CSIRO PUBLISHING
Soil Research, 2016, **54**, 20–29
http://dx.doi.org/10.1071/SR14245

Assessing soil-quality indices for subtropical rice-based cropping systems in India

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Abstract. Rice-based cropping systems are the foundation of food security in countries of Southeast Asia, but productivity of such systems has declined with deterioration in soil quality. These systems are different from other arable systems because rice is grown under submergence, and this may require a different set of key soil attributes for maintenances of quality and productivity. A minimum dataset was screened for assessing quality of soils belonging to three Soil Orders (Inceptisols, Entisols and Alfisols) by using statistical and mathematical models and 27 physical, chemical and biological attributes. Surface soils were collected from farmers' fields under long-term cultivation of rice–potato–sesame cropping systems. Most of the attributes varied significantly among the Soil Orders used. Four or five key attributes were screened for each Soil Order through principal component and discriminate analysis, and these explained nearly 80% and 90% of the total variation in each Soil Order dataset. The attributes were dehydrogenase activity (DHA), available K, cation exchange capacity (CEC) and pH_{Ca} for Inceptisols; organic C, pH_{Ca}, bulk density, nitrogen mineralisation (N_{min}) and β-glucosidase for Entisols; and DHA, very labile C, N_{min} and microbial biomass C for Alfisols. Representation of the screened attributes was validated against the equivalent rice yield of the studied system. Among the selected key soil attributes, DHA and CEC for Inceptisols, organic C for Entisols, and N_{min} and very labile C for Alfisols were most strongly correlated with system yield ($R^2 = 0.45$, 0.77 and 0.78). Results also showed that biological and chemical attributes were most sensitive for indicating the differences in soil quality and have a strong influence on system yield, whereas soil physical attributes largely varied but did not predict system yield.

Additional keywords: indicator, rice cropping systems, soil biological and chemical attributes, soil quality.

Received 3 September 2014, accepted 29 May 2015, published online 12 October 2015

Introduction

Globally, the area of rice (*Oryza sativa* L.) production has increased from 148 Mha in 2002 to 164 Mha in 2011 (FAOSTAT 2013). Asia is the main continent where this expansion has been reported. Food and nutritional security in Asian countries depend largely upon rice, because it is the source of 15% of protein and 21% of energy intake for the population (Depa *et al*. 2011). However, productivity of rice in lowland cultivated areas is low because of declining soil fertility (Haefele *et al*. 2014), degradation of soil structure (Das *et al*. 2014*a*), and unreliable water resources, lack of resources and widespread poverty (Das *et al*. 2014*b*).

Management practices such as pudding, excessive and repeated tillage, planting and leveling on lowland rice soils can affect soil properties differently from management practices used in other agricultural systems. Intensity of cultural practices deficient in drainage can lead to breakdown of stable soil structure and disturbance to habitat of soil biota. Following rice, potato (*Solanum tuberosum* L.) is a profitable crop for marginal landholders and for large-scale growers. For growing potatoes, intensive ploughing is practiced and heavy doses of nitrogen (N), phosphorus (P) and potassium (K) are generally applied. At maturity, potatoes are harvested by uprooting tubers from soil. Above- and belowground crop residue is kept away from the field for early preparation of land to grow sesame (*Sesamum indicum* L.) with residual soil moisture and nutrition. These intensive and cyclic cultural practices may lead to degradation of soil health. Monocropping, exclusion of legumes from rotation, no or low use of organic manure and green manure, and imbalanced and injudicious application of N, P, and K fertiliser may accelerate these problems.

Several authors have reported assessment of soil quality for non-rice systems (Karlen *et al*. 2008; Wienhold *et al*. 2006; Armenise *et al*. 2013; Stott *et al*. 2013). However, such studies are rare for soils under rice-based cropping systems in lowland areas. Attempts have been made in Brazil (Lima *et al*. 2008, 2013) and China (Li *et al*. 2013; Yao *et al*. 2013, 2014; Liu *et al*. 2014) to address soil quality issues in lowland areas under rice crops followed by arable crops. In India, such studies are few

and have been carried out on experimental sites with controlled treatments (Chaudhury *et al*. 2005; Mandal *et al.* 2005; Mohanty *et al*. 2007). Sometimes, these studies may mimic farmers' fields for various Soil Orders. Selecting quality indicators of soils in farmers' fields and assessing soil health provides a measure of its functioning ability and its limitations and deficiencies. These indicators are important keys for expressing soil as a natural resource, an ultimate source for nourishment, ecosystem functions and sustainability.

India has a variety of soils, each of which presents its own opportunity and limitation. Among these, based on area, distribution and supply of agricultural products, Inceptisols, Entisols and Alfisols are dominant Soil Orders (Sarkar *et al*. 2001). Management practices have significant influence on the performances of these soils. Several attempts have been made to assess soil quality at regional and farm scale (Karlen *et al*. 2008; Wienhold *et al*. 2006; Armenise *et al*. 2013) by using various indexing techniques (Andrews *et al*. 2002*a*; Masto *et al*. 2007) based on statistical and mathematical formulations. These attempts have had mixed success because soil quality is very complex.

There has been little assessment of quality for soils collected from farmers' fields belonging to the Soil Orders Inceptisols, Entisols and Alfisols carrying a common rice-based cropping system. Our hypothesis was that a rice management system with puddling, intensive tillage and mud-water practices, followed by potato with heavy fertiliser and excessive tillage and sesame with zero-input cultivation, might have different effects on different soils in terms of physical, chemical and biological properties. As such, the study was initiated with the following objectives: (*i*) to identify soil-quality indicators prepared with a minimum dataset; and (*ii*) to evaluate whether this minimum dataset is correlated with system yield for the Inceptisols, Entisols and Alfisols under rice–potato–sesame production system.

Materials and methods

Soil sampling and crop yield assessment

Sixty geo-referenced composite soil samples (0–0.2 m), 20 each from Inceptisols, Entisols and Alfisols supporting a long-term (>25 years) rice–potato–sesame cropping system under subtropical climate in India, were collected 7–10 days after harvesting of *kharif* rice (Fig. 1). Data on biomass yield for the individual crops (rice, potato and sesame) and the amount of NPK fertiliser used at each of the 60 sites were recorded for three consecutive years (2006, 2007 and 2008) to validate the evaluation of soil quality (Fig. 2). To express yield in a common unit, an equivalent rice yield (ERY) was calculated for all sites for the production system, taking the average yield of the individual crop (rice, potato and sesame) for the last 3 years, according to the equation:

$$\mathrm{ERY} = \frac{\text{Tuber yield of potato} \times \text{unit price of potato}}{\text{Unit price of rice}} + \frac{\text{Grain yield of sesame} \times \text{unit price of sesame}}{\text{Unit price of rice}} + \text{rice yield}$$

Soil analyses

Soil samples collected from each of the sites were divided into three portions. One portion of the samples was processed and analysed immediately for biological attributes: microbial biomass carbon (C_{mic}) and N (N_{mic}), mineralisable C (C_{min}) and N (N_{min}), dehydrogenase activity, fluorescein diacetate hydrolysing activity (FDHA), β-glucosidase activity, aryl sulfatase activity, acid and alkaline phosphatase activity, and urease activity. Soil samples were kept in refrigerated conditions at 4°C until required.

The second portion was dried at room temperature, ground and sieved (2.0-mm nylon sieve), and stored for future analysis of chemical attributes: pH in 0.02 M $CaCl_2$ (pH_{Ca}) or water (pH_w); cation exchange capacity (CEC); pools of soil organic C (SOC) and total C; available N, P and K; exchangeable calcium (Ca) and magnesium (Mg); available iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) and boron (B).

The third portion was used for analysis of physical attributes: bulk density; water-stable aggregates; and clay, silt and sand. Saturated hydraulic conductivity was computed by using a pedotransfer function as proposed by Naskar *et al*. (2010). All of the analyses were performed in triplicate using standard protocols (Table 1).

Computation of soil quality index

Multivariate statistical analyses (principal component analysis (PCA) and discriminate analysis (DA)) were employed to screen the attributes and form a minimum dataset (MDS) from the 27 analysed parameters (Masto *et al*. 2007; Armenise *et al*. 2013). The general rules of principal component and factor analyses were followed; that is, principal components (PC) receiving high eigenvalues (>1.00) and variables with high factor loadings with such components are the best representatives and thus retained for screening of MDS (Armenise *et al*. 2013). In each PC, only highly weighted factors, i.e. those with absolute values within 10% of the highest weight, were screened for the MDS (Andrews *et al*. 2002*b*). To reduce redundancy, correlation analysis was performed amongst the highly weighted variables. Further, DA was employed with the screened MDS to choose the best discriminated variables (Lima *et al*. 2008; Yao *et al*. 2014). Finally, for validation of results, a regression analysis was computed using ERY as dependent variable and the screened soil properties as independent variables to investigate whether the MDS are truly correlated with system yield (Yao *et al*. 2013). For all statistical analyses of data (PCA, DA, regression equations), Microsoft Excel and SPSS (version 16.0, SPSS Inc., Chicago, IL, USA) packages were used.

Results

Soil physical and chemical properties

As expected, the clay content of Inceptisols (257.4 g kg^{-1}) and Entisols (266.2 g kg^{-1}) was significantly higher than that of Alfisols (138.4 g kg^{-1}). Alfisols were more compacted with higher bulk density (1.5 Mg m^{-3}) than Inceptisols (1.3 Mg m^{-3}) and Entisols (1.2 Mg m^{-3}). As such, Inceptisols and Entisols had more total water-stable aggregates than Alfisols (Table 2). Similarly, the mean weight diameter (0.89 and 0.87 mm) and aggregate stability (36.9% and 32.6%) were higher in Inceptisols

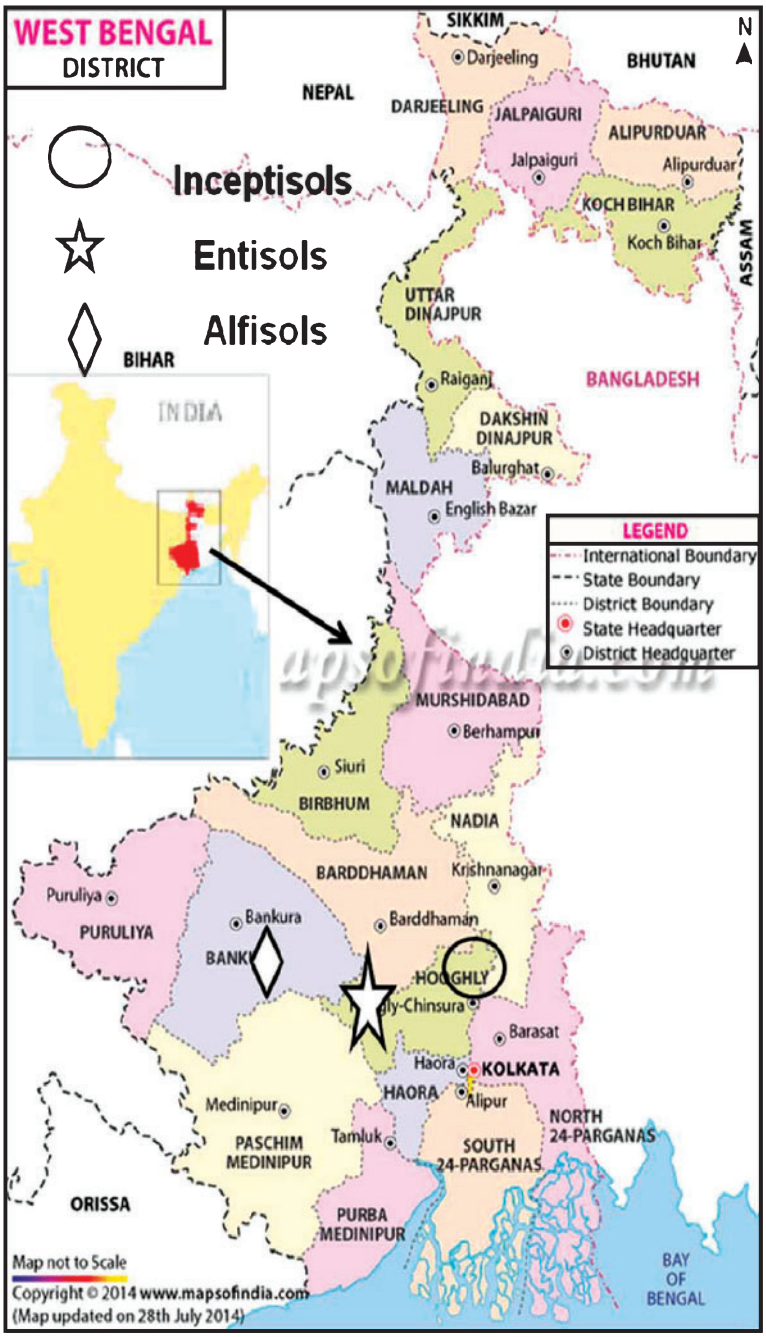

Fig. 1. Location of the study area.

and Entisols than in Alfisols. The experimental soils were acidic, and their pH_{Ca} values were always lower than pH_w values. The CEC were higher for Inceptisols (14.1 $cmol_{(+)}\ kg^{-1}$) and Entisols (14.1 $cmol_{(+)}\ kg^{-1}$) than for Alfisols (8.9 $cmol_{(+)}\ kg^{-1}$). The values of all of the three pools of organic C (OC), that is, very labile, Walkley–Black oxidisable (WBOC) and total OC (TOC), followed the trend Inceptisols > Entisols > Alfisols. A similar trend was evident for available N. However, C : N ratios were narrower for Inceptisols (10.9) followed by Entisols (11.2) and Alfisols (12.4). By contrast, the available K content was higher in Alfisols, followed by Entisols and Inceptisols. The available P and DTPA-extractable cationic micronutrient contents, on average, followed the trend: Inceptisols > Entisols > Alfisols. However, the available B content was in the deficient to medium range, particularly in Inceptisols and Alfisols.

Soil microbiological properties

The C_{mic} of the soils was significantly higher in Inceptisols, followed by Entisols and Alfisols with average values of

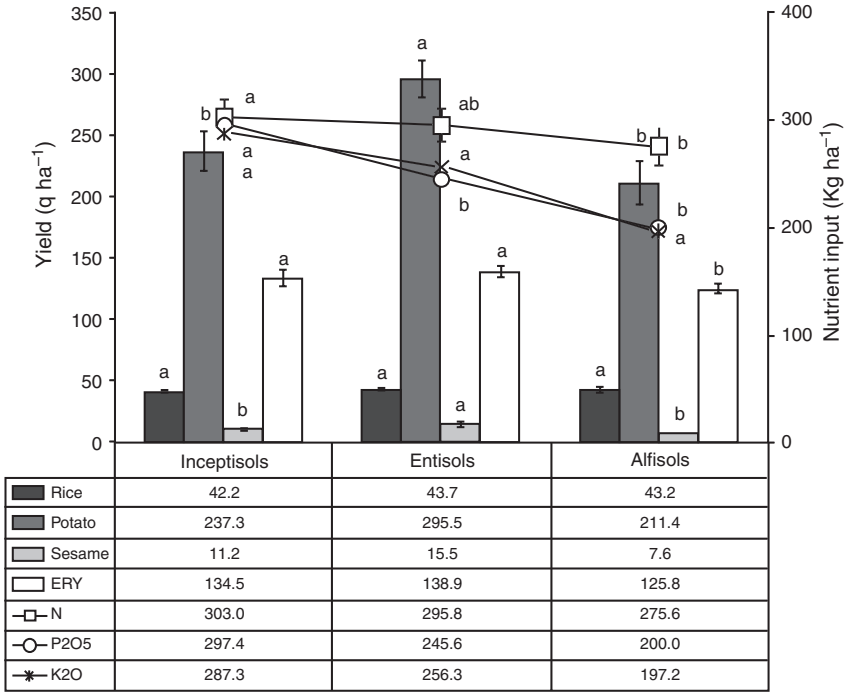

Fig. 2. Gross imposed inorganic fertilisation for rice and potato, and rice, potato, sesame and equivalent rice yield (ERY) of three Soil Orders. For each attribute across Soil Orders, means followed by the same letter are not significantly different at $P = 0.05$). Capped vertical lines are ± standard error.

Table 1. Parameters analysed

Physical attributes	Chemical attributes	Biological attributes
• Bulk density • Clay by hydrometer method • Water-stable aggregates by wet-sieving technique (Yoder 1936); mean weight diameter, geometric mean diameter, aggregate ratio, and aggregate stability were computed from there • Saturated hydraulic conductivity estimated by pedotransfer function, Ks = (0.174 + 0.144 × organic C (%) × clay (%)) proposed by Naskar *et al.* (2010)	• Soil pH: in water (pH_w) and 0.02 M $CaCl_2$ solution (pH_{Ca}) • Cation exchange capacity following Jackson (1973) • Total, oxidisable and pools of soil organic carbon (Mandal *et al.* 2008) • Available nitrogen following Subbiah and Asija (1956), phosphorus and potassium by Jackson (1973) • Exchangeable calcium and magnesium following Schwarzenbach *et al.* (1946) • Available iron, manganese, zinc and copper and boron by following Lindsay and Norvell (1978) and Sarkar *et al.* (2015)	• Microbial biomass C using the relationship: $C_{mic} = ((1/0.38) \times$ C-flush) (Voroney and Paul 1984) and microbial biomass N by Brookes *et al.* (1985) • Mineralisable C by alkali trap method (Anderson 1982) and mineralisable N by Bremner and Keeney (1965) • Dehydrogenase activity by triphenyl formazan production (Dick *et al.* 1996) • Fluorescein diacetate hydrolysing activity by measuring extractable fluorescein (Dick *et al.* 1996) • β-glucosidase, aryl sulfatase, and acid and alkaline phosphatase, activity by determination of *p*-nitrophenol released on incubation of soil with respective substrate: β-glucopyranoside, *p*-nitrophenyl sulfate and *p*-nitrophenyl phosphate (Dick *et al.* 1996) • Urease activity determined by quantifying the NH_4 released on incubation (Dick *et al.* 1996)

524.3, 483.4 and 379.6 μg C g^{-1} soil, respectively (Table 2). C_{mic} showed significant positive correlation with very labile C ($r = 0.62$; $P < 0.01$), WBOC ($r = 0.81$; $P < 0.01$) and TOC ($r = 0.74$; $P < 0.01$) contents of the soils. Microbial quotient (MQ), however, did not show significant differences among the soils. On the other hand, the values of N_{mic} were similar in Entisols (54.4 μg N g^{-1}) and Inceptisols (47.8 μg N g^{-1}), which were higher than Alfisols (36.1 μg N g^{-1}). The ratios of C_{mic} : N_{mic} were thus narrower for Entisols (8.9) and wider for Alfisols and Inceptisols (10.5 and 11.0). N_{mic} showed significant positive correlations with available and total N ($r = 0.42$ and 0.82; $P < 0.01$) contents of the soils. Except for urease, activities

Table 2. Some important physical, chemical and microbial attributes of the soils of three Soil Orders
Within rows, values followed by the same letter are not significantly different at $P = 0.05$ by Duncan's multiple-range test

	Inceptisols ($n = 20$)		Entisols ($n = 20$)		Alfisols ($n = 20$)	
	Range	Mean ± s.e.m.	Range	Mean ± s.e.m.	Range	Mean ± s.e.m.
Clay ($g\,kg^{-1}$)	81.7–444.3	257.4 ± 19.2a	65.5–403.4	266.2 ± 18.5a	90.7–471.2	138.4 ± 18.3b
Bulk density ($Mg\,m^{-3}$)	1.2–1.5	1.3 ± 0.02b	1.1–1.3	1.2 ± 0.01c	1.3–1.7	1.5 ± 0.02a
Mean weight diameter (mm)	0.55–1.11	0.89 ± 0.03a	0.62–1.03	0.87 ± 0.03a	0.42–1.13	0.76 ± 0.04b
Aggregate stability (%)	24.3–62.3	36.9 ± 2.3a	21.9–42.7	32.6 ± 1.3a	15.1–37.2	22.8 ± 1.2b
Total water-stable aggregates (%)	31.4–56.5	44.1 ± 1.4a	30.3–52.2	39.8 ± 1.5b	14.9–37.5	24.3 ± 1.5c
pH_w	4.5–6.6	5.6 ± 0.1	5.1–6.9	5.7 ± 0.1	4.8–6.3	5.5 ± 0.1
pH_{Ca}	3.9–6.0	5.1 ± 0.1	4.1–6.4	5.1 ± 0.1	4.3–5.6	4.8 ± 0.1
Cation exchange capacity ($cmol_{(+)}\,kg^{-1}$)	8.0–19.9	14.1 ± 0.7a	7.5–21.2	14.1 ± 0.8a	4.2–13.8	8.9 ± 0.1b
Walkley–Black organic C ($g\,kg^{-1}$)	4.8–11.3	7.6 ± 0.4a	5.6–9.0	7.2 ± 0.3a	2.9–8.3	5.7 ± 0.3b
Very labile C ($g\,kg^{-1}$)	1.4–5.0	3.5 ± 0.2ab	2.9–5.1	3.7 ± 0.2a	1.5–4.7	3.1 ± 0.2b
C : N	9.5–13.4	10.9 ± 0.3a	10.3–13.4	11.2 ± 0.2a	10.1–13.9	12.4 ± 0.4b
Available N ($kg\,ha^{-1}$)	90.6–283.5	175.1 ± 8.9a	115.0–195.8	160.7 ± 5.3ab	105.0–213.3	142.2 ± 5.8b
Available P ($kg\,ha^{-1}$)	54.7–183.4	105.5 ± 18.6a	56.8–148.1	55.8 ± 5.5b	21.8–80.0	65.0 ± 10.4b
Available K ($kg\,ha^{-1}$)	76.5–300.7	166.3 ± 18.2bc	75.4–319.3	192.2 ± 30.2b	77.0–326.0	257.3 ± 84.6a
Available Zn ($mg\,kg^{-1}$)	0.5–4.5	1.8 ± 0.3a	0.1–3.9	1.5 ± 0.2ab	0.6–2.0	1.2 ± 0.1c
Available B ($mg\,kg^{-1}$)	0.4–1.7	0.7 ± 0.1b	0.4–1.7	1.1 ± 0.1a	0.1–1.1	0.8 ± 0.1b
Microbial biomass C (C_{mic}, μg C g^{-1} soil)	258.1–1086.2	524.3 ± 44.3a	326.0–697.9	483.4 ± 25.9a	230.2–521.0	379.6 ± 22.7b
Mineralisable C (μg C g^{-1} day^{-1} soil)	108.9–354.1	239.6 ± 13.6	153.1–374.5	249.7 ± 43.6	153.3–270.0	220.4 ± 8.2
Metabolic quotient (μg C_{mic} g^{-1} soil TOC × 100)	2.5–9.2	5.8 ± 0.4	4.4–7.0	5.8 ± 0.2	3.0–6.7	5.2 ± 0.2
Microbial biomass N (μg N g^{-1} soil)	22.4–96.3	47.8 ± 4.3a	30.4–91.2	54.4 ± 3.3a	21.2–52.3	36.1 ± 2.1b
Mineralisable N (μg NH_4-N g^{-1} day^{-1} soil)	18.8–71.7	38.8 ± 3.0ab	16.5–76.1	49.2 ± 4.1a	15.6–80.5	35.8 ± 4.3b
Dehydrogenase (μg TPF g^{-1} day^{-1} soil)	38.4–158.7	64.4 ± 7.5a	31.3–76.8	50.3 ± 2.9ab	13.9–63.1	36.9 ± 3.2b
Fluorescein diacetate hydrolysing activity (μg fluorescein g^{-1} soil h^{-1})	31.2–83.5	53.8 ± 3.8	31.3–75.4	45.3 ± 2.9	25.8–79.7	45.5 ± 3.5
Urease activity (μg NH_4-N g^{-1} soil 2 h^{-1})	11.5–95.7	38.8 ± 4.5	10.6–134.0	30.5 ± 5.9	24.1–58.9	41.9 ± 2.3
β-glucosidase (μg *p*-nitrophenol g^{-1} soil h^{-1})	30.0–138.9	66.4 ± 7.2a	44.0–92.8	65.1 ± 2.9a	18.0–62.8	40.1 ± 2.5b
Acid phosphatase (μg *p*-nitrophenol g^{-1} soil h^{-1})	436.1–1132.4	860.9 ± 45.3a	224.0–955.8	586.1 ± 42.8b	219.3–1090.0	509.7 ± 51.9b
Alkaline phosphatase (μg *p*-nitrophenol g^{-1} soil h^{-1})	39.2–224.4	119.8 ± 12.2a	30.1–123.3	67.2 ± 6.8b	29.7–262.2	67.6 ± 11.1b
Aryl sulfatase (μg *p*-nitrophenol g^{-1} soil h^{-1})	15.0–102.4	52.3 ± 5.8a	10.6–51.5	32.2 ± 2.2b	17.3–51.7	32.0 ± 2.2b

of the other six enzymes estimated (dehydrogenase, acid phosphatase, alkaline phosphatase, aryl sulfatase, β-glucosidase and FDHA) were, on average, higher in Inceptisols, followed by Entisols and Alfisols. There were significant positive correlations among the enzymes (Table 3); additionally, alkaline phosphatase had a positive correlation with soil pH, whereas β-glucosidase had positive correlations with all of the pools of organic C in soils.

Grouping of soil-quality indicators based on principal component analysis

The effect of long-term cultivation of similar cropping systems with similar management practices on the quality of soils of three Soil Orders was evaluated by screening soil quality indicators. For this purpose, separate PCA was performed for each of the Soils Orders with 27 soil attributes analysed (Fig. 3 and Table 4). Each PCA analysis generated seven PCs. According to the criteria proposed by Kaiser (1960), the first six PCs were kept in the scree plot because they had eigenvalues >1.00 (Norman and Streiner 2008) and explained >5% of the variance in total dataset. PC1 explained 37%, 37% and 34% of the total variance for Inceptisols, Entisols and Alfisols, respectively. Under PC1 for Inceptisols, CEC was the highest weighted variable with component loading weight of 0.92. The chemical attributes pH_{Ca} and available Zn were screened from PC2 and PC3, respectively. In PC4, dehydrogenase showed highest component loading, explaining 7.8% of the total variance. Available K and aryl sulfatase were the highest weighted variables in PC5 but they were highly correlated ($r = 0.51$; $P < 0.05$). To reduce redundancy, only available K was retained because of its higher weighted loading in PC5 and ease of estimation. Available B was selected from PC6. Many auto-correlated variables appeared in PC1 for both Entisols and Alfisols (data not presented). Among these, WBOC and very labile C were selected because they were higher weighted variables. Several soil chemical properties were screened. Besides these, pH_{Ca} was screened from PC2 and available P from PC6 because they had higher factor loading for Entisols. Again, N_{min} from PC4 and β-glucosidase from PC5 with higher factor loading were also screened in Entisols. Among the physical attributes, bulk density was screened from PC3. For Alfisols, under PC2 dehydrogenase and aryl sulfatase were highly weighted variables but they were significantly correlated ($r = 0.28$); consequently aryl sulfatase was selected for further analysis. The attributes C_{min}, C_{mic} and β-glucosidase with higher factor loading were retained from PC3, PC5 and PC6, respectively.

Selecting soil quality indicators

Discriminate analyses were performed on the basis of results from factor analysis (PCs) for individual Soil Orders. For

Inceptisols, DA revealed that only first two discriminate functions (DFs) were significant and explained 73.6% and 18.3% of the total variance with canonical correlation of 0.95 and 0.84 (Table 5); pH_{Ca} (0.97), CEC (0.83) and available K (0.56) were found to be powerful discriminators with high positive coefficient under the component DF1. Dehydrogenase with high discriminate coefficient (1.08) was a clear choice from DF2 for inclusion in MDS. Available Zn and B were dropped from the MDS because they carried equal and minimum values of discriminate coefficient in DF1. Two separate DAs, one for selected soil attributes from factor analysis and another for highly weighted attributes in PC1, were also performed for selecting MDS for both Entisols and Alfisols (Tables 6, 7). Two segregated DFs explaining ~78.7% and 14.8% of the total variance with canonical correlation of 0.95 and 0.8, respectively, were generated for Entisols. In DF1, pH_{Ca} was discriminated (negative coefficient) from WBOC and N_{min} (positive coefficient). The second DF was also significant with bulk density carrying the highest coefficient loading for inclusion. For Entisols, the first two DFs explained 61.6% and 28.6% of the total variance, with canonical correlation of 0.95 and 0.8. The WBOC and pH_{Ca} were included in MDS, but very labile C was excluded because it is a highly oxidative form of WBOC (Mandal *et al*. 2008) and showed positive correlation with WBOC (data not presented, $P<0.05$). The next highly weighted attribute, C_{mic}, with canonical factor load of –0.86 was also screened for inclusion in MDS. For Alfisols, only one DF appeared explaining 98.5% and 99.5% of the total variance for both DAs irrespective of all selected attributes in PCs and highly weighted attributes in PC1 (Table 7). Dehydrogenase was selected but both C_{min} and aryl sulfatase were dropped from MDS because they yielded a minimum and similar discriminate coefficient. Further, N_{min}, very labile C and C_{mic} with highly weighted discriminate coefficients were retained in MDS.

Table 3. Correlation among the estimated soil enzyme activities
DHA, Dehydrogenase activity; FDHA, fluorescein diacetate hydrolysing activity; URE, urease; β-glu, β-glucosidase ; AcP, acid phosphatase; AlkP, alkaline phosphatase; ArS, aryl sulfatase. *$P<0.05$; ** $P<0.01$

	DHA	FDHA	URE	β-glu	AcP	AlkP
FDHA	0.58**	1.00				
URE	–0.02	0.37**	1.00			
β-glu	0.32*	0.43**	0.15	1.00		
AcP	0.29*	0.23	0.14	0.32*	1.00	
AlkP	0.03*	0.42**	0.34**	0.12	0.22	1.00
ArS	0.34**	0.43**	0.30*	0.34**	0.43**	0.39**

Minimum dataset validation

Results of the validation of the MDS (Table 8) showed that dehydrogenase activity ($P<0.05$) and CEC ($P<0.05$) for Inceptisols ($R^2=0.45$), WBOC ($P<0.01$) for Entisols ($R^2=0.77$), and N_{min} ($P<0.01$) and very labile C ($P<0.05$) for Alfisols ($R^2=0.78$) were identified as main attributes for soil quality influencing significantly the variability of ERY of the systems studied.

Discussion

Most of the soil quality attributes analysed varied significantly among the three Soil Orders, Inceptisols, Entisols and Alfisols. Of the 27 attributes analysed, only four, CEC, dehydrogenase activity, available K and pH_{Ca}, were screened out for their overriding influence in maintaining the productivity of the soils under Inceptisols. However, among the four attributes, only dehydrogenase activity and CEC showed significant correlations with ERY. Results thus indicated that for maintaining soil microbial activity, dehydrogenase appeared to be a good indicator of soil quality for sustaining soil systems. The importance of dehydrogenase activity as an indicator of soil microbiological quality in the initial oxidation of organic matter has been emphasised by others (Chaudhury *et al*. 2005). Dehydrogenase representation as a microbial attribute for assessment of soil quality was reinforced by its significant positive correlation with soil microbial abundance ($r=0.59$ and 0.47; $P<0.01$). Chaudhury *et al*. (2005) also observed that dehydrogenase was a good indicator in their

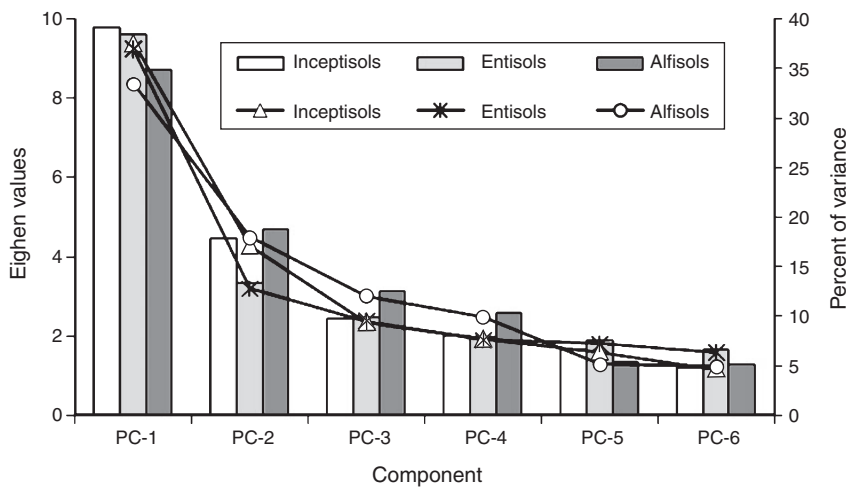

Fig. 3. Scree plot of six principal components of the soils of three Soil Orders.

Table 4. Results of principal component analysis of the soil attributes of soil belonging to three Soil Orders

DHA, Dehydrogenase activity; CEC, cation exchange capacity; WBOC, Walkley–Black organic C. Bold values indicate highly weighted variables for the respective principal components (PC)

	PC1	PC2	PC3	PC4	PC5	PC6
Inceptisols						
Avail. B	0.77	0.32	0.09	0.12	–0.05	**0.50**
DHA	0.26	–0.39	–0.71	**–0.58**	–0.07	0.35
CEC	**0.92**	–0.02	0.72	0.62	–0.12	0.06
pH_{Ca}	0.09	**0.83**	0.21	0.31	–0.12	0.03
pH_w	0.16	**0.82**	–0.13	–0.09	–0.13	–0.04
Avail. K	0.68	–0.10	0.09	0.12	**0.60**	–0.06
Avail. Zn	0.40	0.20	**0.66**	0.53	–0.20	–0.18
Aryl sulfatase	0.79	0.14	–0.28	–0.22	**0.55**	–0.25
Entisols						
pH_w	**0.82**	–0.36	–0.12	–0.12	–0.20	0.55
β-glucosidase	0.34	0.39	–0.54	–0.08	**0.61**	0.37
pH_{Ca}	**0.82**	**0.84**	0.23	0.10	0.06	0.13
Microbial biomass C	**0.89**	0.38	0.04	0.34	–0.20	0.07
Microbial biomass N	**0.86**	0.48	0.43	0.38	0.20	0.05
WBOC	**0.91**	–0.10	0.20	0.04	–0.21	–0.01
Mineralisable N	0.75	0.08	0.24	**–0.72**	–0.02	–0.02
Bulk density	–0.09	0.52	**0.73**	–0.14	–0.28	–0.17
Very labile C	**0.86**	**0.85**	–0.20	0.12	0.24	–0.22
Avail. P	–0.63	0.18	–0.46	0.13	0.39	**–0.51**
Alfisols						
Very labile C	**0.904**	0.083	0.255	0.164	0.099	0.545
WBOC	**0.869**	0.188	–0.098	–0.364	0.246	0.460
Mineralisable N	**0.852**	**0.735**	0.066	–0.010	0.084	0.444
Microbial biomass C	**0.829**	0.302	–0.170	0.622	**0.243**	0.389
CEC	**0.824**	–0.594	–0.040	0.304	–0.234	0.260
Mineralisable C	0.768	–0.396	**0.351**	–0.287	–0.387	0.243
DHA	0.636	**–0.082**	–0.086	**0.124**	0.049	0.004
Aryl sulfatase	0.569	**0.266**	0.140	–0.079	0.325	–0.015
β-glucosidase	0.426	0.251	–0.117	0.029	0.303	**–0.052**

Table 5. Results of discriminate analysis of the attributes of soils belonging to the Soil Order Inceptisols

Bold values indicate highly weighted variables for the respective discriminate function (DF)

	DF1	DF2
From selected properties		
Eigenvalue	9.44	2.35
% of Variance	73.63	18.31
Canonical correlation	0.95	0.84
Variables and discriminant coefficient		
pH_{Ca}	**0.97**	0.81
Cation exchange capacity	**0.83**	–0.39
Available Zn	0.35	0.12
Available B	0.35	–0.13
Dehydrogenase activity	**–0.14**	1.08
Available K	**0.56**	0.33

minimum dataset, contributing 19.9% of variability in soil quality index, when assessing soil quality under long-term rice-based cropping system in Gangetic Inceptisols. CEC represents the capacity of a soil to store nutrients and the content of organic C (Masto *et al.* 2007). CEC values ranged between low and medium in magnitude considering the values found in soils of tropical and subtropical countries. Basak (2011) established that a CEC value of 14.9 $cmol_{(+)}\ kg^{-1}$ was 'optimum' for Inceptisols for harvesting 80% yield potential of a rice-based cropping system. The mean value of CEC of the studied soil was less than this 'optimum' value. This justified its occurrence as one of the main parameters for soil quality in Inceptisols. The available K content of the experimental soils was also in the range low–medium and its deficiency was encountered in some pockets in Inceptisols, justifying its representation in the identified key indicators. There are reports of K deficiency playing an important role for maintaining system productivity in rice-growing regions of the world (Li *et al.* 2013). The other indicator screened out was pH_{Ca} because of its obvious importance in controlling availability of essential nutrients and activities of soil microbes. Rehabilitation of acid soil through low-cost liming materials has been well researched (Bhat *et al.* 2010; Badole *et al.* 2015).

Table 6. Results of discriminate analysis of the attributes of soils belonging to the Soil Order Entisols

WBOC, Walkley–Black organic C. Bold values indicate highly weighted variables for the respective discriminate function (DF)

	DF1	DF2
From selected properties		
Eigenvalue	9.28	1.75
% of Variance	78.71	14.82
Canonical correlation	0.95	0.80
Variables and discriminant coefficient		
WBOC	**0.97**	–0.09
pH_{Ca}	**–0.64**	0.43
Bulk density	0.09	**–0.95**
Mineralisable N	**0.91**	–0.18
β-glucosidase	0.54	0.46
Available P	0.24	0.34
From selected principal component 1		
Eigenvalue	7.11	3.30
% of Variance	61.61	28.56
Canonical correlation	0.95	0.80
Variables and discriminant coefficient		
WBOC	–0.14	–1.37
Microbial biomass C	0.65	–0.86
Very labile C	0.62	**1.58**
Microbial biomass N	0.27	0.25
pH_{Ca}	0.67	–0.54
pH_w	–0.94	1.12

Although differences between Inceptisols and Entisols were small, a different set of key indicators (WBOC, pH_{Ca}, N_{min}, BD and C_{mic}) was found to govern soil quality of Entisols for its improved productivity. Research on assessment of soil quality for typical Entisols in India and elsewhere is rare, even though Entisols support production of a huge amount of food grains in Southeast Asian countries. Basak (2011) in a preliminary experiment showed that the optimum value of WBOC for maintaining good productivity of rice-based cropping system for Entisols was 7.6 $g\ kg^{-1}$. The average WBOC content of the studied Entisols was 7.2 $g\ kg^{-1}$. Considering the importance of

Table 7. Results of discriminate analysis of the attributes of soils belonging to the Soil Order Alfisols
Bold values indicate highly weighted variables for the respective discriminate function (DF)

DF1 *From selected soil properties*		DF1 *From selected principal component 1*	
Eigenvalue	983.61	Eigenvalue	0.94
% of Variance	98.43	% of Variance	99.5
Canonical correlation	1.00	Canonical correlation	1.00
Variables and discriminant coefficient			
Very labile C	2.91	Very labile C	**7.06**
Aryl sulfatase	3.54	Walkley–Black organic C	2.62
Dehydrogenase activity	**–5.72**	Mineralisable N	**8.05**
Mineralisable C	3.98	Mineralisable C	4.05

Table 8. Results of the regression between the indicators retained in the minimum dataset (MDS) and equivalent rice yield
DHA, Dehydrogenase activity; CEC, cation exchange capacity; WBOC, Walkley–Black organic C; C_{mic}, microbial biomass carbon. Bold soil quality indicators have a strong correlation with equivalent rice yield

Indicators	Unstandardised coefficients β	Std. error	*t* (d.f. = 20) for each Soil Order	Significance level
Inceptisols ($R^2 = 0.45$)				
Constant	218.46	61.55	3.55	0.003
pH_{Ca}	–7.32	10.21	–0.72	0.49
DHA	0.38	0.18	2.06	0.05
Available K	0.00	0.09	–0.05	0.96
CEC	–4.95	2.11	–2.34	0.03
Entisols ($R^2 = 0.77$)				
Constant	66.398	59.130	1.123	0.280
WBOC	13.751	4.693	2.930	0.011
pH_{Ca}	–4.732	5.065	–0.934	0.366
Mineralisable N	0.221	0.314	0.703	0.493
BD	–19.859	45.238	–0.439	0.667
C_{mic}	0.019	0.070	0.274	0.788
Alfisols ($R^2 = 0.78$)				
Constant	51.84	10.52	4.93	0.0001
DHA	0.15	0.21	0.73	0.475
Mineralisable N	0.48	0.12	3.91	0.0014
Very labile C	10.51	4.08	2.58	0.021
C_{mic}	0.05	0.03	1.63	0.124

WBOC in productivity, its occurrence as one of the key indicators for Entisols was not surprising. WBOC influences biological, chemical and physical properties of soil by regulating microbial activity, soil pH, response to fertiliser application, nutrient availability and structural stability (Rahmanipour *et al*. 2014). Here, N_{min} and C_{mic} provide less significant influence on ERY. Although a part of WBOC, C_{mic} was found to be one of the screened indicators. Likewise, despite a large amount of N_{min} in Entisols (49.2 μg NH_4-N g^{-1} day^{-1}) compared with Inceptisols (38.8 μg NH_4-N g^{-1} day^{-1}) and Alfisols (35.8 μg NH_4-N g^{-1} day^{-1}), N_{min} also constituted one of the screened key indicators of Entisols. From relationships with ERY, it was found that the WBOC had the highest correlation value, indicating its overall influence on all other screened indicators, as expected.

The major constraints for increasing productivity of Alfisols are its low OC and poor microbiological activity. As such, a large number of microbial attributes, dehydrogenase activity, N_{min}, C_{mic} and very labile C, appeared as key indicators for soil quality for Alfisols. Nitrogen mineralisation in soils plays an important role in N nutrition of wetland rice because half to two-thirds of total N taken up by rice crops, even in N-fertilised paddies, comes from the soil N pool (Sahrawat 1983; Kader *et al*. 2013). It also helps to predict system yield and N extraction from soils and assess environmental pollution risk (Hirzel *et al*. 2012). Occurrence of N_{min} as one of the key indicators was thus justified. However, the method for estimation of N_{min} is tedious and time-consuming. In our soil-testing laboratory, available N is determined by distillation with $KMnO_4$ as an oxidising agent. Because routine estimation of N_{min} in such a laboratory may be difficult, development of a robust relationship between N_{min} and available N in Alfisols may be useful for estimating N-supplying capacity and yield sustainability of such soil. This is reinforced by the existence of significant positive correlation between ERY and N_{min} of the soil.

In a semi-arid tropical Alfisols, Sharma *et al*. (2008), however, observed mean weight diameter (MWD), available N and C_{min} as the key indicators for soil quality and crop productivity. Usefulness of MWD, even in Inceptisols, was also shown by Chaudhury *et al*. (2005). Our statistical approaches failed to screen MWD as a main soil-quality indicator, possibly due to its far greater values than those reported by Chaudhury *et al*. (2005) and Sharma *et al*. (2008).

Occurrence of the very labile pool of soil C as one of the key indicator was expected because it fuels the soil food web, and therefore greatly influences nutrient cycles for maintaining soil quality (Zou *et al*. 2005; Majumder *et al*. 2008). This is more so in Alfisols. Further, the method for estimation of very labile C is analytically attractive and least expensive (Majumder *et al*. 2008).

Conclusion

Of the 27 soil attributes, dehydrogenase activity and CEC for Inceptisols, organic C for Entisols and N_{min} and very labile C for Alfisols were screened as key indicators for assessment of soil quality under a rice-based cropping system (rice–potato–sesame). Biological and chemical attributes were more sensitive than physical attributes in indicating differences in

soil quality and influences on system yield in all three Soil Orders.

Acknowledgements

Authors are extremely thankful to the Indian Council of Agricultural Research (ICAR), New Delhi, for funding the work through the World Bank assisted multi-institutional collaborative National Agricultural Innovation Project (NAIP: Sub-project C-2060) entitled 'Assessment of quality and resilience of soils under diverse Agro-ecosystems'.

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