Vertical assessment of soil quality in permanent manurial experiment of dryland ecosystem, Tamil Nadu, India

V. Venkatesh[1,]*, N. Chandra Sekaran[1], V. Sanjivkumar[1], S. Meena[1], K. T. Parthiban[2], B. Balaganesh[3], K. Subash Chandra Bose[1] and S. Murali[1]

[1]Tamil Nadu Agricultural University (TNAU), Coimbatore 641 003, India
[2]Forest College and Research Institute, TNAU, Mettupalayam 641 301, India
[3]School of Agricultural Sciences, Karunya University, Coimbatore 641 114, India

A study was conducted to assess the impact of different nutrient management practices on soil quality in a permanent manurial experiment cotton field established in 1982 at the Agriculture Research Station of the Tamil Nadu Agricultural University, which falls under the dryland ecosystem of Kovilpatti in Tamil Nadu, India. The experiment was carried out in a randomized block design with nine different treatments. The effect of these treatments in different depths (0–15, 15–30 and 30–45 cm) was compared, and the soil quality index was developed with a total of 27 parameters, including physical, chemical and biological parameters. Principal component analysis was carried out and the principal components with eigenvalue >1 were selected to determine the indicators to be retained in the minimum dataset. The highly weighted variables, viz. field capacity, available water content, cation exchange capacity, nitrogen, phosphorus, potassium, calcium, magnesium, etc. with a variance of 93.57% were retained for MDS. Linear scoring functions were used to transform them into unitless scores ranging from 0 to 1. Three different methods of soil quality were analysed, viz. weighed additive soil quality index (SQI_w), additive soil quality index (SQI_a) and Nemoro soil quality index (SQI_n). In all three methods, the treatment receiving farmyard manure at 12.5 t ha^{-1} showed superiority in maintaining soil quality.

Keywords: Cotton, dryland ecosystem, nutrient management practices, permanent manurial experiment, soil quality index.

SOIL is a non-renewable vital resource that plays an important role in nutrient absorption, water utilization, and increasing productivity[1]. In the recent past, various global challenges, like soil loss and erosion, degradation, nutrient deficiency, soil compaction and pollution have been serious concerns that have put agricultural management in risk[2]. In the past two decades, the importance of soil quality in human-influenced ecosystems has been given serious attention, and the demand for determining soil quality index (SQI) in different regions over time is increasing[3]. Estimating SQI is a time-consuming and difficult task[4], especially when it is linked to multiple functional goals. Nonetheless, substantial progress has been achieved in estimating SQI for a variety of soil types and management practices[5,6]. Among these, soil quality indicators and the scoring method are two common approaches used to assess soil quality[3]. However, most studies on soil quality evaluation are restricted to topsoil layers, with the main focus on physical and chemical properties. The biological properties are given the least importance. The soil quality indicators in different depths pertaining or with respect to individual crops are limited[6,7]. The long-term effects of organic and inorganic fertilizers, either singly or in combination, on the physico-chemical and biological properties of the soil, i.e. permanent manurial experiments (PMEs) are limited. These experiments have been conducted for more than 100 years and assume great significance for evaluating soil quality. One such permanent manurial trial on cotton was chosen for this study at Kovilpatti, a dry region of Tamil Nadu, India, to evaluate SQI in multiple soil layers.

*For correspondence. (e-mail: vunnamvenkatesh010694@gmail.com)

Materials and methods

Site description

The study was undertaken in the 38th cotton (KC 3) crop (cropping system: cotton–fallow–fallow) in a PME started in 1982 at the Agricultural Research Station of the Tamil Nadu Agricultural University, Kovilpatti (9.20′N lat., 77.87′E long., altitude 90 m amsl). The monthly mean maximum temperature ranged from 28°C to 38.5°C, while the monthly mean minimum temperature ranged from 21°C to 27.5°C. With an annual mean rainfall of 743 mm and evapotranspiration of 812 mm, the area is classified as a hot, semiarid region. The soil in the experimental site falls under Kalathur soil series with fine montmorillonitic, isohyperthermic, Udorthentic Chromusterts with heavy clay texture. Appendix 1 shows the initial soil properties of PME taken in 1982.

Treatment details

The experiment consisted of nine treatments. T1 – Control (no manure, no fertilizer); T2 – 100% recommended dose of fertilizer (RDF, urea, di-ammonium phosphate (DAP) and muriate of potash (MOP); 40 : 20 : 40 NPK kg ha^{-1}); T3 – 50% RDF (20 : 10 : 20 NPK kg ha^{-1}); T4 – 50% N (crop residues – green gram (1626 kg ha^{-1})); T5 – 50% N (FYM – farm yard manure (4000 kg ha^{-1})), T6 – 50% inorganic N + 50% organic N (crop residues – green gram) – NEB (nitrogen equivalent basis); T7 – 50% inorganic N+ 50% organic N (FYM) + P (50%) + K (50%); T8 – 100% RDF + 25 kg $ZnSO_4$ ha^{-1}; T9 – FYM (12.5 t ha^{-1}). The experiment was laid out in randomized block design (RBD) with three replications and the plot size was 7.5 × 3.6 m. The total area of PME was 0.06 ha and the spacing followed in cotton crop was 45 × 15 cm.

Soil sample collection

Soil samples were collected in PME of cotton during March 2021 from each treatment in three different depths, viz. 0–15, 15–30 and 30–45 cm, following the quadrant method for the assessment of SQI. The samples were shade-dried, ground with a wooden hammer, and passed through a 2 mm sieve. Finally, 1 kg of representative sample was preserved in a labelled cloth bag for laboratory analysis.

Soil analysis

Soil physico-chemical properties: The soil samples were analysed for physical and chemical properties. Soil bulk density was analysed using the core sampler method[7], infiltration by a double-ring infiltrometer[8], while aggregate stability and hydraulic conductivity were determined by the wet and dry aggregate sieve method (Yoder apparatus) and the constant hydraulic head method respectively[8].

Soil pH and electrical conductivity were measured with 1: 2: 5 soil water extract[9]. Organic carbon was estimated by the chromic acid wet digestion method[10]. Available nitrogen (N) was determined using the alkaline permanganate method[11]. Available phosphorus (P) and potassium (K) were determined according to the methods described by Olsen *et al.*[12], and Standford and English[13]. Exchangeable calcium and magnesium were estimated according to Jackson[9]. Available micronutrients (diethylene triamine pentaacetic acid (DTPA) – Zn, Fe, Mn, Cu) were determined using atomic absorption spectrophotometry[14].

Soil biological properties: Biological properties were analysed using the serial dilution plating method. Microbial populations, viz. bacteria, fungi and actinobacteria were determined using nutrient agar medium[15], rose Bengal medium[16] and Kenknights agar medium respectively. Phosphatase and urease were determined according to the method described by Tabatabai and Bremner[17], while dehydrogenase activity was determined based on chloride reduction method[18].

Soil quality assessment: SQI assessment methods has been widely used in qualitative evaluation. It comprises three steps: (i) minimum dataset (MDS) or expert selection of indicators; (ii) principal component analysis (PCA) transformation of data to remove redundant variables, and (iii) normalization by assigning scores for uncorrelated indicators and integration of scores to develop indices.

Selection of minimum dataset

To avoid dimensionality, PCA was used to select the representative MDS. PCA depicts different principal components (PCs) as a linear combination of indicators that accounts for maximum variance within a set of data. In general, PCs with eigenvalue >1 were chosen for MDS, and highly weighed variables in each component were retained in one PC with 10% of the highly weighed variables. If more number of indicators were retained in a single PC, the indicators will be examined using correlations and the indicator with lowest correlation sum will be eliminated and the remaining variables were retained under MDS based on their functions in soil quality.

Transformation and normalization of variables

To reduce the number of variables, each indicator can be converted into a score ranging from 0 to 1 that represents contribution to soil function. Standard scoring functions, such as linear and nonlinear scoring functions were used to assign scores. Based on the sensitivity of each indicator, which shows that more is better (eq. (1)), the highest observed value (denominator) was divided by the number of observations, and a score of 1 was assigned. In cases where less is better (eq. (2)), such as bulk density, the lowest observed (numerator) value was divided by the number of observations, yielding a score of 1 (ref. 19).

The following equations were used for scoring negative and positive variables by standard scoring function

$$N(x)=\begin{cases}1 & x\le l\\ 1-0.9\ \dfrac{x-L}{U-L} & L\le x\le U,\\ 0.1 & x\ge L\end{cases} \tag{1}$$

$$P(x)=\begin{cases}0.1 & x\le l\\ 0.9\ \dfrac{x-L}{U-L} & L\le x\le U,\\ 1 & x\ge L\end{cases} \tag{2}$$

$$\mathrm{OR}(x)=\begin{cases}0.1 & x\le L\\ 0.9\ \dfrac{x-L}{U-L} & L\le x\le U,\\ 1 & x\ge L\end{cases} \tag{3}$$

where N is negative, P the positive, OR the optimum range, x the score of indicator ranging from 0 to 1, and L is the lower and U is the upper threshold value.

Computation of soil quality index

After normalization of variables, three different methods of SQI was used for calculation[20], viz. (i) weighted soil quality index (SQI_w; eq. (4)); (ii) additive soil quality index (SQI_a; eq. (5)) and Nemoro quality index (eq. (6)).

$$SQI_w = \sum_{i=0}^{n} W_i S_i, \quad (4)$$

where W is the assigned weight of indicators and S is the score of indicators.

$$SQI_a = \frac{\sum_{i}^{n} N_i}{n}, \quad (5)$$

where N_i is the indicator score and n is the number of indicators.

$$SQI_n = \sqrt{\frac{P_{ave}^2 + P_{min}^2}{2}} \times \frac{n-1}{n}, \quad (6)$$

where P_{ave} is the average and P_{min} is the minimum of the scores of indicators selected.

Statistical analysis

The differences among the treatments were compared by the least significant difference (LSD) test at a significance level of $P < 0.05$ using OPISTAT. PCA was performed using STAR software. The correlation was analysed using SPSS version 16.

Results and discussion

Effect of long time application of fertilizers and manures on soil properties

(i) *Physical properties:* Long-term experiments provide realistic scenarios on changes in soil properties and the effect of fertilization on soil quality[21]. In the present study, among the nine treatments, continuous application of organics (FYM @ 12.5 t ha^{-1}) along with inorganics had a significant effect on the physico-chemical properties (Table 1). Similar studies on long-term fertilization involving organic fertilizers have influenced soil aggregates in different agro-ecosystems[22,23]. The lowest bulk density (1.31 Mg m^{-3}) was recorded in FYM @ 12.5 t ha^{-1} treatment at 0–15 cm soil depth when compared to the control (1.50 Mg m^{-3}), due to improved soil aggregation. The organic matter added to the soil decreases bulk density. The reduced bulk density in the upper soil layers may also be attributed to the fine root turnover of cotton. These results are in agreement with those of Das *et al.*[22]. The other physical properties, viz. field capacity, permanent wilting point, available water content, total porosity, dry and wet aggregate stability, performed well at 0–15 cm soil depth under FYM @ 12.5 t ha^{-1} treatment (Table 1). Continued application of these treatments increased the soil organic carbon (SOC) and exhibited better physico-chemical properties than the other treatments, as also reported in previous studies[23,24]. The influence of all the treatments was observed in all the soil depths; however, it was significantly higher in the surface soil (0–15 cm) and decreased with increasing depth (15–30 to 30–45 cm), which might be due to the clayey nature of the soil, and low rainfall resulting in poor eluviation and illuviation process (Table 1).

(ii) *Chemical properties:* After 38 years of cotton–fallow cropping systems, the soil receives a prolonged application of organics alone, viz. FYM @ 12.5 t ha^{-1} had a maximum reduction in pH (8.16–7.81), which was more pronounced in 0–15 cm soil depth. The reduction in soil pH might be due to the release of H^+ ions as well as organic and inorganic acidic species like H_2SO_4 and HNO_3, and soluble salts released during partial decomposition of FYM and crop residues. Similar results of reduction in soil pH have been reported in an earlier long-term manuring and fertilization experiment conducted by Marian *et al.*[25]. Soil soluble salt content was recorded at its maximum (0.19) in the FYM @ 12.5 t ha^{-1} treatment at 0–15 cm soil depth (Table 2). However, statistically on-par results were also obtained for both pH and electrical conductivity (EC) by the application of inorganics tailored with organics. Generally, organic residue application will increase the soil cation exchange capacity (CEC) due to the increase in negative charges related to its carbon addition and its humified compounds. Soil EC increases under increasing rate of continuous application of P- and N-based manure when compared to compost[26]. There was also a 16.3% increase in CEC in the FYM @ 12.5 t ha^{-1} treatment when compared to control at 0–15 cm depth (Table 2).

Chemical properties like SOC, macronutrients (available N, P and K), secondary nutrients (exchangeable Ca and Mg) and micronutrients (Fe, Zn, Cu and Mn) were found to be significantly improved with the application of organics alone (FYM @ 12.5 t ha^{-1}) (Tables 2 and 3). Organic carbon ranged from 3.60 g kg^{-1} (FYM @ 12.5 t ha^{-1} treatment) to 1.40 g kg^{-1} (control) at 0–15 cm depth, which exhibited decreasing trends at 15–30 cm and 30–45 cm depth. The long-term application of organic manure along with inorganic fertilizers can increase SOC and play a vital role in nutrient flux as well as soil chemical properties[27].

Table 1. Effect of different treatments on the physical properties of permanent manorial experiment (PME) on cotton

Treatments	Bulk density ($mg\ m^{-3}$)			Porosity (%)			Field capacity (%)			Permanent wilting point (%)			Available water content (%)			Hydraulic conductivity ($cm\ h^{-1}$)			Dry aggregate stability (mm)			Wet aggregate stability (mm)		
Soil depth (cm)	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45
Control	1.50	1.53	1.55	13.9	12.6	15.2	27.2	24.0	20.7	13.9	12.6	15.2	13.3	11.4	5.5	2.51	2.07	1.80	24.8	23.7	23.26	27.2	24.0	20.7
100% RDF	1.43	1.47	1.49	16.2	16.0	14.7	30.4	26.3	21.2	16.2	16.0	14.7	14.2	10.3	6.5	2.68	2.29	1.95	32.1	30.9	30.6	30.4	26.3	21.2
50% RDF	1.48	1.52	1.54	15.1	15.0	15.1	29.2	24.7	20.8	15.1	15.0	15.1	14.1	9.7	5.7	2.57	2.24	1.91	27.4	26.5	26.2	29.2	24.7	20.8
50% N (crop residues)	1.40	1.44	1.46	15.8	14.1	14.4	30.1	24.8	21.1	15.8	14.1	14.4	14.3	10.7	6.7	2.62	2.40	2.02	37.1	36.7	36.5	30.1	24.8	21.1
50% N (FYM)	1.38	1.41	1.43	16.7	15.2	14.2	30.9	26.0	21.1	16.7	15.2	14.2	14.2	10.8	6.9	2.76	2.46	2.09	37.9	37.3	37.1	30.9	26.0	21.1
50% NPK + 50% crop residue – NEB	1.35	1.40	1.42	17.2	16.5	17.4	31.8	28.1	24.5	17.2	16.5	17.4	14.6	11.6	7.1	2.81	2.52	2.21	46.6	45.3	45.1	31.8	28.1	24.5
50% NPK + 50% FYM – NEB	1.33	1.38	1.40	17.5	16.4	13.8	31.9	28.6	25.3	17.5	16.4	13.8	14.4	12.2	11.5	2.98	2.53	2.27	47.4	46.8	46.8	31.9	28.6	25.3
100% RDF + 25 kg $ZnSO_4$ ha^{-1}	1.43	1.45	1.47	16.8	16.2	15.0	31.0	26.6	21.6	16.8	16.2	15.0	14.2	10.4	6.6	2.78	2.31	2.01	33.6	33.3	33.1	31.0	26.6	21.6
FYM – 12.5 t ha^{-1}	1.31	1.35	1.37	17.7	17.0	18.8	33.2	29.3	27.1	17.7	17.0	18.8	15.5	12.3	8.3	3.11	2.65	2.32	49.02	48.0	48.0	33.2	29.3	27.1
Mean	1.40	1.44	1.46	16.3	15.7	15.4	30.6	26.5	22.6	16.3	15.7	15.4	14.3	11.0	7.20	2.76	2.39	2.06	37.3	36.5	36.3	30.6	26.5	22.6
SEd	0.023	0.024	0.025	0.366	0.271	0.266	0.686	0.588	1.213	0.366	0.271	0.266	0.539	0.633	0.535	0.21	0.182	0.158	1.368	1.361	1.138	0.686	0.588	1.213
CD ($P \leq 0.05$)	0.051	0.052	0.053	0.777	0.575	0.565	1.454	1.248	2.570	0.777	0.575	0.565	1.144	1.342	1.134	0.446	0.385	0.334	2.900	2.886	2.413	1.454	1.248	2.570

Table 2. Effect of different treatments on soil chemical properties of PME on cotton

Treatments	pH			Electrical conductivity (dS m^{-1})			Cation exchange capacity (Cmol (p+) kg^{-1})			Organic carbon (g kg^{-1})			Available nitrogen (kg ha^{-1})			Available phosphorus (kg ha^{-1})			Available potassium (kg ha^{-1})		
Soil depth (cm)	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45
Control	8.16	8.09	7.89	0.12	0.10	0.10	18.3	13.4	10.4	1.40	1.10	0.78	100	90.0	69.0	10.9	8.60	4.53	308	215	137
100% RDF	8.03	7.84	7.71	0.17	0.16	0.14	20.1	16.1	11.6	2.30	1.90	1.80	137	112	94.0	13.6	9.05	7.24	372	295	218
50% RDF	8.05	7.95	7.86	0.13	0.11	0.11	19.6	13.7	10.7	1.80	1.50	1.20	125	103	85.0	11.1	8.60	7.01	313	221	159
50% N (crop residues)	7.94	7.91	7.78	0.13	0.11	0.11	19.2	14.9	10.9	2.00	1.80	1.50	131	106	88.0	12.3	8.70	7.24	329	252	174
50% N (FYM)	7.91	7.87	7.73	0.13	0.12	0.12	19.7	15.5	11.2	2.20	1.90	1.50	134	109	91.0	13.3	8.82	7.24	356	256	201
50% NPK + 50% crop residue – NEB	7.85	7.73	7.62	0.18	0.17	0.14	20.7	18.1	12.3	3.20	2.90	2.50	144	125	102	19.0	9.38	7.69	398	329	247
50% NPK + 50% FYM – NEB	7.84	7.71	7.65	0.18	0.18	0.15	21.1	18.5	12.6	3.40	2.90	2.60	147	128	107	19.5	9.41	8.01	404	336	250
100% RDF + 25 kg $ZnSO_4$ ha^{-1}	7.89	7.81	7.68	0.17	0.16	0.14	20.2	16.7	11.5	2.40	2.10	2.00	141	116	97.0	15.6	9.13	7.47	381	304	227
FYM – 12.5 t ha^{-1}	7.81	7.63	7.60	0.19	0.18	0.16	21.3	18.9	12.8	3.60	3.20	2.80	153	134	110	20.6	10.7	8.68	410	339	255
Mean	7.94	7.84	7.72	0.16	0.14	0.13	20.0	16.2	11.6	2.48	2.14	1.85	135	114	93.7	15.1	9.15	7.23	363	283	208
SEd	0.137	0.135	0.133	0.009	0.008	0.008	0.449	0.359	0.259	0.196	0.162	0.147	5.095	4.309	3.552	1.045	0.689	0.555	6.31	4.92	3.63
CD ($P \leq 0.05$)	0.29	0.286	0.282	0.018	0.016	0.016	0.951	0.762	0.549	0.416	0.344	0.312	10.80	9.135	7.530	2.215	1.460	1.176	13.38	10.42	7.69

Table 3. Effect of different treatments on soil chemical properties of PME on cotton

Treatments	Exchangeable calcium (meq 100 g^{-1})			Exchangeable magnesium (meq 100 g^{-1})			Iron (mg kg^{-1})			Zinc (mg kg^{-1})			Copper (mg kg^{-1})			Manganese (mg kg^{-1})		
Soil depth (cm)	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45
Control	13.7	4.00	1.80	3.20	2.50	0.70	9.22	7.62	5.70	0.48	0.48	0.31	1.63	1.61	1.51	10.0	8.45	6.10
100% RDF	14.2	6.80	2.80	5.10	3.20	1.40	10.3	8.23	6.93	0.65	0.53	0.42	1.98	1.65	1.56	10.2	8.97	6.96
50% RDF	13.8	6.50	2.00	4.00	3.10	0.80	9.29	7.69	6.43	0.63	0.49	0.41	1.58	1.61	1.56	10.2	8.51	6.18
50% N (crop residues)	14.0	6.80	2.50	4.10	3.20	0.80	9.52	8.02	6.74	0.65	0.50	0.41	1.64	1.63	1.56	10.2	8.59	6.63
50% N (FYM)	14.1	6.90	2.50	5.00	3.20	1.00	9.80	8.18	6.79	0.77	0.52	0.41	1.98	1.64	1.56	10.2	8.85	6.80
50% NPK + 50% crop residue – NEB	14.8	9.90	4.60	6.70	3.60	1.50	12.6	8.57	7.36	0.89	0.58	0.44	2.66	1.73	1.58	14.1	9.82	7.66
50% NPK + 50% FYM – NEB	14.9	10.1	5.10	8.10	3.80	1.50	13.1	8.68	7.55	0.90	0.61	0.45	2.72	1.75	1.58	14.6	9.91	8.08
100% RDF + 25 kg $ZnSO_4$ ha^{-1}	14.4	7.30	3.30	5.00	3.40	1.10	10.4	8.31	7.23	0.85	0.58	0.42	1.98	1.65	1.57	10.5	9.03	7.32
FYM – 12.5 t ha^{-1}	15.1	10.5	5.80	8.80	4.30	1.70	13.8	9.12	7.61	0.97	0.63	0.45	2.97	1.80	1.66	15.6	10.3	8.60
Mean	14.3	7.64	3.38	5.56	3.37	1.17	10.9	8.27	6.93	0.75	0.55	0.41	2.13	1.67	1.57	11.7	9.16	7.15
SEd	0.247	0.238	0.279	0.311	0.258	0.088	0.564	0.312	0.156	0.039	0.021	0.009	0.157	0.063	0.035	0.898	0.547	0.547
CD ($P \leq 0.05$)	0.524	0.504	0.592	0.660	0.547	0.187	1.196	0.662	0.331	0.083	0.044	0.020	0.334	0.134	0.074	1.903	1.160	1.160

Table 4. Effect of different treatments on biochemical and biological properties of PME on cotton

Treatments	Dehydrogenase (μg TPF g^{-1} day^{-1})			Phosphatase (μg PNP g^{-1} h^{-1})			Urease (μg of NH_4 released g^{-1} h^{-1})			Bacteria ($\times 10^6$ cfu g^{-1})			Fungi ($\times 10^4$ cfu g^{-1})			Actinobacteria ($\times 10^3$ cfu g^{-1})		
Soil depth (cm)	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30-45
Control	21.9	15.2	14.9	99.8	27.3	9.57	4.69	2.18	1.01	38.7	23.0	9.67	20.3	16.0	12.0	19.3	11.7	9.00
100% RDF	27.7	20.1	18.7	123	98.6	21.3	6.33	2.89	1.86	42.0	27.7	16.3	22.7	21.3	14.7	23.0	17.3	10.7
50% RDF	22.4	18.7	17.4	101	93.5	10.5	4.82	2.38	1.09	41.3	23.7	15.7	20.7	20.7	13.3	20.0	16.3	9.33
50% N (crop residues)	23.3	19.9	18.3	122	95.4	15.2	5.40	2.47	1.58	41.3	25.3	16.0	21.0	21.3	13.7	21.7	16.7	9.67
50 % N (FYM)	25.8	20.1	18.7	123	97.9	20.9	5.47	2.72	1.64	42.0	25.7	16.3	22.3	21.3	14.3	22.3	17.3	9.67
50% NPK + 50% crop residue – NEB	58.9	20.6	19.5	130	99.4	24.0	9.15	3.29	2.26	44.0	31.0	16.7	32.0	21.7	16.3	25.0	18.7	13.0
50% NPK + 50% FYM – NEB	60.5	21.0	19.8	131	99.9	25.8	9.44	3.56	2.35	44.7	31.7	17.0	33.7	22.0	16.7	25.3	18.3	13.3
100% RDF + 25 kg $ZnSO_4$ ha^{-1}	33.3	20.3	19.3	125	99.1	21.7	6.74	2.92	1.98	42.3	29.0	16.3	24.0	21.7	15.3	23.0	17.7	11.7
FYM – 12.5 t ha^{-1}	64.0	22.1	20.3	136	103	26.5	10.0	3.73	2.36	46.0	32.3	17.3	35.3	22.3	18.3	29.0	19.0	13.7
Mean	37.5	19.8	18.5	121	90.4	19.5	6.90	2.90	1.79	42.5	27.7	15.7	25.8	20.9	15.0	23.2	17.0	11.1
SEd	2.913	0.747	0.416	4.593	2.096	1.562	0.413	0.222	0.146	1.605	1.508	0.356	1.942	1.577	1.150	1.779	0.384	0.246
CD ($P \leq 0.05$)	6.175	1.583	0.882	9.737	4.443	3.311	0.876	0.470	0.311	3.402	3.198	0.755	4.116	3.343	2.437	3.771	0.815	0.522

The combined application of FYM and NPK also increases soil SOC in two ways, viz. immobilization (fertilization) and mineralization (cotton crop and root residue)[21]. A similar experiment on continuous application of fertilizers and FYM conducted for 28 years reported significantly higher SOC in manure-applied soil due to the addition of carbon source, root biomass and crop residue from the FYM-applied soil[28].

The exchangeable Ca and Mg increased to the tune of 10.2% and 175% (FYM 12.5 t ha^{-1}) when compared to control. The effect of organic treatment (FYM 12.5 t ha^{-1}) on DTPA-extractable Fe, Zn, Cu and Mn was significantly higher in the present study (Table 3). The application of organic manure significantly increased the availability of native and applied micronutrients such as Fe, Zn, Cu and Mn in the soil through the formation of stable complexes with organic ligands, thereby decreasing their susceptibility to adsorption, fixation and/or precipitation in the soil. Similar results were reported by Chaudhary *et al.*[28] and Gupta *et al.*[29].

Table 5. Principal component analysis of soil quality indicators with different treatments and different depths in PME of cotton

Cropping systems	Cotton–fallow		
	PC_1	PC_2	PC_3
Standard deviation	4.501	1.977	1.047
Proportion variance	0.750	0.145	0.041
Cumulative proportion	0.750	0.895	0.936
Eigen values	20.25	3.907	1.097
Soil parameters[d]			
BD	–0.159	–0.317	–0.058
Porosity	0.104	0.420	0.022
FC	0.213	0.005	0.219
PWP	0.129	0.292	0.120
AWC	0.207	–0.124	0.219
HC	0.177	–0.252	–0.213
DAS	0.196	–0.182	–0.219
WAS	0.195	–0.208	–0.080
pH	0.048	–0.474	0.058
EC	0.131	0.314	0.009
CEC	0.211	–0.074	0.247
OC	0.169	0.314	–0.012
N	0.210	0.085	0.195
P	0.212	–0.020	–0.191
K	0.214	0.029	0.179
Ca	0.207	–0.091	0.239
Mg	0.218[a]	–0.032	–0.076
Fe	0.217	–0.008	–0.065
Zn	0.212	–0.015	–0.079
Cu	0.192	0.061	–0.422
Mn	0.216	0.009	–0.113
DHA	0.192	0.060	–0.441
Ptase	0.198[c]	–0.102	0.282
Urease	0.215	–0.035	–0.146
Bacteria	0.209	–0.124	0.194
Fungi	0.213	0.033	–0.076
Actinobacteria	0.218[ab]	–0.043	0.110

[a]Factor loadings are considered as highest weighted in each principal component.
[b]Highest Pearson's correlation sum.
[c]Lowest Pearson's correlation sum.
[d]BD, Bulk density; FC, Field capacity; PWP, Permanent wilting point; AWC, Available water content; HC, Hydraulic conductivity; DAS, Dry aggregate stability; WAS, Wet aggregate stability; EC, Electrical conductivity; CEC, Cation exchange capacity; OC, Organic carbon; N, Nitrogen; P, Phosphorus; K, Potassium; Ca, Calcium; Mg, Magnesium; Fe, Iron; Zn, Zinc; Cu, Copper; Mn, Manganese; DHA, Dehydrogenase; Ptase, Phosphatase.

(iii) *Biological and biochemical properties:* The biological properties, viz. dehydrogenase (64.0 μg TPF g^{-1} day^{-1}), phosphatase (136 μg PNP g^{-1} h^{-1}) and urease (10.0 μg of NH_4 released g^{-1} h^{-1}) exhibited a higher value range in the organics treatment (FYM 12.5 t ha^{-1}) plot, followed by 50% NPK + 50% FYM–NEB and 50% NPK + 50% pulse crop residue–NEB treatments. Organics treatment resulted in an improvement of the substrate for microorganisms, which directly increased the microbial population (Table 4). The continuous application of FYM acts as a source of N and C to heterotrophs, which in turn provides nutrition to microorganisms and their functions, especially for the production of soil enzymes[30]. These results are in agreement with those of Bhattacharya *et al.*[31]. For biochemical properties, the same trend was observed to be followed, and the microbial population was found to decrease with increasing depth (Table 4).

(iv) *Soil quality:* The soil quality indicators are highly dependent on other soil physico-chemical and biological properties or processes. They need to be land- and crop-specific on both temporal and spatial assessment of soil quality[30]. Table 5 shows the results obtained from PCA for PME of

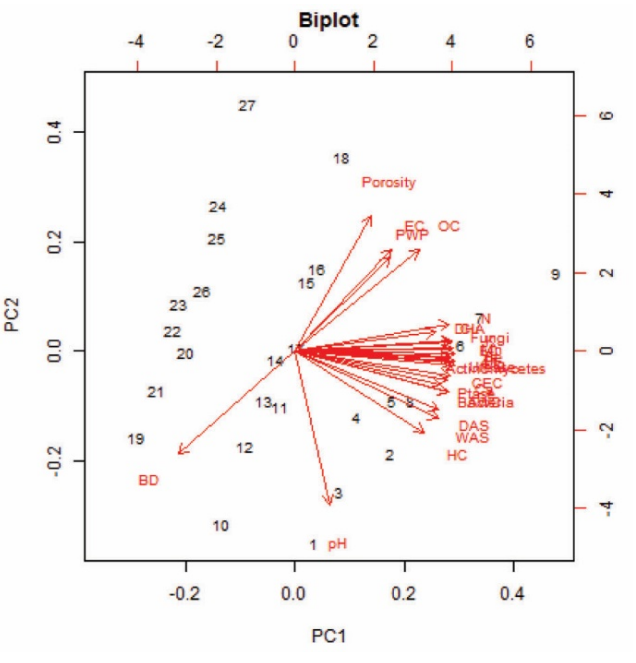

Figure 1. Biplot showing loadings of different variables (soil properties).

Table 6. Pearson correlation matrix for high weighted variables

Parameters	FC	AWC	CEC	N	P	K	Ca	Mg	Fe	Zn	Mn	Ptase	Urease	Bacteria	Fungi	Actinobacteria
FC	1	0.944	0.959	0.939	0.868	0.954	0.947	0.919	0.915	0.887	0.902	0.896	0.895	0.937	0.892	0.961
AWC	0.944	1	0.974	0.879	0.865	0.921	0.974	0.905	0.909	0.876	0.877	0.930	0.887	0.983	0.856	0.958
CEC	0.959	0.974	1	0.926	0.854	0.961	0.975	0.922	0.907	0.898	0.887	0.947	0.890	0.985	0.875	0.971
N	0.939	0.879	0.926	1	0.855	0.968	0.892	0.905	0.898	0.871	0.878	0.868	0.873	0.892	0.892	0.935
P	0.868	0.865	0.854	0.855	1	0.880	0.855	0.940	0.984	0.930	0.939	0.779	0.966	0.872	0.922	0.918
K	0.954	0.921	0.961	0.968	0.880	1	0.932	0.920	0.926	0.915	0.911	0.895	0.908	0.934	0.906	0.960
Ca	0.947	0.974	0.975	0.892	0.855	0.932	1	0.886	0.899	0.872	0.866	0.908	0.905	0.981	0.832	0.956
Mg	0.919	0.905	0.922	0.905	0.940	0.920	0.886	1	0.949	0.948	0.969	0.890	0.947	0.914	0.971	0.967
Fe	0.915	0.909	0.907	0.898	0.984	0.926	0.899	0.949	1	0.946	0.947	0.840	0.956	0.909	0.937	0.954
Zn	0.887	0.876	0.898	0.871	0.930	0.915	0.872	0.948	0.946	1	0.937	0.834	0.921	0.896	0.931	0.928
Mn	0.902	0.877	0.887	0.878	0.939	0.911	0.866	0.969	0.947	0.937	1	0.827	0.950	0.881	0.967	0.939
Ptase	0.896	0.930	0.947	0.868	0.779	0.895	0.908	0.890	0.840	0.834	0.827	1	0.796	0.930	0.875	0.951
Urease	0.895	0.887	0.890	0.873	0.966	0.908	0.905	0.947	0.956	0.921	0.950	0.796	1	0.906	0.903	0.933
Bacteria	0.937	0.983	0.985	0.892	0.872	0.934	0.981	0.914	0.909	0.896	0.881	0.930	0.906	1	0.852	0.960
Fungi	0.892	0.856	0.875	0.892	0.922	0.906	0.832	0.971	0.937	0.931	0.967	0.875	0.903	0.852	1	0.949
Actinobacteria	0.961	0.958	0.971	0.935	0.918	0.960	0.956	0.967	0.954	0.928	0.939	0.951	0.933	0.960	0.949	1
	14.82	14.74	14.93	14.47	14.43	14.89	14.68	14.95	14.88	14.59	14.68	14.17	14.64	14.83	14.56	15.24

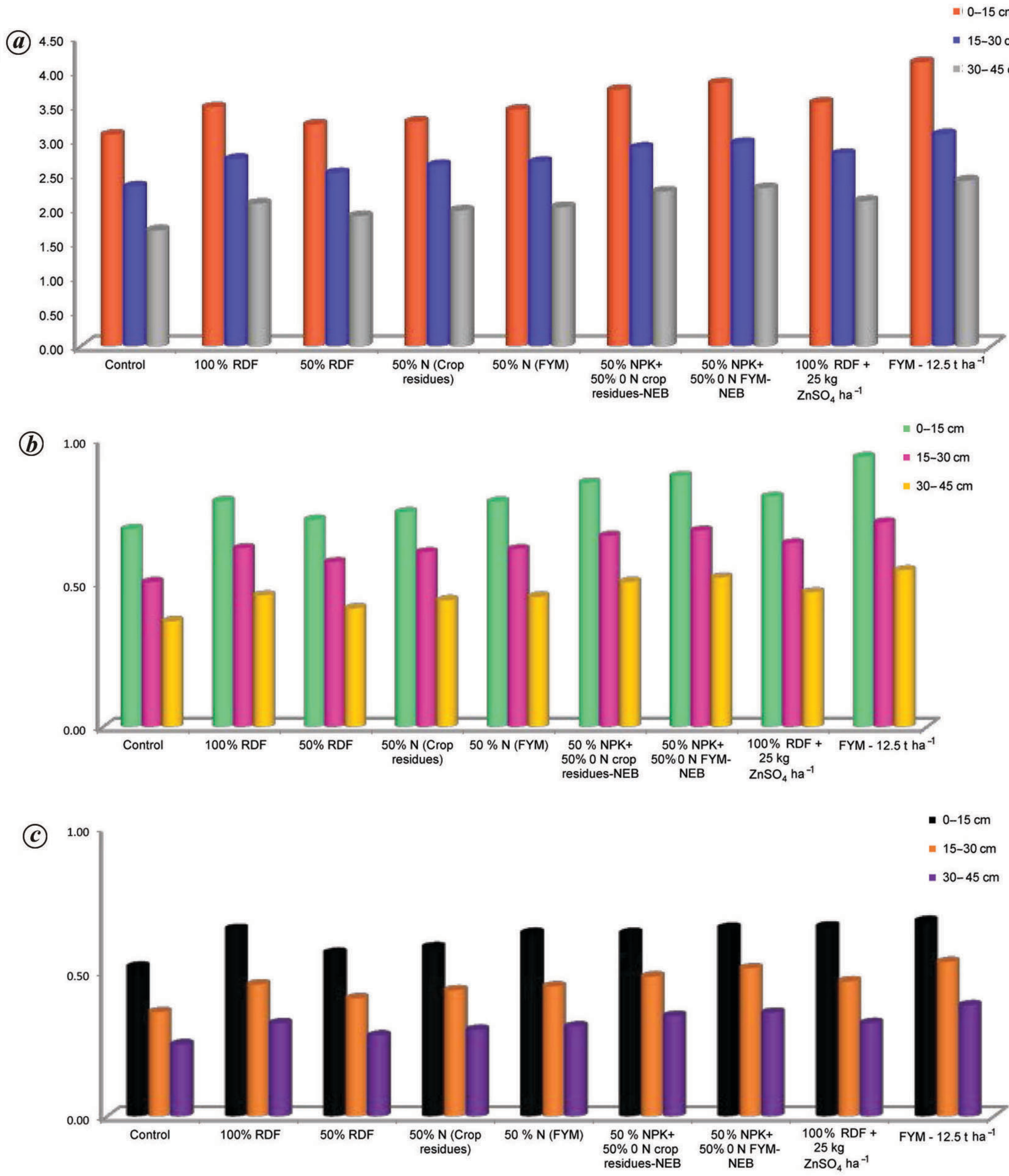

Figure 2. Different methods of soil quality index under dryland ecosystem. ***a***, Weighed additive soil quality index (SQI_w). ***b***, Additive soil quality index (SQI_a). ***c***, Nemoro soil quality index (SQI_n).

Kovilpatti. Three PCs with eigenvalue >1 which explains a variance of 93.57% within the dataset, were considered (Table 5). The variables with high weight in PC_1 were field capacity (FC), available water content (AWC), CEC, N, P, K, Ca, Mg, Fe, Zn, Mn, phosphatase, urease, bacteria, fungi and actinobacteria. The correlation matrix was analysed for these parameters under PC_1, which showed a positive correlation for most of the parameters (Table 6). However, the variable phosphatase with the lowest correlation sum was omitted from PCA, and all the remaining variables were thus retained for MDS. In PC_2 and PC_3, porosity and phosphatase were the highly weighted variables and thus retained for MDS. Hence, the final MDS consisted of FC, AWC, CEC, N, P, K, Ca, Mg, Fe, Zn, Mn, urease, bacteria, fungi, actinobacteria, porosity and phosphatase as the soil quality indicators for the PME field of Kovilpatti.

Figure 1 is a biplot demonstrating the integration of surface and subsurface (dynamic and inherent properties) information on soil quality. The results are in agreement with those of earlier studies[5,32]. However, in the present study, SQI has been determined by comparing three methods, in which the organic manure treatment (FYM 12.5 t ha^{-1}) showed noticeable results in the upper soil layer (0–15 cm depth), followed by a decreasing trend (Figure 2 *a*–*c*). This

Appendix 1. Initial soil properties of PME, ARS, Kovilpatti

Properties	Value
EC (ds m^{-1})	0.49
pH	8.2
Organic carbon (g kg^{-1})	1.5
Available N (kg ha^{-1})	80
Available P (kg ha^{-1})	10
Available K (kg ha^{-1})	586
Available Zn	1.2
Bulk density (Mg m^{-3})	1.23 to 1.30
Particle density (Mg m^{-3})	1.60 to 1.69
Infiltration rate (cm h^{-1})	0.7 to 0.9
Pore space (%)	48.3 to 48.9
Permanent wilting point (%)	14
Field capacity (%)	35
Coarse sand (%)	10.9 to 11.5
Fine sand (%)	9.4 to 14.1
Silt (%)	15.6 to 19.9
Clay (%)	48.0 to 53.0
Texture	Clay

results in an increased microbial population (bacteria, fungi and actinobacteria). Similar results have been reported in the literature[30,33].

Conclusion

The main aim of assessing soil quality is to educate farmers about sustainable soil management practices, which is also the need of the hour. The results of the present study indicate the importance of organics in influencing the soil quality indicators and indices under different treatments and depths of cotton–fallow in the dryland ecosystem of Tamil Nadu, India. They also revealed that the treatment receiving organics has the highest SQI in the surface layer among the three methods used. The indicators used in the present study can be further utilized for the periodical assessment of SQI. Hence, the treatment which received the best SQI (FYM 12.5 t ha^{-1}) can be recommended to the farmers mainly on a long-term basis, and an integrated nutrient management system on a short-term basis to maintain soil quality.

1. Tian, Y., Xu, Z., Wang, J. and Wang, Z., Evaluation of soil quality for different types of land use based on minimum dataset in the typical desert steppe in Ningxia, China. *J. Adv. Transp*., 2022, **2022**, 1–14.
2. Krauss, M., Berner, A., Perrochet, F., Frei, R., Niggli, U. and Mäder, P., Enhanced soil quality with reduced tillage and solid manures in organic farming – a synthesis of 15 years. *Sci. Rep.*, 2020, **10**(1), 1–12.
3. Nortcliff, S., Standardisation of soil quality attributes. *Agric. Ecosyst. Environ.*, 2002, **88**, 161–168.
4. Mandal, U. K. *et al.*, Assessing soil quality in a semiarid tropical watershed using a geographic information system. *Soil Sci. Soc. Am. J.*, 2011, **75**, 1144–1160.
5. Ray, S. K. *et al*., Soil and land quality indicators of the Indo-Gangetic Plains of India. *Curr. Sci.*, 2014, **107**, 1470–1486.
6. Moncada, M. P., Gabriels, D. and Cornelis, W. M., Data-driven analysis of soil quality indicators using limited data. *Geoderma*, 2014, **235**, 271–278.
7. Gupta, R. P. and Dakshinamurthi, C., *Procedures for Physical Analysis of Soils*, Indian Agricultural Research Institute, New Delhi, 1981, pp. 1–293.
8. Richards, L. A., *Diagnosis and Improvement of Saline and Alkali Soils*, US Department of Agriculture Handbook No. 60, Government Printing Office, Washington DC, 1954, pp. 1–154.
9. Jackson, M. L., *Soil Chemical Analysis*, Prentice Hall of India, New Delhi, 1973, pp. 151–154.
10. Walkley, A. and Black, I. A., An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.*, 1934, **37**(1), 29–38.
11. Subbiah, B. V. and Asija, G. L., Alkaline method for determination of mineralizable nitrogen. *Curr. Sci*., 1956, **25**(2), 259–260.
12. Olsen, S. R., Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Department of Agriculture, 1954, p. 939.
13. Stanford, G. and English, J., Use of the flame photometer in rapid soil tests for K and Ca. *Agron. J.*, 1949, **41**(9), 446–447.
14. Lindsay, W. L. and Norvell, W. A., Development of DTPA soil test for Fe, Mn, Zn and Cu. *Soil Sci. Soc. Am. J.*, 1978, **42**(3), 421–428.
15. Collings, C. H. and Lyne, M. P., *Microbiological Methods*, Butterworth, London, UK, 1984, 5th edn, pp. 56–113.
16. Kenknight, G. and Muncie, J. H., Isolation of phytopathogenic actinomycetes. *J. Phytopathol.*, 1939, **29**(11), 1000–1001.
17. Tabatabai, M. A. and Bremner, J. M., Use of *p*-nitrophenyl phosphate for assay of soil phosphatase activity. *Soil Biol. Biochem.*, 1968, **1**(4), 301–307.
18. Casida, J. L. E., Klein, D. A. and Santoro, T., Soil dehydrogenase activity. *Soil Sci.*, 1964, **98**(6), 371–376.
19. Andrews, S. S., Karlen, D. L. and Mitchell, J. P., A comparison of soil quality indexing methods for vegetable production systems in northern California. *Agric., Ecosyst. Environ.*, 2002, **90**(1), 25–45.
20. Doran, J. W. and Parkin, T. B., Defining and assessing soil quality. In *Defining Soil Quality for a Sustainable Environment* (eds Doran, J. W. *et al.*), Soil Science Society of America Journal, Madison, 1934, pp. 3–21.
21. Tripathi, R. *et al*., Soil aggregation and distribution of carbon and nitrogen in different fractions after 41 years long-term fertilizer experiment in tropical rice–rice system. *Geoderma*, 2014, **213**, 280–286.
22. Das, B., Chakraborty, D., Singh, V. K., Aggarwal, P., Singh, R., Dwivedi, B. S. and Mishra, R. P., Effect of integrated nutrient management practice on soil aggregate properties, its stability and

aggregate-associated carbon content in an intensive rice–wheat system. *Soil Tillage Res.*, 2014, **136**, 9–18.
23. Masto, R. E., Chhonkar, P. K., Singh, D. and Patra, A. K., Soil quality response to long-term nutrient and crop management on a semi-arid Inceptisol. *Agric. Ecosyst. Environ.*, 2007, **118**, 130–142.
24. Majhi, P., Rout, K. K., Nanda, G. and Singh, M., Soil quality for rice productivity and yield sustainability under long-term fertilizer and manure application. *Commun. Soil Sci. Plant Anal.*, 2019, **50**(11), 1330–1343.
25. Mairan, N. R., Patil, S. G. and Kachhave, K. G., Physico-chemical properties under sorghum–sunflower cropping sequence in Vertisols. *J. Soils Crops*, 2005, **15**(2), 352–355.
26. Eghball, B., Soil properties as influenced by phosphorus and nitrogen based manure and compost applications. *Agron. J.*, 2002, **94**(1), 128–135.
27. Bellakki, M. A., Badanur, V. P. and Setty, R. A., Effect of long-term integrated nutrient management on some important properties of a Vertisol. *J. Indian Soc. Soil Sci.*, 1998, **46**(2), 176–180.
28. Chaudhury, J., Mandal, U. K., Sharma, K. L., Ghosh, H. and Mandal, B., Assessing soil quality under a long term rice based cropping system. *Commun. Soil Sci. Plant Anal.*, 2005, **36**(9–10), 1141–1161.
29. Gupta, R. K., Arora, B. R., Sharma, K. N. and Ahluwalia, S. K., Influence of biogas slurry and farmyard manure application on the changes in soil fertility under rice–wheat sequence. *J. Indian Soc. Soil Sci.*, 2000, **48**(3), 500–505.
30. Chu, H., Lin, X., Fujii, T., Morimoto, S., Yagi, K., Hu, J. and Zhang, J., Soil microbial biomass, dehydrogenase activity, bacterial community structure in response to long-term fertilizer management. *Soil Biol. Biochem.*, 2007, **39**(11), 2971–2976.
31. Bhattacharyya, P., Pathak, H. and Pal, S. (eds), Soil management for climate-smart agriculture. In *Climate Smart Agriculture*, Springer, Singapore, 2020, pp. 41–56.
32. Vasu, D. *et al.*, Soil quality index (SQI) as a tool to evaluate crop productivity in semi-arid Deccan plateau, India. *Geoderma*, 2016, **282**, 70–79.
33. Romero, E., Fernández-Bayo, J., Díaz, J. M. C. and Nogales, R., Enzyme activities and diuron persistence in soil amended with vermicompost derived from spent grape marc and treated with urea. *Appl. Soil Ecol.*, 2010, **44**(3), 198–204.

Received 5 May 2022; re-revised accepted 3 March 2023

doi: 10.18520/cs/v124/i11/1308-1318