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Long-term effects of fertilizer and manure applications on soil quality and yields in a sub-humid tropical rice-rice system

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Abstract

Widespread yield stagnation and productivity declines in the rice–rice cropping system have been reported and many of the associated issues are related to soil quality. A long-term experimental study was initiated in 1969 to assess the impact of continuous cultivation of rice as a single crop grown in wet as well as dry seasons using varying levels of chemical fertilizer and manure applications on soil quality indicators (physical, chemical and biological), a sustainable yield index (SYI) and a soil quality index (SQI). The treatments comprised chemical fertilizers and farmyard manure (FYM) either alone or in combination *viz*. control, N, NP, NK, NPK, FYM, N+FYM, NP+FYM, NK+FYM and NPK+FYM, laid out in a randomized complete block design with three replications. Soil samples were collected after the wet season rice harvest in 2010 and were analysed for physical, chemical and biological indicators of soil quality. A SYI based on long-term yield data and SQI using principal component analysis (PCA) and nonlinear scoring functions were calculated. Application of NPK fertilizers in combination with FYM significantly increased the average grain yield of rice in both wet and dry seasons and enhanced the sustainability of the system compared to the control and plots in receipt of fertilizers. The SYI for the control was higher in the wet season than in the dry one, whereas the reverse was true for NPK+FYM treatment. The value of the dimensionless SQI varied from 1.46 in the control plot to 3.78 in the NPK+FYM one. A greater SYI and SQI in the NPK+FYM treatment demonstrated the importance of using a chemical fertilizer in combination with FYM. For the six soil quality indicators selected as a minimum data set (MDS), the contribution of DTPA-Zn, available-N and soil organic carbon to the SQI was substantial ranging from 59.4 to 85.7 per cent in NPK+FYM and control plots, respectively. Thus, these soil parameters could be used to monitor soil quality in a subhumid tropical rice–rice system.

Keywords: Principal component analysis, multivariate statistics, fertilizer, farmyard manure, minimum data set, soil quality indicators

Introduction

Long-term experiments provide opportunities for monitoring changes in crop yields and nutrient balances and the identification of factors associated with such changes to help with evaluating the sustainability of agricultural management systems (Rasmussen *et al*., 1998). It is essential that system performance be monitored for productivity, soil nutrient status and nutrient supply capacity in order to decide on sustainable management systems (Powlson *et al*., 1986). Results from many long-term experiments at several locations in India have indicated a declining trend in the productivity of rice after a few years of continuous cropping (Dawe *et al*., 2000; Ladha *et al*., 2003). Many of the issues related to sustainability are concerned with soil quality which is a critical component in sustainable agriculture. While the term ‘soil quality’ is relatively new, it is well known that soils vary in quality and change in response to use and management. A soil system is characterized by attributes that range within limits, are functionally inter-related and thus can be used to quantify soil quality. The assessment of soil quality requires a systematic method for measuring and interpreting soil properties (Granatstein & Bezdicek, 1992). Individual soil properties may not provide an adequate measure of soil quality and integrated soil

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quality indicators based on a combination of soil properties can better reflect the status of soil quality than individual parameters (Dick, 1994). Traditionally, soil quality research has focused on chemical and physical properties because simple methods of analysis were available (Larson & Pierce, 1991); however, more recently, it has been suggested that soil biological properties can serve as early and sensitive indicators of responses to soil management practices (Islam & Weil, 2000). Thus, the measurements of biological along with chemical and physical properties of soil are essential for evaluating the impact of organic amendments on soil quality (Min *et al.*, 2003). A soil quality index (SQI) would help with the interpretation of data from different soil measurements and show whether management and land use are having the desired effects on productivity, environmental protection and health (Granatstein & Bezdicek, 1992). Sustainability of agricultural production systems has become an issue of national and international concern. In India a rice–rice intensive cropping system is the second most common system after rice–wheat and covers 5.5 × 10^6 ha. The present investigation was undertaken in order to (i) identify biological, chemical and physical indicators of soil quality in a long-term rice–rice cropping system, (ii) develop an overall SQI by using these indicators relevant to rice-based agricultural systems and (iii) quantify the long-term effects of chemical fertilizers and organic manures on soil quality and crop productivity.

Materials and methods

Study site

The study site was on the experimental farm of the Central Rice Research Institute, Cuttack, India (20°25′N, 85°55′E; elevation 24 m above mean sea level). Mean annual maximum and minimum temperatures are 39.2 and 22.5 °C, respectively, and the mean annual temperature is 27.7 °C. Annual precipitation is ca. 1500 mm of which 75–80% is received during June to September (Figure 1). The difference between mean summer and winter soil temperature is >5 °C, thus qualifying for the hyperthermic temperature class. The soil on the farm has developed in recent times from deltaic sediments of the Mahanadi River. The soil at the experimental site is an Aeric Endoaquept (Soil Survey Staff, 2010) with a sandy clay loam texture (31% clay, 17% silt and 52% sand). Other soil physical and chemical properties of the experimental field at the beginning of the study were bulk density (BD) 1.40 Mg/m^3, cation-exchange capacity 15.2 cmol(p^+)/kg, pH 6.6 (using 1:2.5, soil/water suspension), organic carbon 6.6 g/kg, total-N 0.8 g/kg, exchangeable K 0.26 cmol(p^+)/kg and available-P 13.0 mg/kg.

Field experiment

The experiment started in 1969 with two crops per year with rice (*Oryza sativa* L.) as a mono-crop in wet (July–November) and dry (January–May) seasons. Treatments were arranged in a randomized complete block design with three replications of control (no fertilizer) and different combinations of chemical fertilizers and farm yard manure (FYM) *viz.* control, N, NP, NK, NPK, FYM, N+FYM, NP+FYM, NK+FYM and NPK+FYM. The wastes from the Institute's dairy farm were used to prepare the FYM which contained 171–189 g total organic C and 4–16 g total-N per kg. The FYM (5 Mg/ha) was applied uniformly in all the treatments which received FYM during the last week of May every year. The chemical fertilizer schedules were 60-40-40 and 80-40-40 N-P_2O_5-K_2O kg/ha for wet and dry seasons, respectively, and the fertilizers were applied according to the required treatment.

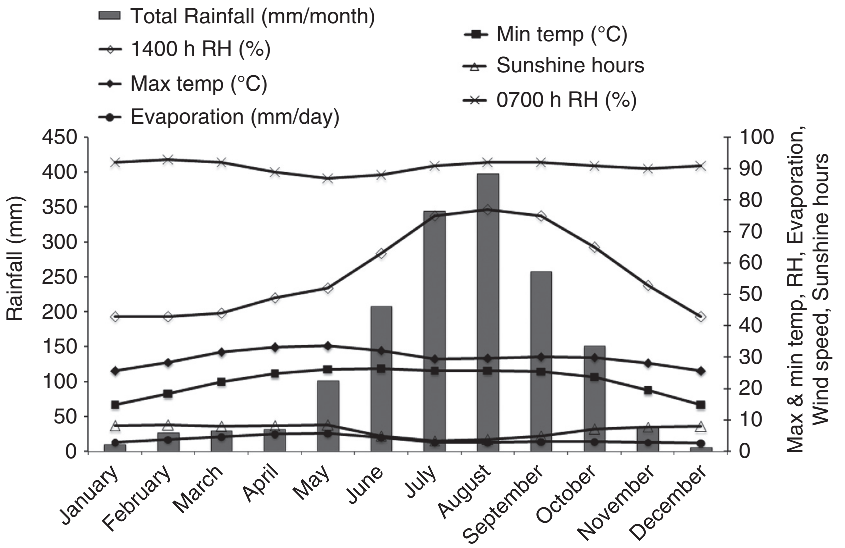

Figure 1 Mean monthly (1969–2010) weather parameters for the study area.

Soil sampling and analyses

Soil samples from three points in each plot at 0–15 cm depth were collected randomly using a posthole auger after harvesting the wet season crop in December, 2010. A composite sample representative of each plot was prepared by mixing the samples. Immediately after collection, part of the soil sample was air-dried and ground to pass through a 2 mm sieve and analysed for soil organic carbon (SOC) and total-N (N_{tot}) with an elemental analyzer (Flash 2000; Thermo Scientific), available-N (Subbiah & Asija, 1956), available-P (Bray & Kurtz, 1945), available-K (Piper, 1966), DTPA-Zn, Cu, Fe and Mn (Lindsay & Norvell, 1978), pH (1:2.5, soil: water suspension), electrical conductivity (EC; 1:2.5, soil: water suspension), clay percentage and clay dispersion index (CDI, Gee & Bauder, 1986). The remainder of the sample was stored in a refrigerator at 4 °C prior to biochemical analysis. Microbial biomass carbon (C_{mic}) and nitrogen (N_{mic}) were determined using the chloroform fumigation extraction methods of Vance *et al.* (1987) and Ross (1990), respectively. Carbon and nitrogen mineralization (C_{min} and N_{min}) were determined by incubating soil for 1 month. Carbon mineralization was evaluated by using alkali traps (Anderson, 1982). To measure N_{min}, mineral N (NH_4-N+NO_3-N) of the incubated soil was determined by extraction with 2M KCl (Keeney & Nelson, 1982) followed by alkali distillation with adding Devard's alloy in an automatic N analyzer. Net mineralized C and N were calculated and cumulative C_{min} and N_{min} were determined. The activity of the dehydrogenase (DHA), urease, acid- and alkaline-phosphatase enzymes were measured as described by Tabatabai (1994). Two undisturbed soil cores were also collected using a core sampler from each plot for measuring BD (Blake & Hartge, 1986) and saturated hydraulic conductivity (HC, Greene *et al.*, 1988).

Soil quality index

The SQI as described by Andrews *et al.* (2002) was used with some modification. The determination of SQI involved four main steps: (i) statement on objective, (ii) selection of a minimum data set (MDS) of indicators that best represented soil functions, (iii) scoring the MDS indicators based on their performance and (iv) integrating the indicator scores into a comparable SQI. A sustainable yield index (SYI) for wet and dry seasons and for the rice–rice system under each treatment was the objective.

A SYI (Singh *et al.*, 1990) was calculated based on rice yield for wet and dry seasons using the following formula:

$$\mathrm{SYI} = (Y - \sigma_{n-1})/Y_{\mathrm{m}}$$

where Y is average yield, σ_{n-1} the standard deviation and Y_{m} the maximum yield obtained during the experiment. For the SYI, low standard deviations (σ) suggest sustainable systems because σ measures variation in yield caused by soil and climatic factors. If the standard deviation (σ) is large, SYI will be low, and this indicates an unsustainable management practice (Singh *et al.*, 1990). Only those soil properties that showed significant treatment differences were selected for a representative MDS. Significant variables were chosen for the next step in MDS formation through principal component analysis (PCA; Andrews *et al.*, 2002). The principal components (PC) with high Eigen values (>1; Brejda *et al.*, 2000) and variables with high factor loadings (>0.700; absolute value) were assumed to be variables that best represented system attributes and were retained for the MDS. When more than one factor was retained under a single PC, multivariate correlation coefficients were used to determine if the variables could be considered redundant and therefore eliminated from the MDS (Andrews *et al.*, 2002). Highly correlated variables were considered redundant and only one was considered for the MDS. If the highly weighted variables were not correlated, each was considered important and retained in the MDS. To check how well the MDS represented the management systems, multiple regressions were performed using the indicators retained as independent variables and the end point measures such as the SYI for the wet season (wet-SYI), dry season (dry-SYI) and the system (system-SYI) as dependent variables. If any variable within the MDS did not contribute to the coefficient of determination from the multiple regressions, it was also ignored. After the MDS indicators were determined, results were transformed using a nonlinear scoring method (Andrews *et al.*, 2002). The shape of each decision function which was either a bell-shaped curve ('mid-point optimum'), a sigmoid curve with an upper asymptote ('more is better') or a sigmoid curve having a lower asymptote ('less is better'); such curves were then evaluated on the basis of the available literature and the opinions of the collaborating researchers (Table 1). A score (S) for each MDS variable was calculated using the following equation (Bastida *et al.*, 2006)

$$S = a/(1 + (x/x_0)^b)$$

where x is the soil property value, a is the maximum score (1.00) of the soil property, x_0 is the baseline or value of each variable where the score equals 0.5 and equals the mid-point between threshold soil property values (Table 1) and b is the value of the slope of the equation. With b equal to −7.5 for the 'more is better curve' and 7.5 for the 'less is better curve' (http://www.meta-calculator.com/online/), we obtained curves that fitted a sigmoidal one tending to '1' in the case of 'more is better curve' and '0' in the case of 'less is better curve' for the MDS variables.

Once transformed, the MDS variables for each observation were weighted using the PCA results. We then summed the weighted MDS variable scores for each observation using the following equation:

Table 1 Soil quality indicators and scoring functions

Indicator	Scoring curve	Lower threshold	Upper threshold	Lower baseline	Upper baseline	Optimum	Source of limits
Clay (%)	More is better	0	40	20	–	–	
Bulk density (Mg/m^3)	Less is better	1.0	2.0	1.5	–	–	Glover *et al.*, 2000;
Hydraulic conductivity (cm/h)	Optimum	0.2	2.0	0.6	1.5	1.0	Lal (1994)
Clay dispersion index	Less is better	0	36	18	–	–	
pH	Optimum	4.5	9.0	5.5	7.5	6.5	
Electrical conductivity (dS/m)	Less is better	2.0	12.0	6.0	–	–	
Organic carbon (g/kg)	More is better	0	12	6	–	–	Rao (1995)
Microbial biomass carbon (mg/kg)	More is better	0	400	200	–	–	Haynes (2005)
Carbon mineralization (mg/kg)	More is better	0	1200	600	–	–	Haynes (2005)
Total nitrogen (mg/kg)	More is better	0	1200	600	–	–	
Available nitrogen (kg/ha)	More is better	0	400	200	–	–	
Microbial biomass nitrogen (mg/kg)	More is better	0	60	30	–	–	Haynes (2005)
Nitrogen mineralization (mg/kg)	More is better	0	60	30	–	–	Haynes (2005)
Bray's phosphorus (kg/ha)	More is better	0	50	25	–	–	
Available potassium (kg/ha)	More is better	0	400	200	–	–	
DTPA Zinc (mg/kg)	More is better	0	1.5	0.75	–	–	
DTPA Copper (mg/kg)	More is better	0	5	2.5	–	–	
DTPA Iron (mg/kg)	More is better	0	50	25	–	–	
DTPA Manganese (mg/kg)	More is better	0	20	10	–	–	
Urease (μg NH$_4^+$/g/h)	More is better	0	200	100	–	–	
Dehydrogenase (μg TPF/g/h)	More is better	0	100	50	–	–	
Acid Phosphatase (μg PNP/g/h)	More is better	0	600	300	–	–	
Alkaline Phosphatase (μg PNP/g/h)	More is better	0	400	200	–	–	

$$\mathrm{SQI} = \sum_{i=1}^{n} W_i \times S_i$$

where W_i is the weighing factor derived from the PCA (absolute value) and S_i is the score for the subscripted variable. The assumption was that higher scores meant better soil quality, which leads to greater productivity. Furthermore, the percentage contribution of each final key indicator was also calculated. The resultant SQI values were tested for their significance at $P < 0.05$.

Statistical analyses

In order to compare the treatments, a one-way analysis of variance (ANOVA) was performed following standard procedures (Gomez & Gomez, 1984), and treatment means were compared at the 5% probability level. The MDS of soil quality indicators was derived from the PCA, Pearson's correlation coefficient and the multiple regression equation. All the analyses were performed using the SAS software package (SAS Institute Inc, 2008).

Results and discussion

Soil quality indicators

The mean values (n = 3) of all the soil physical, chemical and biological properties are given in Table 2. The BD ranged from 1.40 in NPK+FYM to 1.59 Mg/m^3 in the control with no added fertilizer, and the respective hydraulic conductivities were 2.6 and 2.1 cm/day and the CDIs were 13.7 and 25.4. The improvement in soil physical parameters in the plots with continuous application of NPK along with FYM may be due to the increase in SOC and that might have decreased BD and CDI (Reeves, 1997). The pH of the treated plots declined significantly from an initial value of 6.6 in 1969 to a lowest value of 5.6 and a highest value of 6.2 recorded in NP and FYM treatments, respectively. The SOC concentration in the control plots (6.3 g/kg) was maintained close to its initial value (6.6 g/kg in 1969). Maintenance of the SOC in the control even after 41 years can be explained by the reduced decomposition of both added and native SOC due to anaerobic conditions which prevail throughout the year in a rice–rice system (Guo & Lin, 2001). The C$_{\mathrm{mic}}$ content varied from 180 to 361 mg/kg, and the greatest was reported for the NPK+FYM treatment, while was least in the control plots. The reason for increased C$_{\mathrm{mic}}$ might be due to increased SOC, particularly the light carbon fractions (Alvarez & Alvarez, 2000) and the favourable environment for microbial activity for C enrichment through plant residue incorporation as well as FYM application. The lower value for C$_{\mathrm{mic}}$ in the control treatment might be due to its unfavourable environment as a result of depletion of nutrients from the continuous cropping without any added fertilizers (Grego *et al.*, 1998). C$_{\mathrm{min}}$ provides an early

Table 2 Effect of chemical fertilizers and farmyard manure (FYM) on physical, chemical and biological soil quality indicators

	Physical				Chemical											Biological						
Treatments	BD	% Clay	HC	CDI	pH	EC	SOC	N_{tot}	Avail-N	Bray's P	Avail-K	DTPA-Zn	DTPA-Cu	DTPA-Fe	DTPA-Mn	C_{mic}	C_{min}	N_{mic}	N_{min}	DHA	Urease	Acid-P	Alk-P
Control	1.59	36.5	2.1	25.4	6.0	0.05	6.3	740	154	9.9	117	0.86	3.7	39.1	13.1	180	727	19.3	19.6	19.7	102	359	251
N	1.53	37.4	2.2	22.4	5.9	0.07	7.1	880	218	11.1	117	0.72	3.9	37.9	11.2	213	754	24.5	22.1	35.5	141	372	261
NP	1.51	36.7	2.3	19.1	5.6	0.07	7.5	910	227	18.3	108	0.89	3.5	37.2	12.1	254	787	28.3	23.1	31.3	148	415	272
NK	1.52	36.3	2.3	19.8	5.9	0.09	7.0	921	227	9.9	136	0.68	4.4	35.4	12.0	227	735	28.6	23.2	37.2	151	389	264
NPK	1.48	36.2	2.4	17.5	5.7	0.10	7.9	911	225	22.7	125	0.81	3.7	33.6	11.5	306	787	31.3	23.0	41.4	167	405	271
FYM	1.50	37.3	2.3	22.0	6.2	0.09	7.3	960	206	18.8	128	1.26	4.9	40.6	14.4	230	691	28.0	22.5	25.9	117	424	270
N+FYM	1.44	39.4	2.4	19.4	6.0	0.11	8.8	1041	237	18.8	134	1.02	4.1	42.1	13.8	292	790	30.8	25.0	44.1	145	442	277
NP+FYM	1.42	39.1	2.4	18.3	5.9	0.12	9.2	1040	246	33.7	126	1.19	4.3	41.7	13.2	327	851	34.2	24.8	43.2	150	485	283
NK+FYM	1.43	39.2	2.5	16.5	6.1	0.12	9.2	1010	251	19.9	154	0.92	4.5	42.4	14.2	322	846	31.5	23.9	47.9	158	450	275
NPK+FYM	1.40	38.6	2.6	13.7	6.1	0.12	9.3	990	245	33.2	147	1.12	4.4	45.8	14.1	361	846	36.0	25.8	57.7	172	496	285
LSD ($P < 0.05$)	0.09	2.3	0.24	2.4	0.4	0.01	1.1	45	17	2.1	10	0.08	0.5	3.9	1.4	26.2	99	3.0	2.5	2.5	9	27	17

BD, Bulk density (Mg/m^3); HC, Hydraulic conductivity (cm/day); CDI, Clay dispersion index; EC, Electrical conductivity (dS/m); SOC, Soil organic carbon (g/kg); N_{tot}, Total N (mg/kg); Avail-N, Available Nitrogen (kg/ha); Bray's-P, Available Phosphorus (kg/ha); Avail-K, Available Potassium (kg/ha); DTPA-Zn, DTPA extractable Zinc (mg/kg); DTPA-Cu, DTPA extractable Copper (mg/kg); DTPA-Fe, DTPA extractable iron (mg/kg); DTPA-Mn, DTPA extractable manganese (mg/kg); C_{mic}, Microbial biomass carbon (mg/kg); C_{min}, Carbon mineralization (mg/kg); N_{mic}, Microbial biomass nitrogen (mg/kg); N_{min}, Nitrogen mineralization (mg/kg); DHA, Dehydrogenase (μg TPF/g/h); Urease, Urease (μg NH_4^+/g/h); Acid-P, Acid Phosphatase (μg PNP/g/h); Alk-P, Alkaline Phosphatase (μg PNP/g/h).

indication of a possible degrading or aggrading effect of different management practices on soil quality (Powlson, 1994), and varied from 691 to 851 mg/kg (Table 2). The N_{tot} content in the treatments with N, NP, NK and NPK ranges from 980 to 1020 mg/kg, whereas, combined use of chemical fertilizer and FYM gave results for N_{tot} ranging from 1050 to 1140 mg/kg. Chavan *et al.* (2010) report that long-term and continuous application of fertilizer and organic matter to rice–rice systems result in significant change in the N_{tot} status of surface soil. All the treatments receiving FYM along with chemical fertilizer had a greater N_{mic} concentration than the treatments with chemical fertilizer alone. The concentration of N_{mic} varied from 19.3 to 36.0 mg/kg, and the greatest was in NPK+FYM treatment. The greatest N availability (251 kg/ha) for the surface soil was for the treatment where NK was applied along with FYM which is significantly greater than for the control, FYM and NPK treatments. Application of FYM and P through chemical fertilizers enhanced Bray's P. Greater available-K of 147 and 154 kg/ha was determined for the NPK+FYM and NK+FYM treatments, respectively, which were statistically on a par and significantly greater than the other treatments. Continuous exclusion of K in fertilizer schedules resulted in a decline in soil K under an intensive rice–rice system (Masto *et al.*, 2007). Application of chemical fertilizers without P reduced the DTPA-Zn over the control; however, inclusion of P in the fertilizer schedule maintained it on par with the control because Zn present in the superphosphate fertilizer offset its loss due to the crop harvest from the plots. Application of FYM alone or in combination with chemical fertilizer increased the DTPA-Zn over the control treatment. The other micronutrients of Cu, Mn and Fe were not limited in all the treatments, and the plants did not show any deficiency symptoms. Application of NPK along with FYM led to a significant increase in DHA, urease, acid- and alkaline-phosphatase activities in the rice soil. Organic matter often leads to an increase in the activity of various enzymes (Crecchio *et al.*, 2001; Bhattacharyya *et al.*, 2005).

Rice yields and SYI

Compared to the control, application of fertilizers, either alone or in combination with FYM significantly increased the average grain yield of rice for both wet and dry seasons and also for the system (Table 3). The yield data reveal that the treatments receiving FYM along with chemical fertilizers have greater values than those receiving only chemical fertilizers in both seasons. The highest grain yield was found for the NPK+FYM treatment both in wet (5.43 t/ha) and dry (4.89 t/ha) seasons, whereas the lowest yields were in the control plots in both seasons (3.38 and 2.40 t/ha) and for the system (5.78 t/ha). Greater yields were found when N was applied in combination with P than when applied in combination with K in both wet and dry seasons to indicate

Table 3 Long-term effects of chemical fertilizer and farmyard manure (FYM) treatments on average crop yields (t/ha) and sustainable yield index (SYI) for wet season, dry season and rice–rice system

Treatments	Wet season yield	Wet-SYI	Dry season yield	Dry-SYI	System yield	System-SYI
Control	3.38	0.46	2.40	0.35	5.78	0.39
N	4.18	0.58	3.32	0.51	7.50	0.52
NP	4.56	0.64	4.04	0.62	8.60	0.59
NK	4.34	0.62	3.51	0.52	7.85	0.54
NPK	4.89	0.68	4.39	0.70	9.28	0.63
FYM	4.27	0.59	3.16	0.46	7.43	0.49
N+FYM	5.03	0.68	4.25	0.66	9.28	0.64
NP+FYM	5.11	0.69	4.60	0.72	9.72	0.66
NK+FYM	5.14	0.70	4.54	0.72	9.68	0.66
NPK+FYM	5.43	0.74	4.89	0.79	10.32	0.70
LSD ($P < 0.05$)	0.32	0.14	0.43	0.17	1.21	0.18

Table 4 Results of principal component analysis (PCA) of soil quality indicators

Principal components	PC1	PC2	PC3
Eigen value	15.009	3.581	1.387
% of total variance	65.257	15.568	6.030
Cumulative %	65.257	80.825	86.855
Factor loadings/Eigen vectors			
BD	**−0.851**	−0.240	−0.408
Clay	0.490	0.384	0.554
HC	**0.880**	0.282	0.220
CDI	**−0.933**	−0.085	−0.088
pH	−0.132	**0.918**	0.272
EC	**0.824**	0.382	0.277
SOC	**0.822**	0.196	0.444
N_{tot}	**0.732**	0.300	0.376
Avail-N	**0.907**	0.101	0.067
Bray's P	0.670	−0.059	0.635
Avail-K	0.560	**0.774**	−0.042
DTPA-Zn	0.104	0.302	**0.880**
DTPA-Cu	0.139	**0.842**	0.233
DTPA-Fe	0.255	0.488	0.679
DTPA-Mn	0.066	0.672	0.638
C_{mic}	**0.892**	0.081	0.332
C_{min}	**0.814**	−0.111	0.278
N_{mic}	**0.896**	0.124	0.288
N_{min}	**0.866**	0.163	0.301
DHA	**0.920**	0.204	0.054
Urease	**0.946**	−0.104	−0.201
Acid-P	**0.718**	0.208	0.619
Alk-P	**0.816**	0.078	0.503

BD, Bulk density (Mg/m^3); HC, Hydraulic conductivity (cm/day); CDI, Clay dispersion index; EC, Electrical conductivity (dS/m); SOC, Soil organic carbon (g/kg); Ntot, Total N (mg/kg); Avail-N, Available Nitrogen (kg/ha); Bray's-P, Available Phosphorus (kg/ha); Avail-K, Available Potassium (kg/ha); DTPA-Zn, DTPA extractable Zinc (mg/kg); DTPA-Cu, DTPA extractable Copper (mg/kg); DTPA-Fe, DTPA extractable iron (mg/kg); DTPA-Mn, DTPA extractable manganese (mg/kg); C_{mic}, Microbial biomass carbon (mg/kg); C_{min}, Carbon mineralization (mg/kg); N_{mic}, Microbial biomass nitrogen (mg/kg); N_{min}, Nitrogen mineralization (mg/kg); DHA, Dehydrogenase (μg TPF/g/h); Urease, Urease (μg NH_4^+/g/h); Acid-P, Acid Phosphatase (μg PNP/g/h); Alk-P, Alkaline Phosphatase (μg PNP/g/h). Factor loadings in bold are considered highly weighted.

that rice had a greater response to P application than K in lowland situations. The difference between these two treatments narrowed when applied with FYM.

The SYI for rice varied significantly with nutrient management practices. Under the control plot with no added fertilizers, the SYI values for wet season, dry season and system were 0.46, 0.35 and 0.39, respectively. The combined application of chemical fertilizer and FYM increased crop yields with the SYI for wet and dry seasons being 0.74 and 0.79, respectively, and an overall of 0.70 for the system. The SYI for the control was greater in the wet season than in the dry one, whereas the reverse was true for the NPK+FYM treatment. Our results indicate that a combined application of chemical fertilizers with manure promotes a high and stable yield.

Selection of a soil quality indicator

Three PCs had Eigen values >1 that explained 86.8% of variation in the data (Table 4). A correlation matrix for the highly weighted variables under different PCs was run separately (Table 5). It was assumed that the variables having the highest correlation sum best represented the group. All the fifteen highly weighted variables under PC1 were also highly correlated. The studied soils were slightly acidic to neutral, and the range of EC was from 0.05 to 0.12 dS/m; however, this does not affect crop productivity and hence was dropped from the MDS, even though it had a high correlation sum and factor loading. Andrews *et al.* (2002) report that choice among well-correlated variables could also be based on the practicability of the variables. Among the physical parameters BD (highest correlation sum) and CDI (highest factor loading) were retained. Selection of CDI was also important for its significance under waterlogged soil conditions, and in our study the plots were saturated/puddled twice in a year for the last 41 years. The SOC was retained in the MDS because of its easy determination and had a comparable factor loading to the other organic carbon fractions. Microbial biomass carbon and C_{min} were highly correlated with SOC and hence were excluded from the MDS. Among different N fractions, Avail-N had a higher factor loading, is easy to analyse and thus was retained for the MDS. The other fractions were highly correlated with Avail-N, hence were ignored. For the soil enzymes DHA, Urease and Alk-P were retained because they

Table 5 Correlation matrix (Pearson's Correlation) for highly weighted variables under principal components with high factor loadings and eligible to be used in soil quality index

Variables	BD	Hydraulic conductivity (HC)	CDI	Electrical conductivity (EC)	Soil organic carbon (SOC)	C_{mic}	C_{min}	N_{tot}	N_{mic}	N_{min}	Avail-N	DHA	UREASE	ACID-P	ALK-P
PC1 variables															
BD	1.00														
HC	**0.94**	1.00													
CDI	**0.87**	**0.96**	1.00												
EC	**0.96**	**0.91**	**0.83**	1.00											
SOC	**0.98**	**0.90**	**0.83**	**0.93**	1.00										
C_{mic}	**0.96**	**0.95**	**0.93**	**0.91**	**0.95**	1.00									
C_{min}	**0.81**	**0.76**	**0.80**	**0.72**	**0.88**	**0.88**	1.00								
N_{tot}	**0.91**	**0.79**	**0.70**	**0.90**	**0.86**	**0.77**	**0.60**	1.00							
N_{mic}	**0.95**	**0.94**	**0.93**	**0.93**	**0.89**	**0.94**	**0.74**	**0.87**	1.00						
N_{min}	**0.94**	**0.89**	**0.86**	**0.89**	**0.89**	**0.88**	**0.72**	**0.91**	**0.95**	1.00					
Avail-N	**0.87**	**0.83**	**0.85**	**0.84**	**0.83**	**0.81**	**0.73**	**0.89**	**0.89**	**0.91**	1.00				
DHA	**0.89**	**0.92**	**0.92**	**0.86**	**0.87**	**0.90**	**0.82**	**0.72**	**0.87**	**0.89**	**0.85**	1.00			
UREASE	**0.73**	**0.81**	**0.92**	**0.70**	**0.68**	**0.81**	**0.73**	0.59	**0.82**	**0.78**	**0.86**	**0.88**	1.00		
ACID-P	**0.95**	**0.87**	**0.80**	**0.87**	**0.93**	**0.90**	**0.76**	**0.84**	**0.90**	**0.88**	**0.74**	**0.77**	0.57	1.00	
ALK-P	**0.96**	**0.90**	**0.86**	**0.88**	**0.92**	**0.92**	**0.75**	**0.90**	**0.96**	**0.95**	**0.85**	**0.80**	**0.70**	**0.96**	1.00
Correlation sums	13.72	13.39	13.06	13.14	13.34	13.52	11.71	12.24	13.57	13.33	12.75	12.98	11.57	12.74	13.32

PC2 variables

	pH	Avail K	DTPA Cu
pH	1.00		
Avail-K	**0.66**	1.00	
DTPA-Cu	**0.82**	**0.68**	1.00
Correlation sums	2.48	2.33	2.50

PC3 variables

	DTPA Zn
DTPA-Zn	1.00

BD, bulk density; CDI, clay dispersion index; DHA, Dehydrogenase. Correlations in bold are significant at $P < 0.05$.

Table 6 Results of multiple regressions of the minimum data set (MDS) components using management goal attributes at different probability (*P*) levels

Goal or function	R^2	Most significant MDS variables	*P*
SYI-Wet Season	0.969**	Clay dispersion index (CDI), Avail-N, Avail-K	<0.001, <0.003, <0.032
SYI-Dry Season	0.986**	CDI, soil organic carbon (SOC), Avail K	<0.000, <0.000, <0.000
SYI-System	0.983**	CDI, SOC, Avail-N, DHA, Avail-K, DTPA-Zn	<0.001, <0.001, <0.009, <0.027, <0.000, <0.039
Regression equations			
$\text{SYI-Wet Season} = 0.76 - 0.70\ \text{CDI} + 0.51\ \text{Avail-N} - 0.25\ \text{Avail-K}$			
$\text{SYI-Dry season} = 0.51 - 0.52\ \text{CDI} + 0.62\ \text{SOC} - 0.35\ \text{Avail-K}$			
$\text{SYI-System} = 0.60 - 0.50\ \text{CDI} + 0.42\ \text{SOC} + 0.31\ \text{Avail-N} + 0.24\ \text{DHA} - 0.34\ \text{Avail-K} - 0.14\ \text{DTPA-Zn}$			

**Significant difference at $P < 0.01$.

represent different groups of enzymes and are responsible for different biochemical reactions and are considered effective indicators of soil quality change from environmental stress or management (Quilchano & Maranon, 2002). Acid-P was highly correlated with Alk-P and also had a low factor loading and correlation sum and hence was not included. In PC2, pH and Avail-K were retained in the MDS given their importance in lowland rice cultivation. DTPA-Cu was correlated highly with pH ($r = 0.82$) and also its values were well above the critical limits (Dobermann & Fairhurst, 2000) and thus was excluded from the MDS. Under PC3, DTPA-Zn was the only highly weighted variable which has a significant role in lowland rice cultivation and hence was retained. Multiple regressions between MDS and management goals revealed that CDI and Avail-K significantly influenced all three management goals, while the effect of Avail-N was significant on Wet-SYI and System-SYI. Soil organic carbon had significant influence on Dry-SYI and System-SYI, whereas DHA and DTPA-Zn were significantly correlated with System-SYI (Table 6). In summary CDI, SOC, Avail-N, Avail-K, DHA and DTPA-Zn were retained for SQI estimation.

Table 7 Nonlinear scoring results and effect of chemical fertilizer and farmyard manure (FYM) treatments on soil quality index (SQI)

Treatments	DTPA-Zn	SOC	Avail-N	CDI	DHA	Avail-K	SQI
Control	0.59	0.45	0.21	0.10	0.04	0.07	1.46
N	0.44	0.49	0.54	0.21	0.17	0.07	1.93
NP	0.62	0.63	0.59	0.41	0.12	0.07	2.44
NK	0.41	0.56	0.59	0.35	0.19	0.13	2.23
NPK	0.51	0.67	0.58	0.48	0.27	0.09	2.59
FYM	0.85	0.62	0.48	0.21	0.07	0.10	2.33
N+FYM	0.75	0.75	0.64	0.38	0.32	0.12	2.96
NP+FYM	0.83	0.76	0.69	0.47	0.30	0.10	3.15
NK+FYM	0.66	0.76	0.70	0.58	0.40	0.18	3.27
NPK+FYM	0.81	0.77	0.68	0.74	0.63	0.15	3.78
LSD ($P < 0.05$)	0.18	0.13	0.14	0.24	0.21	0.04	0.53

DTPA-Zn, DTPA extractable Zinc (mg/kg); SOC, Soil organic carbon (g/kg); Avail-N, Available Nitrogen (kg/ha); CDI, Clay dispersion index; DHA, Dehydrogenase (μg TPF/g/h); Avail-K, Available Potassium (kg/ha).

Soil quality index

Among all the treatments, the SQI had wide variation (0.10–0.74) for CDI and least (0.07–0.15) for Avail-K (Table 7). The value of the dimensionless SQI varied from 1.46 in the control plot to 3.78 in NPK+FYM plot. The indicators DTPA-Zn, SOC, Avail-N, CDI, DHA and Avail-K contributed 21.4, 20.4, 18.0, 19.5, 16.6 and 4.1% to the SQI, respectively, for the NPK+FYM treated plot, while for the control plot, the corresponding contributions were 40.4, 31.0, 14.3, 7.9, 2.5 and 4.8%, respectively (Figure 2). If NPK+FYM is taken as the ideal treatment, then the SQI would decline by 31.4% if there was exclusion of FYM; similarly, if no manure and fertilizers were applied, the SQI would decline by 61.4%. Chaudhury *et al.* (2005) report a decline by 56.7% in the SQI for no manure and fertilizer compared to NPK+FYM treated plots in a long-term rice–wheat–jute system. Similarly, when compared with a NPK treatment, SQI declined by 43.7, 35.6, 5.7 and 14.0% in control, N, NP and NK treatments, respectively. This indicates that N and FYM are important for maintaining and improving soil quality. In the present study, the contributions of DTPA-Zn, Avail-N and SOC to the SQI were substantial and ranged from 59.4 to 85.7% in NPK+FYM and control, respectively. Avail-N plays a dominant role in maintaining the yield of rice. It helps to increase vegetative growth as well as root biomass. This in turn enhances the SOC, which influences a wide range of physical, chemical and biological properties of soil, and is considered the most important indicator of soil quality (Carter *et al.*, 1999). Rice is one of the highly sensitive crops to zinc deficiency, and zinc is the most important micronutrient limiting rice growth and yield (Alloway, 2004). Masto *et al.* (2007) report that the Zn status is a sensitive indicator of soil quality. Dehydrogenase enzyme also contributed significantly to SQI and its contribution

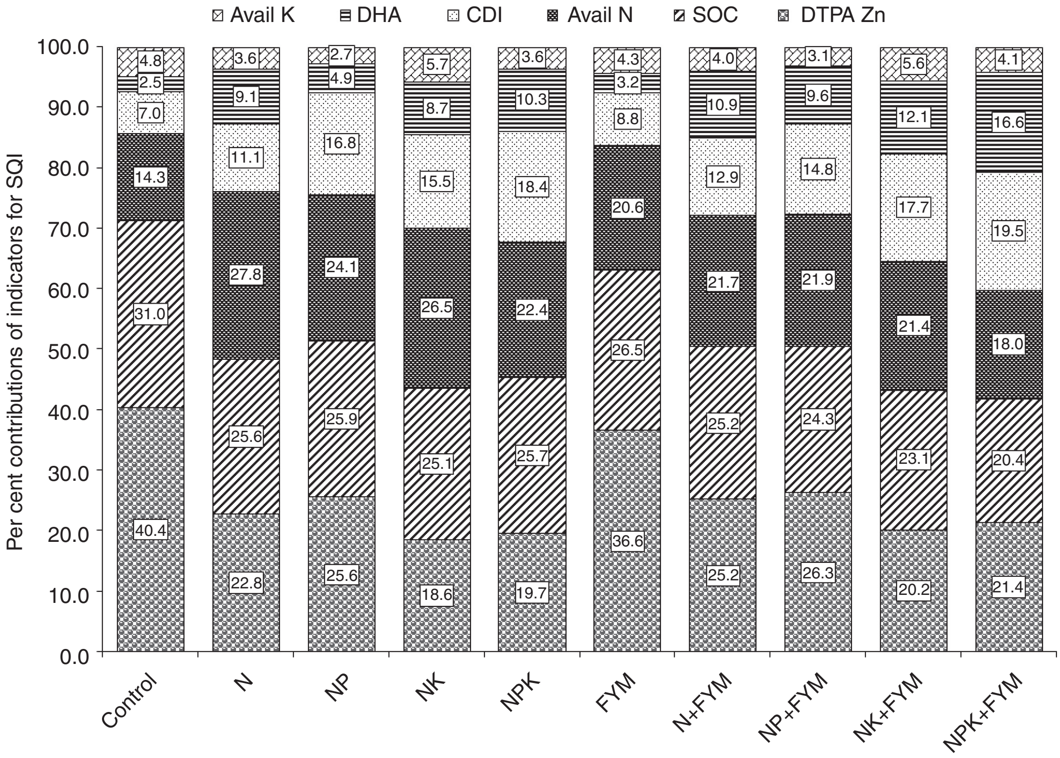

Figure 2 Per cent contribution of each indicator to the soil quality index under chemical fertilizer and farmyard manure treatments.

ranged from 2.5% in control to 16.6% in NPK+FYM treatments (Figure 2). Enzyme activity in the soil is a major contributor to overall soil microbial activity (Frankenberger & Dick, 1983) and soil quality (Dick, 1994). Dehydrogenase activity is thought to reflect the full range of oxidative activity of soil microflora and may be a good indicator of microbial activity (Nannipieri *et al.*, 1990).

Conclusion

This study has shown that selection of a MDS based on PCA and multiple regression analysis can be used to obtain a set of variables relevant to soil quality determination. Data in a MDS can be transformed using nonlinear scoring curves to obtain scores varying between 0 and 1, and these scores can then be used to derive a SQI. Application of chemical fertilizer alone or in combination with FYM significantly improves soil quality and sustainability of the rice–rice cropping system. Omission of N, P, K and Zn from treatments and continuous cultivation for 41 years causes depletion in these nutrients to affect yield and soil quality. Inclusion of FYM in a fertilizer regime maintains micronutrients at nonlimiting levels for the rice–rice system. Improvement in soil physical and chemical as well as in biological activity through continuous application of chemical fertilizers along with FYM results in a greater SQI and enhanced sustainability. The results from this study demonstrate for lowland rice in subhumid tropical regions that soil quality can be improved and sustained if management is designed to increase SOC.

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