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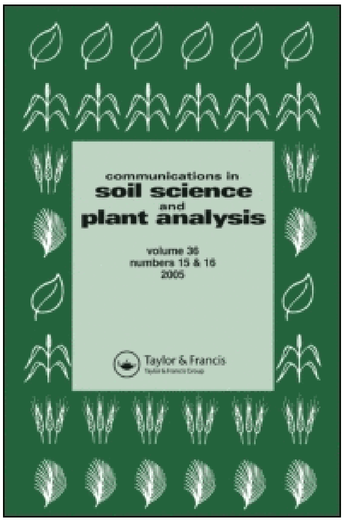

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Effect of Soil and Nutrient-Management Treatments on Soil Quality Indices under Cotton-Based Production System in Rainfed Semi-arid Tropical Vertisol

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Rainfed semi-arid tropical Vertisols of the Indian subcontinent encounter many problems on account of the physical, chemical, and biological soil qualities and consequently have poor crop yields. To ensure sustainable crop production, there is a need to improve and periodically assess the quality of these soils by adopting suitable soil and nutrient-management practices on a long-term basis. Hence, soil quality assessment studies were conducted at the Central Research Institute for Dryland Agriculture, Hyderabad, India, by adopting an ongoing long-term experiment from Akola Centre (Maharashtra) of All-India Coordinated Research Project for Dryland Agriculture (AICRPDA) for the rainfed Vertisol. This long-term experiment was initiated in 1987 with six soil and nutrient management treatments: T1, control; T2, 50 kg nitrogen (N) + 25 kg phosphorus pentoxide (P_2O_5) ha^{-1}; T3, 25 kg N ha^{-1} through leuceana; T4, 25 kg N ha^{-1} through farmyard manure (FYM); T5, 25 kg N + 25 kg P_2O_5 + 25 kg N ha^{-1} through FYM; and T6, 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana under cotton + greengram intercropping (1:1). Out of the 19 soil quality parameters studied, significant influence of the soil and nutrient-management treatments was observed on almost all the parameters except exchangeable calcium (Ca), available iron (Fe), labile carbon (LC), and bulk density (BD). A standard methodology using principal component analysis (PCA) and linear scoring technique (LST) was adopted to identify the key indicators and for computation of soil quality indices. The various key soil quality indicators identified for these Vertisols under cotton + green gram system were pH, electrical conductivity (EC), organic carbon (OC), available K, exchangeable magnesium (Mg), dehydrogenase assay (DHA), and microbial biomass carbon (MBC). The soil quality indices as influenced by different long-term soil and nutrient-management treatments varied from 1.46 to 2.10. Among the treatments, the conjunctive use of 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana green biomass (T6) maintained significantly higher soil quality index with a value of 2.10 followed by use of 25 kg N +

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25 kg P_2O_5 + 25 kg N ha^{-1} through FYM (T5) (2.01). The order of percent contribution of these identified indicators to soil quality indices was OC (28%) > MBC (25%) > available K (24%) > EC (7%) > pH (6%) = DHA (6%) > exchangeable Mg (4%). Thus, the findings of the present study could be of immense use to the researchers, land managers, farmers, nongovernment organizations (NGOs) and other stakeholders for making periodical assessment of key indicators of soil quality, identifying the best soil and nutrient-management treatments and practices, and planning for improving soil quality to achieve higher productivity goals on a sustainable basis in rainfed semi-arid tropical Vertisol regions. The methodology of the study could also be useful for other rainfed semi-arid tropical Vertisol regions of the world.

Keywords Conjunctive use of nutrients, cotton, green gram, integrated nutrient management, intercropping, leuceana, soil quality, soil quality indicators, Vertisol

Introduction

Vertisols, or black lands, occupy a great deal of acreage the world over. The major areas of Vertisols and associated soils are in Australia (70.5 m ha), India (72.9 m ha), Sudan (40 m ha), Chad (16.5 m ha), and Ethiopia (10 m ha). These five countries contain more than 80% of the total area (250 m ha) of Vertisols in the world (Dudal 1965; ICRISAT 1989). In India, Vertisols and associated soils with vertic characteristics cover an area of about 72.9 million ha, constituting roughly 22.2% of the total geographic area of the country. They occur mainly in the peninsula region between 8° 45′ and 26° 0′ N latitude and 66° 0′ and 83° 41′ E longitude in India (Murthy et al. 1982; Hati et al. 2006). In India, these soils are predominantly found in agrarian regions of Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka, and Tamilnadu (Murthy 1981). They are derived from base-rich rocks (basalt) or the related colluvium or alluvium parent materials (Rajput et al. 2009) and are generally alkaline and heavy in texture (clay, clay loam, or silty clay loam) (Virmani, Rao, and Srivastava 1989). These soils are dominated by a smectite group of clay minerals, leading to expansion and shrinkage on wetting and drying. Murthy (1988) emphasized that low infiltration rate, high plasticity and stickiness, high bulk density when dry, high cation exchange capacity, and calcareousness are some of the features associated with these soils. From the viewpoint of crop production, low organic matter is one of the major constraints in addition to low plant-available nutrients, particularly nitrogen (N), phosphorus (P), and zinc (Zn), thus affecting the productivity of these soils (Blaise, Majumdar, and Tekale 2005). In addition to poor fertility, limited soil moisture availability and poor drainage are the main soil-related problems in Vertisols (Murthy 1988). Vertisols are also highly prone to sheet erosion (Rajput et al. 2009), particularly in situations where the soil cover is sparse and where concentrated flow of water occurs through unprotected channels (ICRISAT 1989). Poor management of these soils leads to further degradation. The predominant cropping pattern followed in medium to deep Vertisols is cotton and cotton-based systems (Mandal, Mandal, and Venugopalan 2005). There are reports that when cotton is grown continuously, soil structural degradation, particularly that due to shearing and compaction during tillage operations and harvesting under wet conditions, and fertility decline because of the wider nutrient removal use gap (Hullugalle et al. 2007). Owing to all these causes, these Vertisol soils, especially in a rainfed semi-arid tropical (SAT) environment, encounter many problems on account of physical, chemical, and biological soil quality and consequently result in poor crop yields. Some other reports reveal that the quality and productivity of black soils can be improved by adopting suitable practices such as inclusion of legumes as intercrops or in rotation with cotton and other main crops, integrated use of organic and inorganic sources of nutrients, and balanced fertilization (Burford, Sahrawat, and Singh 1989; Murthy 1988; Rajput et al. 2009). These practices may not only help in improving the soil fertility and organic-matter status of soil but also help in improving physical and biological parameters. Smith and Elliot (1990) have emphasized the need to adopt appropriate soil and nutrient-management practices that avert the effects of soil degradation or maintain soil quality at a desirable level in rainfed regions.

Supplementing the nutrient requirement of crops through organic manures, especially the farm-based organics, plays a key role in sustaining soil fertility and crop productivity, reducing use of fossil fuels and restoring overall soil quality (Patra, Anwar, and Sukhmal Chand 2000). These sources are often cheaper and more efficient than inorganic compounds, and their use focuses on recycling nutrients rather than on supplying nutrients on a regular basis (Lampkin 1990). Meelu et al. (1994) emphasized that integrated supply of nutrients to plants through organic and inorganic sources is becoming an increasingly important aspect of environmentally sound and sustainable agriculture. Organic materials hold great promise as sources of multiple nutrients because of their ability to improve soil characteristics (Patra, Anwar, and Sukhmal Chand 2000). To understand and predict the impacts of these management practices on soil quality and related indicators, long-term experiments are of huge importance (Clapp et al. 2000). Recently, Sharma et al. (2005, 2008), while conducting soil quality assessment studies in rainfed SAT Alfisols, reported significant influence of long-term use of soil restorative practices such as conservation tillage, farm-based residue application, and conjunctive nutrient management on predominant physical, chemical, and biological soil quality indicators and soil quality indicators (SQIs). However, similar information is lacking in rainfed cotton-growing Vertisols and related soils, which is a soil order that says vast acreage of land not only in India but the world over. According to Hullugalle et al. (2007), much of the published research on soil quality changes caused by crop rotations in cotton-based farming systems in Vertisols is available for irrigated regions, but the information for rainfed regions is very scanty. Moreover, the concepts and methodology of assessing soil quality in a systematic manner have rarely been applied for rainfed cotton. The term *soil quality* in recent times has been comprehensively elaborated by including several aspects. Karlen et al. (1997) and a committee for the Soil Science Society of America defined soil quality as 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. Soil quality cannot be measured directly but could be inferred by measuring soil attributes or properties that serve as soil quality indicators. Brejda and Moorman (2001) stated that the changes in these indicators are used to determine whether soil quality is improving, stable, or declining with changes in management, land use, or conservation practices. According to Nortcliff (2002), there are potentially many soil properties that might serve as indicators of soil quality, and research is required to identify the most suitable. To evaluate changes in soil quality resulting from various management systems, a minimum number of soil quality indicators (minimum data set, MDS) need to be identified from a large data set for which various techniques and procedures exist (Grace and Sharma 2010). Further, combining these indicators in a meaningful way into a single index may help assess soil quality more precisely (Jaenicke and Lengnick 1999; Bucher 2002), which is used to gauge the level of an improving or declining soil condition (Wienhold 2004). Hence, it becomes essential to re-examine soil quality in the context of state-of-the-art concepts and methodologies.

In India, among the regions, which represent SAT rainfed Vertisols, Akola, in Maharashtra state representing the Deccan Plateau, is famous for growing cotton in black soils in combination with legumes such as green gram as an intercrop. Cotton + green gram intercropping is one of the economically remunerative systems adopted by farmers of this region. As the region is rainfed, besides moisture constraints, yields of these crops are severely affected by poor soil quality because of the low organic-matter content, poor fertility, and poor physical and biological conditions. Based on the foregoing discussion, it was hypothesized that by following appropriate soil and nutrient-management practices on a long-term basis, chemical, physical, and biological soil properties could be improved in cotton-growing rainfed Vertisols of the SAT region of India. With this consideration, an ongoing long-term experiment was initiated during 1987 and was adopted for the present study with specific objectives: (i) quantify the long-term impact of soil and nutrient-management treatments on physical, chemical, and biological soil quality parameters, (ii) identify the key indicators of soil quality for these rainfed Vertisols under cotton + green gram system, and (iii) identify the best soil and nutrient-management treatments using the SQI approach.

Materials and Methods

The field experimental site is located in Akola of eastern Maharashtra of the Deccan Plateau representing a hot semi-arid ecoregion (20^o 32′ to 20^o 35′ N latitude and 77^o 7′ to 77^o 10′ E longitude at an elevation of 325 m above sea level) with an average annual rainfall of 825 mm and annual potential evapotranspiration of 604 mm. The soils of the study area represent Vertisol soil order with medium and deep clay loams to heavy clays, calcareous, and with lime concretions at varying depths. Predominantly, these soils are susceptible to severe water erosion with moderate loss of topsoil. The soils are medium to high in available water capacity, and the occurrence of drought is once in 10 years. Soils, in general, are neutral to alkaline in pH, low to medium in organic carbon (C), low to medium in phosphate with high P-fixation capacity, and high in potash. An experiment initiated at the research farm of Akola Centre of All-India Coordinated Research Project for Dryland Agriculture in 1987 in a randomized block design with six soil and nutrient-management treatments, three replications, and cotton (*Gossypium hirsutum*) + greengram [*Vigna radiata* (L.)] intercropping (1:1) system was adopted for soil quality assessment study carried out at the Central Research Institute for Dryland Agriculture, Hyderabad, India. The treatments were as follows: T1, control; T2, 50 kg nitrogen (N) + 25 kg phosphorus pentoxide (P_2O_5) ha^{-1}; T3, 25 kg N ha^{-1} through leaves and twigs of leuceana (*Leuceana leucocephala*); T4, 25 kg N ha^{-1} through farmyard manure (FYM); T5, 25 kg N + 25 kg P_2O_5 + 25 kg N ha^{-1} through FYM; and T6, 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana. Fertilizer N was supplemented through urea, and P was applied through single superphosphate (SSP). These treatments were applied to the crop each year. Cotton (spacing 60 × 30 cm) with green gram (spacing 30 × 10 cm) as intercrop was grown every year as yearly rotation. Depending upon the rainfall every year, both the crops were sown during the month of June. The period of harvest of cotton spread from October to December (three or four pickings) whereas green gram was harvested during September (two or three pickings). Other management practices were followed for both the crops as per the recommendations defined for that region.

Collection of Soil Samples and Analysis

Soil samples were collected from the plow layer (0.0–0.15 m deep) from the experimental site after the harvest of crop during 2005. Soil samples were partitioned and passed through

8-mm, 4.75-mm, 2-mm, and 0.2-mm sieves and used for different kinds of analysis. Soil samples that passed through the 8-mm sieve and retained on the 4.75-mm sieve were used for aggregate analysis. Soil samples that passed through the 2-mm sieve were used for chemical analysis for pH, electrical conductivity (EC), available N, P, and potassium (K), exchangeable calcium (Ca) and magnesium (Mg), available sulfur (S), and micronutrients such as zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), and boron (B). The soil sample that passed through the 0.2-mm sieve was used for organic C and labile C. For biological properties such as microbial biomass C and dehydrogenase assay, 2-mm sieved soil samples were used. The various standard procedures adopted for estimation of different soil quality parameters were as follows: pH and electrical conductivity (Rhoades 1982) measured in 1:2 soil/water suspension; organic C by wet oxidation with sulfuric acid (H_2SO_4) + potassium dichromate ($K_2Cr_2O_7$) (Walkley and Black 1934); available N by alkaline–potassium permanganate ($KMnO_4$) oxidizable N method (Subbaiah and Asija 1956); available P by 0.5 M sodium bicarbonate ($NaHCO_3$) 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 (0.005 M) + triethanolamine (TEA; 0.1 M) + calcium chloride ($CaCl_2.2H_2O$; 0.01 M) reagent (pH 7.3) using inductively coupled plasma spectrophotometry (ICP-OES, GBC, Hampshire, Ill.) (Lindsay and Norvell, 1978); extractable B by DTPA–sorbitol extraction (Miller, Vaughan, and Kotuby-Amacher 2001); bulk density (BD) by Keen's box method; aggregate stability using wet sieve technique (Yoder 1936), mean weight diameter (MWD) (Van Bevel 1949); microbial biomass C by fumigation extraction (Jenkinson and Powlson 1976); dehydrogenase activity by triphenyl tetrazolium chloride method (TTC) (Lenhard 1956); and labile C by $KMnO_4$ (0.01 M) method (Weil et al. 2003) with slight modification.

Methodology for Soil Quality Assessment

The data on chemical, physical, and biological soil quality indicators as influenced by conjunctive nutrient use treatments were tested for their level of significance using randomized block design, and the qualified variables were considered for computation of soil quality analysis using principal component analysis (PCA) and the linear scoring technique (LST). For identification of key indicators and computation of SQIs, the following steps were used: (i) testing the level of significance for various soil indicators as influenced by various management treatments, (ii) fixing or defining the goals, (iii) selecting representative minimum data set (MDS) through principal component analysis (PCA), (iv) correlation analysis among soil variables to reduce spurious grouping among highly weighted variables within each PC, (v) multiple regressions using the final MDS components as the independent variables and each goal attribute as a dependent variables, (vi) scoring of the MDS indicators based on their performance of soil function, and (vii) computation of SQIs.

To identify the MDS, the procedures earlier suggested by Doran and Parkin (1994) and Andrews, Karlen, and Mitchell (2002a) and followed by Sharma et al. (2005, 2008) were used. Subsequent to the test for level of significance, the data were subjected to PCA to reduce the dimensionality (number of variables) of the dataset and retain most of the original variability in the data. As per the criteria set by Brejda et al. (2000a, 2000b), those principal components that received eigenvalues ≥ 1, which explained at least 5% of the variation in the data (Wander and Bollero 1999), and variables that had high factor loading were considered the best representatives of system attributes. 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, Karlen, and Mitchell 2002a). Among the well-correlated variables ($r > 0.70$), only one variable was considered for the MDS. However, flexibility criteria were also followed in most of the circumstances, depending upon the importance of the variables. If the highly weighted variables were not correlated, each was considered important and was retained in the MDS. After screening the variables through PCA and correlation for MDS, multiple regressions were performed as a check of how well the MDS represented the management system goals. This was done considering the indicators retained in the MDS as independent variables and the functional goals such as long-term average yields of crops and SYIs as dependent variables. The variables qualified under these series of steps were termed as the key indicators and were considered for computation of SQI after suitable transformation and scoring.

After identifying the indicators retained in the MDS, all the observations of each MDS indicator were transformed using a linear scoring method as suggested by Andrews, Karlen, and Mitchell (2002a). 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 the case 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 the SQI, the weighted MDS indicator scores for each observation were summed up using the following relation:

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

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 higher index scores meant better soil quality or greater performance of soil function. For better understanding and relative comparison of the long-term performance of the conjunctive nutrient-use treatments, the SQI values were reduced to a scale of 0–1 by dividing all the SQI values with the greatest SQI value. The numerical values thus obtained clearly reflect the relative performance of the management treatments and hence were termed as the relative SQIs (RSQIs). Further, the percentage contributions of each final key indicator were also calculated.

Results and Discussion

Effect of Conjunctive Nutrient-Use Treatments on Soil Quality Parameters

Soils of the experimental field were found to be alkaline in nature with pH values ranging from 7.85 to 8.45 (Table 1) and were significantly influenced by the management treatments. Electrical conductivity of the soils was in the range of 0.17 to 0.22 dS m^{-1}. Among

Table 1

Effect of different long-term integrated nutrient-management treatments on physicochemical and chemical soil quality indicators (macronutrients and secondary nutrients) under cotton + green gram intercropping in Vertisol soil of Akola

Treatments	pH	EC (dS m^{-1})	OC (g kg^{-1})	N (Kg ha^{-1})	P (Kg ha^{-1})	K (Kg ha^{-1})	Ca (c mol kg^{-1})	Mg (c mol kg^{-1})	S (μg g^{-1})	Zn (μg g^{-1})	Fe (μg g^{-1})	Cu (μg g^{-1})	Mn (μg g^{-1})	B (μg g^{-1})
T1 = control	8.40	0.18	5.72	173.1	17.7	255.4	10.9	2.41	5.00	0.55	11.9	0.50	15.2	0.50
T2 = 50 kg N + 25 kg P_2O_5/ha	8.34	0.19	6.07	181.4	20.8	323.9	11.2	2.93	10.48	0.83	14.9	0.64	17.9	0.58
T3 = 25 kg N ha^{-1} through leuceana	8.45	0.18	5.86	179.2	18.7	272.0	10.8	3.55	9.89	0.70	12.6	0.50	15.0	0.52
T4 = 25 kg Nha^{-1} through FYM	7.85	0.17	6.96	185.9	16.1	285.5	11.1	2.81	7.95	0.97	13.2	0.56	16.5	0.59
T5 = 25 kg N + 25 kg P_2O_5 + 25 kg N ha^{-1} through FYM	8.40	0.17	7.24	188.5	22.2	327.0	11.1	2.89	11.80	0.74	12.5	0.66	17.4	0.67
T6 = 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana	8.19	0.24	7.32	191.3	36.0	395.3	12.6	3.75	11.15	1.48	12.1	0.66	18.1	0.63
CD @ 0.05	0.24	0.02	0.37	11.2	3.28	38.1	NS	0.46	1.41	0.32	NS	0.11	2.12	0.07

the different nutrient-management treatments, application of 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana (T6) recorded the greatest electrical conductivity of 0.22 dSm^{-1}. Organic C in the soils ranged from 5.72 to 7.32 g kg^{-1}. Application of 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana (T6) showed the greatest organic C content of 7.32 g kg^{-1} followed by 25 kg N + 25 kg P_2O_5 ha^{-1} +25 kg N ha^{-1} through FYM (T5) (7.24 g kg^{-1}).

Conjunctive nutrient-management treatments showed significant effect on most of the chemical soil quality parameters. Among all the treatments, application of 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana (T6) recorded the significantly greatest available N (191.3 kg ha^{-1}), available P (36.0 kg ha^{-1}), available K (395.3 kg ha^{-1}), and exchangeable Mg (3.75 c mol kg^{-1}), followed by application of 25 kg N + 25 kg P_2O_5 ha^{-1} + 25 kg N ha^{-1} through FYM (T5). In the case of available S, application of both 25 kg N + 25 kg P_2O_5 ha^{-1} + 25 kg N ha^{-1} through FYM (T5) (11.8 μg g^{-1}) and application of 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana (T6) (11.2 μg g^{-1}) recorded the greater levels. Nutrient-management treatments did not show any significant effect on available Fe, whereas the other micronutrients have been significantly influenced by the integrated nutrient management (INM) treatments. However, Fe content in the soils was high and ranged from 11.93 to 14.94 μg g^{-1} of soil. Available Zn content was found to be in the medium range (0.55 to 0.97 μg g^{-1}) across all the treatments except in 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana (T6) (1.48 μg g^{-1}). Available B content under various treatments varied from 0.50 to 0.67 μg g^{-1} of soil and was greatest with 25 kg N + 25 kg P_2O_5 + 25 kg N ha^{-1} through FYM (T5) (0.67 μg g^{-1} of soil). The superiority of field application of green biomass of leuceana in terms of soil fertility improvement had earlier been established by Patil and Sheelavantar (2004). This was probably attributed to faster rate of mineralization and faster decomposition with increased nutrient availability (Bellaki and Badanur 1994; Venkateswarlu 1984; Ramamoorthy et al. 2002).

Among the biological soil quality parameters, dehydrogenase assay (DHA), MBC, and LC were monitored, and it was observed that except for LC, the other two indicators were significantly influenced by the nutrient-management treatments (Table 2). The DHA reveals the microbial activity in soil and has been considered as an important biological indicator for functional capacity of soil (i.e., soil quality). In the present study, the dehydrogenase activity in the soil was found to be very low, and it ranged from 0.13 to 0.35 μg TPF hr^{-1} g^{-1} soil across the nutrient-management treatments. Application of 25 kg N + 25 kg P_2O_5 ha^{-1} + 25 kg N ha^{-1} through FYM (T5) recorded the greatest DHA of 0.35 μg TPF hr^{-1} g^{-1} followed by 25 kg N ha^{-1} through FYM (T4) (0.27 μg TPF hr^{-1} g^{-1}). It has been established that soil microorganisms play an important role in the mobilization and immobilization of nutrients and energy, and it is beneficial to assess microbial biomass whenever there is a need to assess nutrient and energy flow in soils (Paul and Voroney 1980). Based on the data presented in Table 2, it was observed that MBC content in soil across the treatments ranged from 132.0 to 228.7 μg g^{-1} soil, the greatest being in 25 kg N + 25 kg P_2O_5 ha^{-1} + 25 kg N ha^{-1} through FYM (T5) (228.7 μg g^{-1} soil), which was at par with application of 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana (T6) (220.9 μg g^{-1} soil). The corresponding values of LC in these two treatments were 215.6 mg kg^{-1} and 215.8 mg kg^{-1}, respectively. Among the physical soil quality parameters, bulk density as well as the mean weight diameter, which reflect the structural stability of soil and are considered the important physical soil quality indicators, were also assessed. Bulk density varying from 1.16 to 1.21 Mg m^{-3} was not conspicuously influenced by the nutrient-management treatments. Application of 25 kg N ha^{-1} through FYM showed greater mean weight diameter of 0.36 mm, which was at par with few other treatments. On

Table 2

Effect of different long-term integrated nutrient-management treatments on biological and physical soil quality indicators under cotton + green gram intercropping in Vertisols of Akola

Treatments	DHA (µg TPF hr^{-1} g^{-1} soil)	MBC (µg g^{-1} soil)	LC (mg kg^{-1})	BD (Mg m^{-3})	MWD (mm)	SQI	RSQI
T1 = control	0.13	132.0	184.15	1.21	0.25	1.46	0.66
T2 = 50 kg N + 25 kg P_2O_5 ha^{-1}	0.31	188.4	189.45	1.17	0.29	1.82	0.82
T3 = 25 kg N ha^{-1} through leuceana	0.25	144.0	192.33	1.18	0.32	1.60	0.73
T4 = 25 kg N ha^{-1} through FYM	0.27	212.5	202.09	1.17	0.36	1.84	0.84
T5 = 25 kg N + 25 kg P_2O_5 + 25 kg N ha^{-1} through FYM	0.35	228.7	215.61	1.19	0.35	2.01	0.91
T6 = 25 kg $P_2O_5ha^{-1}$ + 50 kg N ha^{-1} through leuceana	0.21	220.9	215.82	1.16	0.32	2.10	0.95
CD @ 0.05	0.05	29.3	NS	NS	0.03	0.11	

the whole, in the present study, it was observed that application of leuceana biomass and FYM in combination with chemical fertilizers, rather than their sole application, performed better in improving many of the physical, chemical, and biological soil quality parameters, and these treatments could act as the best alternatives to supplement the chemical nutrients, especially N, thus reducing the costs under cotton + green gram (1: 1) intercropping system in Vertisols of Akola.

Effect of Conjunctive Nutrient-Use Treatments on Soil Quality Indices

Another objective of the study was to assess the key indicators that influence the soil quality and also the best nutrient-management treatments in maintaining or aggrading the soil quality. To assess the key SQIs, at the outset, the significant influence of the management treatments on the 19 soil quality variables taken up in this study was evaluated. Out of the 19 variables, only 15 variables were significantly influenced by the management treatments, and four variables (viz., exchangeable Ca, available Fe, LC, and BD) were not significantly influenced and hence were not subjected to PCA. In the PCA of 15 variables, four PCs had eigenvalues > 1 and explained 81.7% variability in the data (Table 3). The highly weighted variables in PC1 included organic C, available K, available Cu, and MBC. The correlation matrix run for these variables revealed significant positive correlations between all the parameters (Table 4). In spite of their correlations, only Cu, having the lowest correlation sum, was dropped from the MDS, and the other three variables (viz., OC, K, and MBC) were retained, considering their active role in these Vertisol soils under study. In PC2, electrical conductivity and dehydrogenase assay were highly weighted variables and were retained for the final MDS as both of these variables did not have any significant correlation with each other. However, in PC3 and PC4, pH and Mg were the respective variables, which were highly weighted and were retained for the MDS. Hence, the various soil quality indicators retained in the final MDS consisted of pH, electrical conductivity, organic C, available K, exchangeable Mg, DHA, and MBC. To corroborate their influence on management goals, the MDS variables thus identified were regressed with average (over 9 years) cotton yield (which varied from 325 to 460 kg ha^{-1} across the treatments) and sustainability yield indices (SYI) (which varied from 0.08 to 0.22 across the treatments) (AICRPDA 2006), and only DHA was found to be significant (Table 5). The coefficients of multiple determination when these indicators were regressed as independent variables with yield ($R^2 = 0.781$) and SYI ($R^2 = 0.770$) as dependant variables were significant with a reasonable degree of confidence ($P = 0.01$), and hence these variables were finally considered qualified as key indicators and were used for computation of SQIs.

The data on SQIs computed using the key indicators identified for this cotton + green gram intercropping system are represented in Figure 1. The SQIs as influenced by different long-term conjunctive nutrient-management treatments varied from 1.46 to 2.10 across the management treatments. It was observed that, of all the treatments, application of 25 kg P_2O_5 ha^{-1} + 50 kg N ha^{-1} through leuceana (T6) significantly maintained higher soil quality with SQI of 2.10, which was at par with application of 25 kg N + 25 kg P_2O_5 + 25 kg N ha^{-1} through FYM (T5) (2.01). The next best nutrient-management treatment in aggrading soil quality in these soils was the sole organic treatment (viz., 25 kg N ha^{-1} through FYM, T4) with SQI of 1.85, which was statistically at par with the sole inorganic treatment (50 kg N + 25 kg P_2O_5 ha^{-1}, T2) (1.82). However, the control plot maintained the lowest SQI of 1.46. The relative order of performance of these treatments in aggrading soil quality was T6, 25 kg $P_2O_5ha^{-1}$ + 50 kg N ha^{-1} through leuceana (2.10) > T5, 25 kg

Table 3
Principal component analysis of soil quality indicators under cotton + green gram intercropping in Vertisols of Akola

Parameter	PC1	PC2	PC3	PC4
Total eigenvalues	7.165	2.402	1.363	1.329
Variance (%)	47.768	16.012	9.088	8.857
Cumulative (%)	47.768	63.780	72.868	81.726
Eigenvectors				
pH	−0.286	0.218	0.836	−0.129
EC	0.522	0.738	−0.081	−0.038
OC	0.846	−0.208	−0.229	0.072
N	0.674	−0.232	0.019	−0.151
P	0.749	0.568	0.086	0.033
K	0.888	0.354	0.040	−0.155
Mg	0.453	0.380	0.271	0.631
S	0.764	−0.137	0.509	0.220
Zn	0.722	0.294	−0.290	0.386
Cu	0.792	0.035	0.112	−0.325
Mn	0.768	0.024	−0.044	−0.440
B	0.732	−0.195	0.028	−0.430
DHA	0.393	−0.711	0.375	0.065
MBC	0.851	−0.325	−0.137	0.052
MWD	0.592	−0.604	−0.077	0.414

Table 4
Pearson's correlation matrix for highly weighted variables under PCs with high factor loading

Variables under PCs				
PC1	**OC**	**K**	**Cu**	**MBC**
OC	1.00	0.643**	0.532*	0.825**
K	0.643**	1.00	0.633**	
Cu	0.532*	0.765**	1.00	0.680**
MBC	0.825**	0.633**	0.680**	1.00
Correlation sum	3.00	3.041	2.977	3.138
PC2	**EC**	**DHA**		
EC	1.00	−0.258		
DHA	−0.258	1.00		
Correlation sum	1.258	1.258		

N + 25 kg P_2O_5 + 25 kg N ha^{-1} through FYM (2.01) > T4, 25 kg N ha^{-1} through FYM (1.85) = T2, 50 kg N + 25 kg P_2O_5 ha^{-1} (1.82) > T3, 25 kg N ha^{-1} through leuceana (1.60) > T1, control (1.46). For better understanding and comparison, the SQI values were reduced to the scale of 1 and termed as RSQIs, which varied from 0.66 to 0.95 across the management treatments. The average percentage contributions of the key indicators to the

Table 5
Multiple regressions of the minimum data set (MDS) components with management goal attributes at different probability (*P*) levels

Goal or function	R^2 **	Most significant MDS variables	P
Cotton average yield	0.781	DHA	> 0.086
SYI	0.770	DHA	> 0.086

** Significant at $P = 0.01$ level.

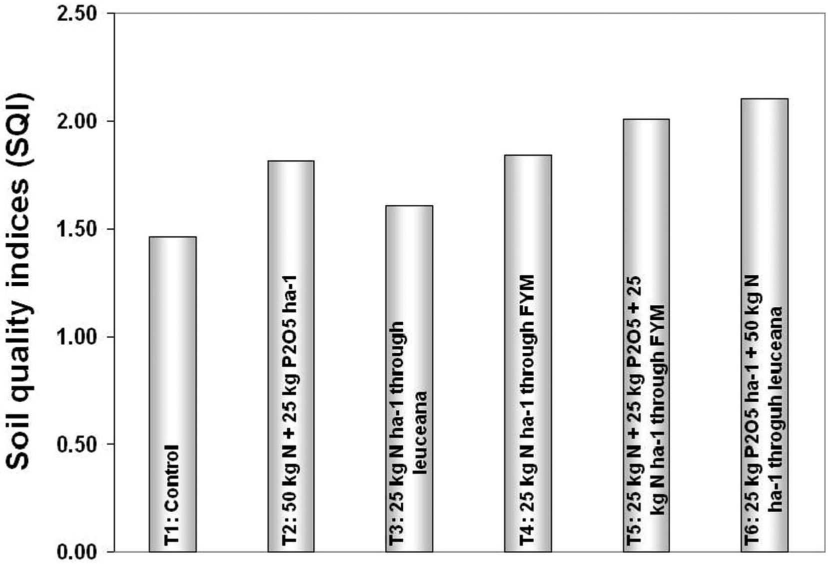

Figure 1. Soil quality indices as influenced by different long-term integrated nutrient-management treatments under cotton + green gram intercropping in Vertisol soil of Akola.

SQIs were also computed (Figure 2). It was observed that of all the key indicators, organic C contributed the maximum (28%) followed by MBC (25%) and available K (24%), while the contribution of the other four indicators was meager [i.e., EC (7%), pH (6%), DHA (6%), and exchangeable Mg (4%)].

The indicators identified as key indicators has a great relevance in the context of improving soil functions in these rainfed Vertisol soils, which are constrained by low organic matter, poor soil fertility, and poor physical and biological soil functions. Zhang, Song, and Wenyan (2007) opined that SOC is an important factor affecting soil quality and long-term sustainability of agriculture. Decrease in SOC leads to a decline in cation exchange capacity of soils, soil aggregate stability, and crop yield (Freixo et al. 2002). Hussain et al. (1999) stated that organic C is a major source of nutrients, and depletion of organic matter is associated with the loss of soil productivity. Further, organic matter affects crop growth and yield, either directly by supplying nutrients or indirectly by modifying soil physical properties that can improve the root environment and stimulate plant growth (Kononova 1961; Hati et al. 2007). Besides being a source and sink of nutrients for plants, SOC plays an important role in the C cycle, as it accounts for the major terrestrial pool of this element. The importance of organic C as key indicator lies in the fact that

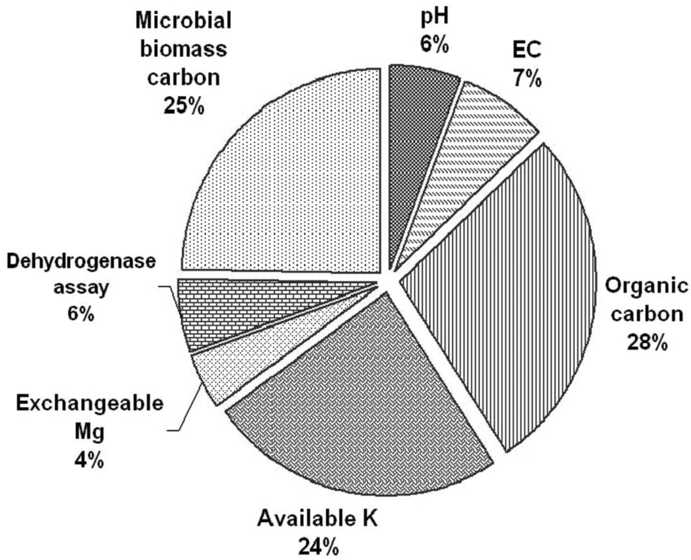

Figure 2. Percentages of contributions of key soil quality indicators to soil quality indices as influenced by different long-term integrated nutrient-management treatments under cotton + green gram intercropping in Vertisol soil of Akola.

because it is a relatively simple property to measure, it provides an integrated measure of sustainable ecosystems (Karlen et al. 1997; Nortcliff 2002). Decline in organic-matter content may also lead to physical degradation of these soils. Hence, as supported by Wander and Drinkwater (2000), organic matter and organic-matter-dependent properties are the most promising indicators for use in a soil quality assessment where the information will be used in management decisions.

Soil MBC, which has emerged as another important indicator, contributing about 25% toward SQIs, is a labile source and sink of nutrients. It affects nutrient availability and nutrient cycling and is a good indicator of potential microbial activity (Dalal and Mayer 1987) and net nutrient mobilization. Several researchers have reported that microbial biomass can be a sensitive indicator of changes in soil processes because it has much faster rate of turnover than the SOM (Jenkinson and Ladd 1981; Paul 1984; Wright, Hons, and Matocha 2005), and the trends in the microbial biomass content of soils will predict longer term trends in total organic-matter contents (Powlson and Jenkinson 1981; Powlson, Brookes, and Christensen 1987; Sparling 1997). Although useful as a research tool, its cumbersome measurement and variability with short-term environmental conditions makes its use as a routine soil health indicator currently difficult (Sparling 1997; Dalal 1998). Though these Vertisol soils are medium to high (> 280 kg K ha^{-1}) in available K, as a key indicator it has contributed significantly (about 24%) to SQIs. Vertisols are generally rich in K content, and application of potassic fertilizers is not recommended to these soils. Nevertheless, the importance of K in regulating and improving water functions in plant system and enabling the crop to withstand drought under rainfed conditions where intermittent dry spells are usual, cannot be undermined. Dehydrogenase activity, another key soil quality indicator, has been reported to reflect the total range of oxidative activity of soil microflora and consequently may be considered to be a good indicator of microbial activity (Nannipieri, Grego, and Ceccanti 1990). This enzyme is only active in living cells, so it could give results similar to soil microbial biomass measurements (Chander and Brookes 1991).

Soil pH also emerged as one of the key SQIs, which is an index of the soil chemical environment. In native soils, pH is closely linked to annual rainfall and permeability of parent material during soil development. Doran and Parkin (1996) reported that soil pH is an indicator that can provide trends in change in terms of soil acidification (surface and subsurface) (Moody and Aitken 1997), soil salinization, electrical conductivity (salinity trends), exchangeable sodium (soil structural stability) (Rengasamy and Olsson 1991), limitations to root growth, increase incidence of root disease, biological activity, and nutrient availability (e.g., P availability at either pH > 8.5 or pH < 5; and Zn availability at pH > 8.5). Schoenholtz, Van Miegroet, and Burger (2000) reported that many chemical reactions that influence nutrient availability (e.g., chemical form, adsorption, precipitation, etc.) are influenced by the soil chemical environment, and soil pH in particular. Thus, it is logical that pH should be included as a key chemical indicator, especially because it is routinely included in soil surveys and soil databases and is easily and inexpensively measured when such data are not available. Though with relatively less contribution to SQIs, electrical conductivity and exchangeable Mg have also reflected their importance in the present study by emerging as key indicators. Thus, land managers need to look at these indicators periodically, and the management should be tailored accordingly. They have the discretion to include any other indicators for the periodical assessments depending upon the situation and localized problem.

From the foregoing discussion, it is clear that soil and nutrient-management practices play an important role in influencing the key indicators of soil quality and in improving the SQIs under cotton + green gram system in rainfed Vertisols. Further, the findings that emerged out of these studies could be of immense use to researchers, farmers, land managers, nongovernmental organizations, and other stakeholders associated with agricultural profession in Vertisol areas. Besides this, the methodology adopted for computation of soil quality could also be an easy tool for assessing soil quality periodically by focusing only on key indicators. This would in turn help the network of laboratories involved in soil quality assessment to monitor the suggested indicators periodically and to suggest strategies to improve these indicators for improving soil quality and to achieve greater sustainability in regions representing Vertisol soils or blacklands of India. Further, this research could also be of immense use in similar locations of the SATs across the world.

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