify and was retained for the MDS. As a whole, from PC1 to PC5, the variables that qualified and were retained for final MDS were: available N, DTPA-Zn and Cu, MBC, exchangeable Ca, HC, and MWD.

As a check of how well the MDS represented the management system goals, and to identify the key indicators, multiple regressions were performed using the indicators retained in the MDS as independent variables and the end-point measures such as mean yields of sorghum and mung bean, SYIs of sorghum and mung bean, and SOC as dependent variables (Table 4). When the MDS was regressed with these functional goals, the coefficient of determination (R^2) varied from 0.72 to 0.93. The variables that were found significant at $P = 0.000$–0.083 were accepted for the final MDS. Hence, based on the series of analytical data screening steps, only available N, Zn, and Cu, MBC, MWD, and HC were declared the key indicators for Alfisol under the sorghum–mung bean system under conventional and reduced tillage.

After identifying the MDS indicators, every observation of each MDS indicator was transformed using a linear scoring method as suggested by Andrews *et al*. (2002*b*). To assign the scores, indicators were arranged in order depending on whether a higher value was considered ‘good’ or ‘bad’ in terms of soil function. In case of ‘more is better’ indicator, each observation was

Table 1. Soil quality parameters as influenced by tillage and conjunctive nutrient use treatments after 8 years of the study in a semi-arid tropical Alfisol

CT, Conventional tillage; RT, reduced tillage; Till, tillage; NUT, nutrient-use treatments (st, at same till; sdt, at same or different till); n.s., not significant at $P = 0.05$. EC, Electrical conductivity (dS/m); OC, organic carbon (g/kg); N, P, K: available nitrogen, phosphorus, potassium (kg/ha); Ca, Mg: exchangeable calcium, magnesium ($cmol_c$/kg); S, Zn, Fe, Cu, Mn, B: available sulfur, zinc, iron, copper, manganese, boron (μg/g); MBC, microbial biomass carbon (μg/g soil); DHA, dehydrogenase activity (μg TPF/h/g); MBN, microbial biomass nitrogen (kg/ha); LC, labile carbon (mg/kg); BD, bulk density (Mg/m^3); MWD, mean weight diameter (mm); HC, saturated hydraulic conductivity (cm/h)

	pH	EC	OC	N	P	K	Ca	Mg	S	Zn	Fe	Cu	Mn	B	DHA	MBC	MBN	LC	BD	MWD	HC
CT	6.51	0.08	6.1	160.5	33.1	145.4	3.64	1.42	10.2	1.11	9.4	0.95	13.7	0.72	1.78	145.1	53.4	236.4	1.75	0.12	3.77
RT	6.70	0.07	6.5	168.6	29.0	146.3	3.65	1.23	11.6	1.16	9.2	0.91	12.1	0.73	1.84	153.7	56.2	244.0	1.74	0.14	2.79
l.s.d. ($P = 0.05$)	0.14	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	1.09	n.s.	n.s.	n.s.	1.42	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.16
T1	6.57	0.06	5.7	145.3	27.5	135.5	3.32	0.98	8.21	0.86	7.5	0.82	11.4	0.38	1.40	120.5	44.2	217.0	1.79	0.11	2.78
T2	6.45	0.06	6.1	158.4	28.9	142.7	3.60	1.33	13.1	1.08	11.0	1.05	15.5	0.68	1.75	147.1	53.9	246.2	1.74	0.13	3.19
T3	6.75	0.10	6.6	171.4	32.4	154.9	4.13	1.40	10.1	1.17	9.7	1.00	14.2	0.83	1.68	154.3	56.6	232.2	1.74	0.15	3.39
T4	6.59	0.06	6.4	166.5	32.5	140.5	3.46	1.36	11.9	1.29	10.9	0.93	12.0	0.96	2.02	158.1	58.0	244.7	1.73	0.12	3.32
T5	6.67	0.09	6.9	180.9	34.2	155.9	3.73	1.56	11.2	1.28	7.4	0.87	11.6	0.76	2.18	167.2	61.4	261.0	1.73	0.15	3.70
l.s.d. ($P = 0.05$)																					
NUT	n.s.	0.03	0.37	8.22	3.08	9.38	n.s.	0.13	1.44	0.06	1.3	0.09	1.3	0.04	0.16	7.72	2.85	9.42	0.03	0.17	0.17
NUTst	n.s.	n.s.	n.s.	n.s.	4.36	13.3	n.s.	n.s.	n.s.	0.09	1.8	n.s.	n.s.	n.s.	0.23	n.s.	n.s.	13.3	n.s.	n.s.	n.s.
NUTsdt	n.s.	n.s.	n.s.	n.s.	5.48	20.5	n.s.	n.s.	n.s.	0.09	1.6	n.s.	n.s.	n.s.	0.23	n.s.	n.s.	12.8	n.s.	n.s.	n.s.

Table 2. Performance of soil quality indicators in terms of factor loading/eigen vector values in principal component analysis
Bold values indicate the eigen vectors within 10% of the highest factor loadings

PCs	PC1	PC2	PC3	PC4	PC5
Eigen value	8.564	2.925	2.669	1.951	1.037
% Variance	40.782	13.930	12.712	9.290	4.939
Cumulative %	40.782	54.712	67.424	76.714	81.652
Factor loading/eigen vector					
pH	0.257	**0.790**	−0.064	−0.313	−0.159
EC	0.412	**0.780**	0.260	0.150	−0.086
Organic C	0.793	0.110	−0.340	−0.028	−0.009
Avail. N	**0.816**	−0.056	−0.276	−0.009	0.039
Avail. P	0.407	−0.303	−0.082	**0.721**	−0.223
Avail. K	0.589	0.602	0.095	0.183	0.219
Exch. Ca	0.360	**0.765**	0.375	−0.057	−0.051
Exch. Mg	0.722	−0.142	0.129	0.454	0.281
Avail. S	0.546	−0.531	0.045	−0.424	0.350
Zn	**0.863**	−0.201	−0.109	−0.057	−0.291
Fe	0.213	−0.357	0.697	−0.381	−0.119
Cu	0.328	−0.060	**0.821**	−0.188	−0.018
Mn	0.132	−0.057	**0.825**	0.096	0.361
B	0.810	−0.216	0.184	−0.043	−0.369
Dehydrogenase assay	0.774	−0.164	−0.151	0.031	0.244
Microbial biomass C	**0.907**	−0.071	−0.113	−0.161	−0.177
Bulk density	–0.778	0.077	−0.084	0.203	−0.000
Mean wt diam.	0.632	0.248	−0.398	−0.007	**0.453**
Hydraulic cond.	0.410	−0.097	0.343	**0.762**	−0.079
Labile C	0.749	−0.042	−0.131	−0.160	0.062
Microbial biomass N	**0.919**	−0.006	−0.098	−0.134	−0.170

Table 3. Inter-correlations between highly weighted variables under different PCs
$^{**}P < 0.01$

PC1 variables	N	Zn	MBC	MBN
N	1	0.689**	0.774**	0.774**
Zn	0.689**	1	0.846**	0.854**
MBC	0.774**	0.846**	1	0.997**
MBN	0.774**	0.854**	0.997**	1
PC2 variables	pH	EC	Ca	
pH	1	0.632	0.606**	
EC	0.632**	1	0.809**	
Ca	0.606**	0.809**	1	
PC3 variables	Cu	Mn		
Cu	1	0.668**		
Mn	0.668**	1		
PC4 variables	P	HC		
P	1	0.644**		
HC	0.644**	1		

divided by the highest observed value such that the highest observed value received a score of 1. For 'less is better' indicator, 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. In this study, all of the indicators retained in the MDS were considered good from the view point of soil quality when they are in increasing order, and hence the 'more is better' approach was followed. After transformation using a linear scoring method, the MDS indicators scores thus obtained for each observation were multiplied with the weighted factor obtained from the PCA results Each PC explained a certain amount (%) of the variation in the total dataset. This percentage, when divided by the total percentage of variation explained by all the PCs with eigen vectors >1, gave the weighted factors for indicators chosen under a given PC. The weighted factors (percent variation of each PC divided by the cumulative percent variation explained by all the PCs) for PC1, PC2, PC3, PC4, and PC5 were 0.50, 0.17, 0.16, 0.11, and 0.06, respectively.

After performing these steps, to obtain SQI, the weighted MDS indicator scores for each observation were summed up using the following relationship:

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

where S_i is the score for the subscripted variable and W_i is the weighing factor obtained from the PCA. The SQI thus obtained were normalised with respect to the maximum possible SQI, i.e. summation of maximum PCA weighting factors of each key indicator, and the data are presented in Table 5.

The results revealed that the SQI varied from 0.66 (control) to 0.86 (4 Mg compost + 20 kg N as urea) under CT, while under RT, it varied from 0.66 (control) to 0.89 (4 Mg compost + 2 Mg gliricidia loppings). Tillage alone did not show any significant effect on SQI, whereas the conjunctive nutrient-use treatments significantly influenced the SQI in these semi-arid tropical Alfisols. Among all the treatments, when averaged over tillage, application of 4 Mg compost + 2 Mg gliricidia loppings showed the highest SQI (0.87) followed by 2 Mg gliricidia loppings + 20 kg N as urea (0.84), which was at par with 4 Mg compost + 20 kg N as urea (0.82). The interaction effects of tillage and conjunctive nutrient-use treatments were also significant on SQI. On an average, under both CT and RT, the sole organic treatment out-performed in improving the soil quality to the extent of 31.8% over control. The conjunctive nutrient-use treatments improved the soil quality by 24.2–27.2%, while the sole inorganic treatment improved soil quality only by 18.2% over the control. Interestingly, even the control, which did not receive any N input in the form of treatment, except P, also maintained SQI of as high as 0.66. This may be attributed to the beneficial effect of legume crops grown in rotation with cereals, as various rotations, mainly cereal/legumes, combined with reduced tillage, could influence soil organic matter and associated aggregation and related hydraulic properties (Masri and Ryan 2006). In the present study, the overall order of superiority of the treatments from the viewpoint of soil quality indices was: T5 > T4 = T3 > T2 > T1.

In order to know the contribution of each of the indicators towards soil quality, their average linear scores under each soil–nutrient management treatment were computed and have been depicted in Fig. 1. Considering the average linear scores,

Table 4. Verification of minimum dataset (MDS) variables through multiple regressions using functional goals as dependent variables—identification of key indicators

Functional goals	R^2	Most significant MDS variables	Probability levels (*P*)
Average sorghum yield	0.78	MBC, Cu, HC	>0.115, >0.013, >0.001
Sustainability yield index of sorghum	0.82	MBC, Cu, HC	>0.066, >0.036, >0.000
Average mung bean yield	0.89	Zn, MBC, Cu, HC	>0.083, >0.163, >0.004, >0.000
Sustainability yield index of mung bean	0.93	Zn, Cu, HC	>0.163, >0.000, >0.000
Organic carbon	0.72	Zn, N, MWD	>0.117, >0.092, >0.064

Table 5. Effect of soil-nutrient management treatments on overall soil quality indices

	Conjunctive nutrient use treatments equal to 40 kg N/ha	Conventional tillage	Reduced tillage
1	T1, Control	0.66	0.66
2	T2, 40 kg N as urea	0.78	0.77
3	T3, 4 Mg compost + 20 kg N as urea	0.83	0.82
4	T4, 2t Gliricidia loppings + 20 kg N as urea	0.80	0.87
5	T5, 4 Mg compost + 2 Mg gliricidia loppings	0.86	0.89
l.s.d.	Between tillage means	n.s.	
($P = 0.05$)	Between treatment means	0.02	
	Between two treatment means at same tillage	0.03	
	Between two treatment means at same or different tillage	0.03	

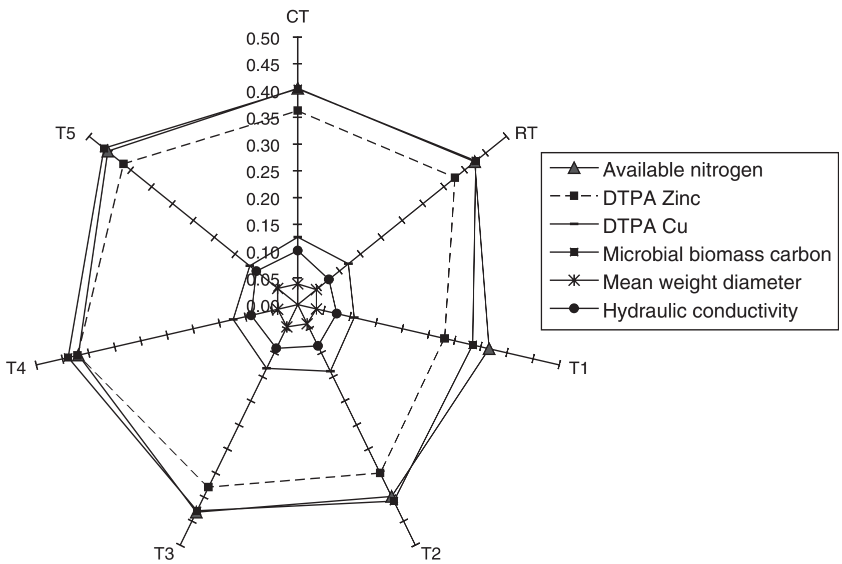

Fig. 1. Radar graph depicting the average linear scores of key indicators as influenced by soil-nutrient management treatments. CT, Conventional tillage; RT, reduced tillage; T1, Control; T2, 40 kg N as urea; T3, 4 Mg compost + 20 kg N as urea; T4, 2 Mg gliricidia loppings + 20 kg N as urea; T5, 4 Mg compost + 2 Mg gliricidia loppings.

the order of importance of the key indicators in influencing soil quality was MBC (0.41) = available N (0.41) > DTPA-Zn (0.37) > DTPA-Cu (0.12) > HC (0.09) > MWD (0.04), with a corresponding contribution of 28.5%, 28.6%, 25.3%, 8.6%, 6.1%, and 2.9%, respectively, in these soils. This showed that these key indicators have a considerable role to play in influencing various soil functions and in turn the functional goals.

In order to establish the quantitative relationship between SQI and functional goals, linear regressions were worked out between yields and SYIs of sorghum and mung bean as dependent variables (*Y*) and SQI as independent variable (*X*). The linear regression equations along with linear regression coefficients (R^2) are given in Table 6. The regression coefficients varied from a minimum of 0.39 with mung bean SYI to a maximum of 0.67 with mung bean yield and were

Table 6. Prediction equations for functional goals using normalised soil quality indices (SQI)

Goal or function	R^2	P	Regression equations
Average sorghum yield (Y_S)	0.56	>0.000	$Y_S = -1018.6 + 3204.5 \times SQI$
Sustainability yield index of sorghum (SYI_S)	0.47	>0.000	$SYI_S = -0.302 + 0.9592 \times SQI$
Average mung bean yield (Y_{MB})	0.67	>0.000	$Y_{MB} = -348.2 + 1448.9 \times SQI$
Sustainability yield Index of mung bean (SYI_{MB})	0.39	>0.000	$SYI_{MB} = -0.104 + 0.5906 \times SQI$

found highly significant. These simple equations help in understanding the changes in functional goals with a given change in SQI.

Our study has clearly indicated that in a semi-arid tropical rainfed Alfisol, available N, DTPA-Zn and Cu, MBC, MWD, and HC were the key indicators of 'soil quality', which greatly influence the soil functions and overall soil quality and, in turn, help in achieving the functional goals. Among these indicators, the available N contributing 28.5% towards soil quality in the present study is low in these soils. This happens because the major portion of N in soil comes from soil organic matter (Smith and Elliott 1990), which itself is very low because of the nature of the climate in semi-arid tropics. Nitrogen plays an important role in soil and plant functions. It is a well-established fact that the vegetative growth of a plant is primarily governed by soil N. Adequate supply of N not only helps in improving the above ground biomass and grain yields, but also plays an important role in improving the below ground biomass by way of contributing more root biomass. This, in turn, is crucial for improving SOC and influencing the mineralisation and immobilisation processes and other rhizosphere activities, ultimately leading to improved functional capacity of soil. Further, among the chemical soil quality indicators, DTPA-extractable Zn and Cu have also emerged as important key indicators, contributing about 25.3% and 8.6%, respectively, towards relative SQI. Since the soils in the present study were slightly acidic in reaction, these 2 elements play a crucial role in influencing the soil and plant functions. Among the biological soil quality indicators, MBC emerged as the key indicator contributing about 28.5% towards SQI. Soil microbial biomass is a labile source and sink of nutrients influencing predominant soil functions such as nutrient availability and their cycling and is a good indicator of potential microbial activity (Dalal and Meyer 1987; Myrold 1987). Therefore, any management practice which helps in improving MBC in soil would definitely contribute towards aggradation or improvement of soil quality. Among the set of physical soil quality indicators, MWD and HC qualified as the key indicators, contributing about 2.9% and 6.1%, respectively, towards soil quality indices. It is well established that MWD is an index presenting the structure of soil and the quality of organic inputs as well as the quantity (Tisdall and Oades 1982). However, MWD is mostly affected by quantity of organic matter, types of clays, wetting and drying, freezing and thawing, types and amounts of electrolytes, biological activity, cropping systems, and tillage practices (Arshad *et al*. 1996). Further, HC also has importance for these soils, as it influences the predominant soil functions such as water infiltration rate, aeration, porosity, conductance, and transmission of water, etc., and could be a good predictor of soil quality. Keeping in view the foregoing discussion, the set of key indicators qualified in the present study was considered as the most relevant to compute soil quality for these soils under sorghum–mung bean system.

Conclusions

Present study clearly indicated that available N, DTPA-Zn and Cu, MBC, MWD, and HC were the key indicators of 'soil quality' in a semi-arid tropical rainfed Alfisol. These indicators greatly influenced the soil functions and overall soil quality, which in turn influenced the functional goals such as mean yields and SYIs of sorghum and mung bean, and SOC. Among the subtreatments, application of sole organic treatment (4 Mg compost + 2 Mg gliricidia loppings) emerged as the best combination in maintaining the highest SQI under both conventional and reduced tillages. However, the order of general performance of treatments in influencing SQI was T5 > T4 = T3 > T2 > T1, indicating that sole organic treatment performed better, followed by conjunctive nutrient use treatments. These findings would help in providing advice to the growers/farmers to choose suitable soil–nutrient management practices and to improve these dynamic indicators for enhancing soil quality to achieve desired functional goals. Further, the methodology followed and the results obtained in this study will also be useful to researchers and land managers in identifying the indicators and computing SQI for other varying soil types and predominant cropping systems worldwide.

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