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Soil Quality Changes Resulting from Long-Term Fertilizer Application Under Intensive Cropping System in Alluvial Soils

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ABSTRACT
Soil quality is one of the most important factors which reveal the soil–environment functionality for identifying whether soil quality is improving, remain constant, or declining. This paper evaluated change in soil quality after 40 years of chemical fertilizer use and continuous cultivation of multiple crops (jute–rice–wheat) on alluvial soils. The concepts of relative soil quality index (RSQI) and Cumulative Rating Index (CRI) were used in the evaluation. It was observed that soil of class III reduced to class II after 20 years and to class I after 40 years of fertilizer application with manure, nitrogen, phosphorus, and potassium ($NPK_{100+FYM}$). There was a strong correlation between SQI and CRI ($r = 0.82^{**}$) which showed more promising effects on soil sustainability. Significant positive relationship between ΔRSQI and crop yield of jute ($r = 0.89^{**}$) and wheat ($r = 0.90^{**}$) was found. However, rice yield declined up to 44% of its initial yield ($r = 0.20$).

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Alluvial soil; jute–rice–wheat cropping; long-term fertilizer trial; soil quality

Introduction

Alluvial soils constitute the largest and most important soil group of India and contribute most to the agricultural wealth of the country. The soils are derived mainly from the deposition of Ganges and Brahmputra river systems. They cover about 75 million hectares (M ha) in the Indo-Gangetic Plains (IGP) and Brahmaputra Valley (Govinda Rajan and Rao Gopal 1978). In general, they carry ample potash, lime, and phosphoric acid. However, they are lacking in nitrogenous and organic substance. In the eastern plains, Bengal basin and Assam alluvial soil regions of India, jute–rice–wheat (JRW) cropping system is the most important predominant cropping system. The rapid spread of JRW system has mainly been attributed on account of its better adaptability, availability of high-yielding varieties and mechanization of crops. Therefore, the farmers of eastern plain zone are adopting rice–wheat–jute system in large scale. For over a decade, JRW yields in high-productivity zones have either stagnated or declined. The most important reason is a decline in factor productivity resulting from depletion of soil quality. The system commonly shows signs of fatigue and is no longer exhibiting increased production with higher input use based on the current pattern (CRIJAF 2015). Even with current generalized recommended rates of fertilization for such cropping system, a negative balance of the primary nutrients exists (Shukla et al. 2005; Singh 2007).

Land use and management practices greatly impact the direction and degree of soil quality changes. Soil changes are dynamic over time (Hoosbek and Bryant 1992; Wang and Gong 1998). Therefore, only by comparing and analyzing changes in soil properties between two or more time periods, can essence and mechanism of soil changes be better understood. In studies of impacts of land use on soil changes, many researchers evaluated the degree of soil degradation and soil improvement by comparing soil properties within the same time period but under different land

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use patterns (Ayoubi et al. 2011; Matano et al. 2015). Single soil property evaluations, such as changes in soil organic matter (OM), nitrogen (N), phosphorus (P), and potassium (K) were usually emphasized, and much less attention was paid to a comprehensive assessment of soil quality changes.

In this study, a combination of physical and chemical soil properties were used for the evaluation of soil quality changes as a result of application of manure and fertilizers for 40 years in alluvial soil under JRW crop system. The selected measurements comply with the proposed selection criteria of soil quality indicators in that they are sensitive to variations in management. They define major chemical processes in soil and they reflect conditions as they actually exist in the field under a given management system.

Materials and methods

Study site

The study was conducted over a 40 year period (1972–2013) at Research Farm of Central Research Institute for Jute and Allied Fibre (CRIJAF). The study area located in Barrackpore of West Bengal (India), at 88°26′ E, 22°45′ N and elevations of 9 m. According to the National Agricultural Research Project classification (NARP 1979) of Agriculture Climatic Zone (India), the study area belongs to the New Alluvial Zone (WB-4). Climate is humid (rainfall >1600 mm) with a distinct wet monsoon, summer, and a cool winter season. Average maximum and minimum temperatures during the experimental period were 36.9 °C and 19.7 °C, respectively. The study site had never been cultivated before 1968 and was previously covered with natural forest vegetation such as perennial weeds and grasses. Rice was the first crop grown in 1969 followed by jute, rice, and wheat from 1971 to 1972.

During the study period (1972–2013), three crops were grown in rotation, that is, jute, rice, and wheat under upland situation. The trial involved eight different management strategies consisting of different combinations of chemical fertilizer and farm yard manure (FYM). Chemical fertilizer application rates were based on percentages of the recommended doses for rice, wheat, and jute. Three of these fertilizer management strategies (NPK_{000}, NPK_{100}, and $NPK_{100+FYM}$) were chosen for soil quality evaluation on the basis that they are most representative of current practices found in farmer's field of India.

Management practices, soil sampling, and analysis

Field plots of 200 m^2 (20 × 10 m) with three replications were established for each fertilizer treatments. Jute plant (*Corchorus olitorius* and *Corchorus capsularis*) as fiber crop was grown in summer season (April–July) followed by rice (*Oryza sativa*) during rainy season (July–November), while wheat (*Triticum aestivum*) in post-rainy season (December–March). Seeds of jute and wheat were sown, while rice was transplanted as seedlings following standard methods. Three treatments of fertilizer applied for growing JRW crops are given in Table 1. FYM were incorporated a week before transplantation/sowing, phosphorous (P) and potash (K) were applied as single super phosphate (16% total P) and muriate of potash (60% of total K), respectively, before transplantation/sowing. Nitrogen (N) was applied as urea (46% of total N) in three splits before and after 25th and 50th days of transplantation/sowing. During the first tillage operation for rice cultivation, the shedded leaves and roots of previous crop (jute) were mixed in soil in all the treatments of the study. Need-based irrigation, weeding, and plant protection measures were taken. The experiment was laid out in randomized block design (RBD).

Table 1. Agronomic practices for growing jute–rice–wheat crop system in new alluvial soils.

	Fertilizer applied [FYM:N:P:K (kg^{-1} hm^2)]			
Crop	Control (NPK_{000})	Fertilizer-I (NPK_{100})	Fertilizer-II ($NPK_{100+FYM}$)	Growing period (month)
Jute	00:00:00	60:13:50	60:13:50:10000	April–July
Rice	00:00:00	120:26:50	120:26:50:00	August–November
Wheat	00:00:00	120:26:50	120:26:50:00	December–March

Three representative soil samples (0–22.5 cm) were collected from each of the plots every year during 1973–2013 and analyzed following standard procedures (Jackson 1967) for their physical and chemical properties such as pH (1:2 soil–water suspension), texture (hydrometer method), soil rooting depth, soil organic matter (Walkley and Black method), extractable N (alkaline $KMnO_4$ method), extractable P (Olsen's $NaHCO_3$ method), extractable K (NH_4OAc method), and cation exchange capacity (CEC).

Method of evaluation of changes in soil quality

In this research, a minimum dataset (MDS) called indicators for characterizing and monitoring soil quality was used. Expert opinion (EO) approach were considered for selecting an MDS from the 25 potential SQ indicators based on researcher knowledge and literature recommendations (Doran and Parkin 1996; Larson and Pierce, 1994). In this study, nine soil quality (SQ) indicators were used based on their sensitivity to management practices, ability to describe major soil processes, ease and cost of sampling and laboratory analysis, and significance of increasing productivity (agronomic), and protecting environmental soil functions. The selected indicators include rooting soil depth, soil texture, land slope, organic carbon, available N, available P, available K, cation exchange capacity (CEC), and soil pH. Soil depth, slope, and soil texture reflect the suitability of soil physical conditions and water availability for plant growth. Organic carbon, N, P, and K show the nutrient status of the soil for plants. Organic carbon, CEC, and pH influence the habitat for soil organisms. These factors have therefore been adopted to reflect the various aspects of soil quality in relation to plant growth. Changes in indicator reflected the combined effects of land use.

The methodology for evaluation of soil quality is described below:

Weights of the indicators

The weight for each indicator was assigned on the basis of existing soil conditions, cropping pattern, and agro-climatic conditions (Table 2). The sum of all weights is normalized to 100%.

Subdivision of the indicators

Each of the indicators was divided into four classes. Class I is the most suitable for plant growth; Class II is suitable to plant growth but with slight limitations; Class III is with more serious limitation than Class II; and Class IV is with severe limitations for plant growth. Marks of 4, 3, 2, and 1 were given to class I, II, III, and IV, respectively. The range for each class is shown in Table 2.

Table 2. Soil quality and their weights and classes for the evaluation of soil quality.

Indicators	Weight	Class I	Class II	Class III	Class IV
Soil texture	13	Loam	Silt, silty loam, silty clay loam	Clay loam, sandy loam, silty clay	Loamy sand, clay, sand
Soil depth (cm)	6	>150	100–150	50–100	<50
Slope (%)	6	< 3	3–5	5–10	>10
Soil pH	11	6.0–7.4	5.5–6.0 7.4–7.8	5.0–5.4 7.8–8.2	<5.0 >8.2
Organic C (g kg^{-1})	13	>100	75–100	50–75	<50
Available N (kg ha^{-1})	13	>400	300–400	200–300	<200
Available P (kg ha^{-1})	13	>25	15–25	10–15	<10
Available K (kg ha^{-1})	12	>280	170–280	100–170	<100
CEC (cmol (p^+) kg^{-1})	13	>20	15–20	10–15	<10
Marks allotted	100	4	3	2	1

Quantitative evaluation of changes in soil quality

By introducing the concept of relative soil quality index (RSQI), the nine indicators were combined into an RSQI (Karlen and Stott, 1994). The equation for calculating RSQI value is given below:

$$\mathrm{RSQI} = \frac{\mathrm{SQI}}{\mathrm{SQI_m}} \times 100$$

where SQI is soil quality index, and $\mathrm{SQI_m}$ is the maximum value of SQI.

The maximum value of SQI for soil is 400 and the minimum value 100 (Wang and Gong 1998). SQI is calculated from the equation:

$$\mathrm{SQI} = \sum \mathrm{W_i\, I_i}$$

where $\mathrm{W_i}$ is weights of the indicators and $\mathrm{I_i}$ is the marks of the indicators classes.

SQI of every indicator was calculated separately by multiplying weight of indicators and marks allotted to the class (Table 2). Summing up of all nine indicators produced the SQI value for a soil under study.

An optimum soil in any region will have a normalized RSQI of 100, but real soils will have lower values which indicate directly their distance from the optimal soil. According to the RSQI values, soils were classified into five classes from best to worst, represented as follows by Class I (RSQI value: 90–100), Class II (RSQI value: 80–90), Class III (RSQI value: 70–80), Class IV (RSQI value: 60–70), and Class V (RSQI value: <60). Similarly by computing ΔRSQI values, change in soil quality in different regions can be compared even if they are evaluated with different evaluation systems, weightings, and classes. Changes in soil quality (ΔRSQI) were grouped into six classes differentiated as follows:

Change classes	ΔRSQI
Great increase	>15
Moderate increase	10–15
Slight increase	10–0
Slight decrease	0 to −10
Moderate decrease	−10 to −15
Great decrease	<−15

Cumulative rating index

Soil sustainability evaluation was done by using cumulative rating (CR) approach. It was calculated by assigning relative weighting factors (RWF) to each soil indicator values to test its efficiency (Table 3). CR was obtained by summing the RWFs determined on the basis of critical levels ranging from 1 to 5

Table 3. Relative weighting factors (RWF) according to the threshold values of soil quality indicators using the cumulative rating (CR) approach.

	Limitation				
Soil indicator	None	Slight	Moderate	Severe	Extreme
Soil texture	Loam	Silt, silty loam, silty clay loam	Clay loam, sandy loam	Silty clay, loamy sand	Clay, sand
Soil pH	6.0–7.0	5.8–6.1	5.4–5.7	5.0–5.5	<5.0
		7.1–7.5	7.6–7.8	7.9–8.2	>8.2
Organic C (g kg^{-1})	>100	75–100	50–75	30–50	<30
Available N (kg ha^{-1})	>400	300–400	200–300	100–200	<100
Available P (kg ha^{-1})	>25	20–25	10–20	5–10	<5
Available K (kg ha^{-1})	>250	200–250	150–200	100–150	<100
CEC (cmol (p^+) kg^{-1})	>20	15–20	10–15	5–10	<5
Soil depth (cm)	>150	100–150	50–100	25–50	<25
Slope (%)	<3	3–5	5–10	10–15	>15
RWF	1	2	3	4	5

showing "no limitation" to "extreme limitation" classes (Lal 1994; Singh 2007). Then CR was categorized into five classes and each class was assigned to a soil sustainability status (from highly sustainable to unsustainable).

Sustainability	Cumulative rating index
Highly sustainable	<14
Sustainable	14–18
Sustainable with high input	18–22
Sustainable with another land use	22–26
Unsustainable	>26

Results and discussion

The soil quality changes were evaluated quantitatively for three soil treatments for continuous 40 years in the same field. The data on selected soil indicators vis-à-vis soil properties of the experimental soil before 1973 and after 2013 trials where jute, rice, and wheat were grown in sequence every year are presented in Table 4.

Soil quality evaluation using data before first fertilizer application in 1972 and after 40 years of continuous fertilizer application showed that soil quality at this experimental field was toward higher side (Table 5). In the year 1972, experimental field had poor soil quality, that is, Class III. After fertilizer management of 20 years, land of Class III reduced to Class II in all the fertilizer treatments. However, $NPK_{100+FYM}$ treatment could reach to Class I after 40 years of fertilizer and crop management. No change in soil class was observed in NPK_{100}-treated soil and quality of NPK_{000} reversed back from class II to class III.

The change in ΔRSQI was above 10 for both NPK_{100} and $NPK_{100+FYM}$, and for NPK_{000} below 5, showing that soil quality increased with or without fertilizer application during first 20 years of JRW cultivation. However, RSQI value of NPK_{000} decreased significantly during 20th to 40th years (ΔRSQI = 0.6). Soil quality in $NPK_{100+FYM}$ was dominated by improvements (ΔRSQI = 22.5) in total 40 years of crop and fertilizer management. The average RSQI value of NPK_{100}- and $NPK_{100+FYM}$-treated soil increased from 77.5 to 88.9 and 100, respectively, after 40 years (Figure 1).

The results of sustainability by using cumulative rating index (CRI) approach showed a strong correlation between SQI and CRI ($R^2 = 0.82$, $p < 0.05$). $NPK_{100+FYM}$ treatment of soils was found near to highly sustainable (CR = 14) followed by NPK_{100} (CR = 16) after 40 years of fertilizer and crop treatment. The relationship between SQI and CRI proved both indices had good efficiency in determining soil quality (Figure 2). These approaches were negatively correlated with each other as it was expected.

Directions and intensity of changes in soil quality were same for NPK_{100} and $NPK_{100+FYM}$ treatments. In case of NPK_{000} also the changes in soil quality was found slightly positive during first 20 years. This indicates that soil recovered the loss of nutrients and other physical and chemical changes due to its

Table 4. Physicochemical properties of experimental field.

	Fertilizer treatment and year-wise changes in soil properties						
	Initial	NPK_{000}		NPK_{100}		$NPK_{100+FYM}$	
Soil indicator	1972	1993	2013	1993	2013	1993	2013
Soil texture	Sandy loam	Sandy loam	Sandy loam	Loam	Loam	Loam	Loam
Slope (%)	<3	<3	<3	<3	<3	<3	<3
Soil depth (cm)	>150	>150	>150	>150	>150	>150	>150
Soil pH	7.20	7.0	7.60	6.90	7.62	6.95	7.50
Organic C (g kg^{-1})	41	41	56	39	71	57	89
Available N (kg ha^{-1})	230	233	270	270	290	269	316
Available P (kg ha^{-1})	31	41	40	94	89	105	120
Available K (kg ha^{-1})	108	176	139	166	212	149	236
CEC (cmol (p^+) kg^{-1})	18.6	17.9	17.2	21.5	24.1	22.4	25.3

Table 5. Soil quality changes after 40 years of fertilizer application under JRW crops in alluvial soils.

	Fertilizer treatment and year-wise changes in soil quality						
	Initial	NPK_{000}		NPK_{100}		$NPK_{100+FYM}$	
Rating Index	1972	1993	2013	1993	2013	1993	2013
SQI	272	284	274	298	312	313	351
RSQI	77.5	80.9	67.8	84.9	88.9	89.2	100
DRSQI	–	3.4	0.6	7.4	11.4	11.7	22.5
CRI	–	19	21	18	16	16	14
Class	III	II	III	II	II	II	I
Change class	–	Slight increase	No change	Slight increase	Moderate increase	Moderate increase	Great increase
Sustainability	–	Sustainable with high input		Sustainable		Sustainable	Highly Sustainable

SQI, soil quality index; RSQI, relative SQI; CRI, cumulative rate index.

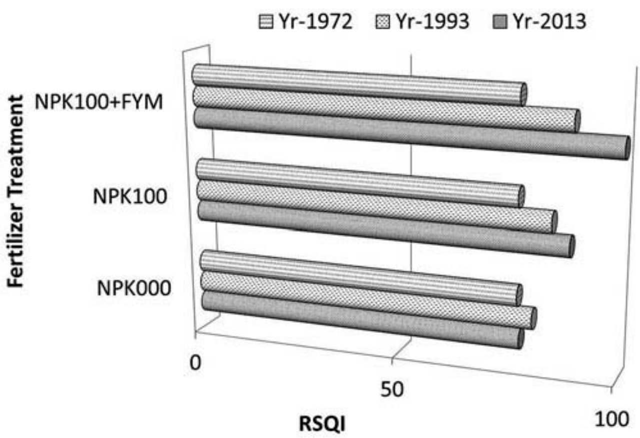

Figure 1. RSQI after 20th and 40th years of fertilizer application in alluvial soils.

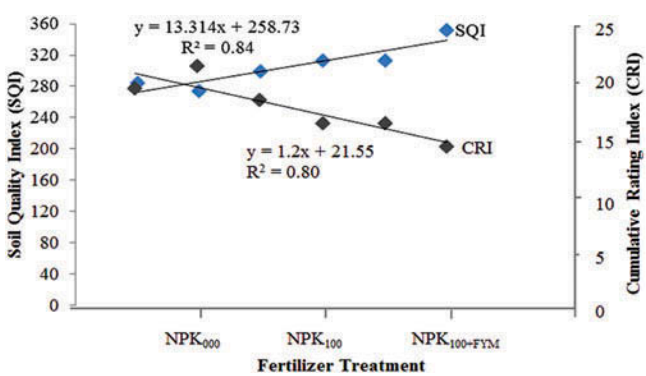

Figure 2. Relationship between soil quality index (SQI) and cumulative rating index (CRI) calculated based on minimum dataset selected under long-term fertilizer application in alluvial soils.

inherent buffering capacity and yearly addition of shedded leaves and roots of jute as manure in the soil. Recommended dose of NPK application along with manure improved low-quality soils, but it took almost 40 years to reach Class I quality. Organic carbon content of soil increases by 26% through addition of jute leaves during 40 years of JRW crop cultivation. A study identifying several biological, chemical, and physical indicators of soil quality also concluded that the highest SQI was found in $NPK_{100+FYM}$ treatment followed by NPK_{100} and control treatment under rice-based cropping system (Chaudhury

Table 6. Changes in crop yield after 40 years of fertilizer application in alluvial soils.

	Crop yield (t ha^{-1})								
	Control (NPK_{000})			Fertilizer-I (NPK_{100})			Fertilizer-II ($NPK_{100+FYM}$)		
Year	Jute	Rice	Wheat	Jute	Rice	Wheat	Jute	Rice	Wheat
1973	1.49	2.34	0.96	2.50	5.07	2.83	2.41	4.41	2.88
2013	0.87	1.43	0.70	2.17	2.83	2.45	2.49	3.01	2.68
% Change	−41.61	−38.89	−27.08	−13.20	−44.18	−13.42	3.32	−31.74	6.94
CD (p = 0.05)	Jute: 0.51; Rice: 0.97; Wheat: 0.63								
SE ±	Jute: 0.23; Rice: 0.44; Wheat: 0.29								

et al. 2005). In another study, soil quality change of 45.1% was observed for jute–rice–wheat cropping system and 18.7% for rice–wheat–fallow cropping system (Mandal et al., 2005). This indicates that inclusion of jute crop in the cropping system also played an important role in improving the soil quality. It has been estimated that one hectare of jute crop produces 3.5–7.0 tonnes of green leaves and roots (Bhattacharya, 2013; Alam et al. 2001; Gani et al. 1999; Rahman, Islam, and Rahman 1995). The shedded leaves contains about 20–40 kg nitrogen, 6.25–10 kg phosphates, and 17.5–32.5 kg potash in addition to sulfur and organic matter (Bhattacharya, 2013; Alim et al. 2002). The incorporated organic matter through decomposition of jute leaves together with the chemical nutrients improved both the physical and fertility status of the soil. A study also showed the beneficial effect of jute residues on soil properties (Sidhu and Beri 1989). Therefore, we cannot simply conclude that only fertilizer application leads to a constant change in soil quality.

The yield of jute and wheat was significantly influenced after recommended dose of fertilizer (NPK_{100}) was applied in combination with FYM ($NPK_{100+FYM}$). However, increase in yield of jute and wheat was only about 3–7% as compared with initial yield level. In contrary, the rice crop suffered a substantial yield decline (32–44%) in all the fertilizer treatments (Table 6). Decline in rice productivity suggest that the native soil nutrient supply and nutrient mineralization under fixed management fertilization under upland condition was not sufficient to sustain average rice productivity during wet season. Similar declining yield trends were reported by Dawe et al. (2000) and Ladha et al. (2003) under long-term rice–wheat experiments in Asia. It is important to note that rice being a shallow-rooted crop suffers from nutrient deficiency much earlier than wheat and jute crop in addition to their deeper root system. The change in crop yield and ΔRSQI were correlated in which a steady increase in ΔRSQI and yield of jute ($r = 0.62^*$) and wheat ($r = 0.80^{**}$) and decline of rice yield ($r = 0.10$) was obtained after 40 years of fertilizer application.

Conclusions

This study demonstrated the potential usefulness of selected physicochemical indicators for an integrated assessment of soil quality in the long-term fertilizer application and intensive cropping system. The combination of a soil change database has proved to be an effective method for evaluating changes in soil quality. Also, both soil quality and cumulative rating index approaches indicated similar results in evaluating soil sustainability. It was observed that unless the concept of suitable time and initial conditions of soil are considered in the study of changes in soil quality, it is difficult to demonstrate the increase and decrease of soil quality and the improvement or degradation on soil quality. The implementation of appropriate management strategies such as use of organic wastes through inclusion of crop like jute in crop rotations can improve soil sustainability and quality.

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