Communications in Soil Science and Plant Analysis, 36: 1141–1161, 2005

ISSN 0010-3624 print/1532-2416 online
DOI: 10.1081/CSS-200056885

Assessing Soil Quality Under Long-Term Rice-Based Cropping System

Jaladhi Chaudhury
Central Research Institute for Jute and Allied Fibres, Barrackpore,
West Bengal, India

Uttam Kumar Mandal and K. L. Sharma
Central Research Institute for Dryland Agriculture, Santoshnagar,
Hyderabad, India

H. Ghosh
Central Research Institute for Jute and Allied Fibres, Barrackpore,
West Bengal, India

Biswapati Mandal
Bidhan Chandra Krishi Viswavidyalaya, Nadia, West Bengal, India

Abstract: Productivity of the rice-based cropping system is low, and it continues to decline in India because of worsening soil-related constraints. Keeping in view the importance of soil quality in rice-based intensive cropping system, the present investigation was undertaken with the objective of identifying several biological, chemical, and physical indicators of soil quality using data collected from a long-term experiment being conducted since 1972 on rice-wheat-jute cropping system in Indo Gangetic alluvial soils of India. The experiment was laid out in a randomized block design with five treatments, under long-term fertilizer experiment [i.e., control (no fertilizer and manure); 100% of the recommended dose of nitrogen (100% N); 100% of the recommended dose of N and phosphorus (100% NP); 100% of the recommended

Received 14 October 2003, Accepted 1 June 2004

Address correspondence to Jaladhi Chaudhury, Department of Soil Science and Microbiology, Central Research Institute for Jute and Allied Fibres, Barrackpore, North 24 Parganas, West Bengal 700120, India. E-mail: jaladhic@hotmail.com or Uttam Kumar Mandal, Division of Resource Management, Central Research Institute for Dryland Agriculture, Santoshnagar, P.O. Saidabad, Hyderabad 599958, India. E-mail: jaladhic@hotmail.com

dose of N, P, and potassium (100% NPK); and 100% of the recommended dose of N, P, K, and farm yard manure (100% NPK + FYM]. Soil samples were collected after the harvest of rice during the 2002 experiment and were analyzed for physical, chemical, and biological parameters. On the basis of the long-term yield data, sustainable yield index was calculated. Multivariate statistical techniques were used to determine the smallest set of chemical, physical, and biological indicators that account for at least 95% of the variability in the total data set. The total soil N, available P, dehydrogenase activity, and mean weight diameter of the aggregates were the most important indicators in this case study. A multiple regression was run to evaluate the efficacy of minimum data set (MDS) taking sustainable yield index as goal ($r^2 = 0.69$). Each MDS was transformed into score. The soil quality index (SQI) was calculated by using weighing factors derived from principal component analysis for each scored MDS variable. The highest SQI was found in 100% NPK + FYM treatment followed by 100% NPK, 100% NP, 100% N, and control treatment, respectively. To compare the soil aggradation or degradation, an undisturbed fallow soil was taken as reference, and it has been observed that 100% NPK + FYM and 100% NPK showed positive change in soil quality that is aggradation of soil quality, but the other three treatments, 100% N, 100% NP, and control, showed negative change of soil quality and indicates degradation of the system.

Keywords: Rice-wheat-jute system, soil quality indicators, sustainable yield, principal component analysis, FYM

INTRODUCTION

Rice-wheat is the most predominant cropping system in India, but the productivity of crops under this cropping system has reached a plateau and, in fact, is showing a decreasing trend in many areas in India where this cropping system has been practiced for a long time. There are reports of declining factor productivity [i.e., increased rate of fertilizer are needed to maintain the current yield level (Hobbs et al. 1990)], which is cited as the evidence of unsustainability of the cropping system. The low or declining productivity of rice is associated with soil constraints, erratic rainfall, and inappropriate cultural management practices adopted by the farmers (Mahapatra et al. 1985). Assessment of the quality of soil resources of rice ecosystem is required to raise crop productivity and its sustainability. However, assessing soil quality is difficult, because unlike water and air quality for which standards have been established primarily by legislation, soil quality assessments are purpose oriented and site specific (Karlen et al. 1994). As a complex functional state, soil quality cannot be measured directly, but it may be inferred from management-induced changes in soil properties. Traditionally, soil quality research focused primarily on chemical and physical properties because simple methods of analysis were available (Larson and Pierce 1991); however, more recently, it has been suggested that soil biological properties can serve as early and sensitive indicators of agro ecosystems in response to soil management practices (Islam and Weil 2000; Kennedy and Papendick 1995). Thus, biological aspects, along with chemical and physical properties of soil, are essential to evaluate soil quality responses to organic amendment (Min et al. 2003). To assess soil quality, indicators (soil properties) are usually linked to soil function (Howard 1933; Doran and Parkin (1994); Larson and Pierce 1994; Karlen and Stott 1994; Acton and Gregorich 1995; Karlen, Parkin, and Eash 1996; Doran, Sarrantonio, and Lieberg 1996). A valid soil quality index would help interpret data from different soil measurements and show whether management and land use are having the desired results for productivity, environmental protection, and health (Granatstein and Bezdicek 1992). Moreover, can these indices provide an early indication of soil degradation and the need for remedial measures and characterize changes in soil properties that would reflect the extent of rehabilitation or regeneration of degraded soils?

Maintaining soil quality at desirable level is a very complex issue due to involvement of climatic, soil, plant, and human factors and their interactions. This issue is more challenging in rice-based cropping system. The puddling practice, so essential for optimizing production of rice, destroys the soil structure, increases bulk density, and reduces hydraulic conductivity, thus leading to a nonconducive soil physical environment for the subsequent wheat crop (Lal 1985; Painuli, Woodhead, and Pagliai 1988). The recommended dose of NPK fertilizers alone does not sustain productivity under continuous intensive cropping system (Nambiar and Abrol 1989; Yaduvanshi 2003), whereas inclusion of organic manures improves physical properties (Swarup 1987; Kumar and Tripathi 1990; Mandal et al. 2003), the biological status of soil (Ghai, Rao, and Batra 1988), and soil fertility and crop yields (Swarup 1987; Mandal et al. 2003; Ghai, Rao, and Batra 1988; Bhardwaj 1982; Singh 1994; Lal and Mathur 1989). There is urgent need to adopt appropriate soil and crop management practices in this ecosystem, which reduce soil degradation or maintain soil quality at desirable level. Moreover, most of the soil quality research has been conducted on the soils of temperate region; soil quality research on tropical soils is much more limited (Ericksen and McSweeney 1999; Palm, Swift, and Woomer 1996). In recent years, soil quality research has focused on the linkages among the following: management practices and systems; observable soil characteristics; and soil processes and performance of soil functions (Lewandowski, Zumwinkle, and Fish 1999). Choosing the appropriate soil attributes to include in an index must include consideration of soil function and management goals that are site specific and user oriented and must focus on sustainability rather than just crop yields. These indices would be useful in ascertaining the fragility of soil and for understanding how improved management might strengthen its resilience.

By keeping in view the importance of soil quality in rice-based intensive cropping system, the present investigation was undertaken with the objective of identifying several biological, chemical, and physical indicators of soil quality using data collected form a long-term rice-wheat-jute cropping system. An attempt has also been made to develop an overall soil quality index by using these indicators that are meaningful to the rice-based agricultural systems; further studies determined, whether the traditional system of farming is aggrading or degrading the soil considering an undisturbed fallow as benchmark.

MATERIALS AND METHODS

Field Site, Experiment Layout, and Treatments

A permanent field trial was laid out in 1972 at Central Research Institute for Jute and Allied Fibres, Barrackpore (88°26′ E longitude, 22° 45′ N latitude and at 9 m high above sea level) West Bengal, India with rice-wheat-jute cropping sequence under All India Coordinated Research Project on Long-Term Fertilizer Experiment. The climate of region is hot moist subhumid. The mean maximum temperature ranges from 35.4 to 31.5°C during summer months (May, June, and July), and mean minimum temperature ranges from 12.4°C to 13.1°C during the winter season (December to February). The mean annual maximum and minimum temperatures were 31.05 and 20.84°C, respectively. The mean annual rainfall is 1666 mm (average of past 30 years).

The soil of the experimental site belongs to New Gangetic Alluvium (Eutrochrept) with sandy loam texture up to 20 cm depth, and illite and montmorrilonite are dominant clay minerals that belong to Nilgunj Series (Table 1).

Table 1. Physical and chemical properties of soil of 0 to 20-cm depth of the experimental field at the beginning of the study (1971)

Soil properties	Soil layer of 0–20 cm
Sand (2–0.02 mm), %	54
Silt (0.02–0.002 mm), %	28
Clay (<0.002 mm)	18
Bulk density ($Mg\,m^{-3}$)	1.35
pH (1:2 soil to water)	7.1
Electrical conductivity ($dS\,m^{-1}$)	0.23
CEC (c mol (p^+) kg^{-1})	19.0
Organic carbon in percent	0.714
Total nitrogen in parcent	0.086
Available P ($kg\,ha^{-1}$)	41.5
Available K ($kg\,ha^{-1}$)	143

The experiment was laid out in a randomized block design with three replications and with five treatments [i.e., control (no fertilizer and manure); 100% of the recommended dose of N (100% N); 100% of the recommended dose of N and P (100% NP); 100% of the recommended dose of N, P, and K (100% NPK); 100% of the recommended dose of N, P, K, and farmyard manure (100% NPK + FYM)] under long-term fertilizer experiment. The recommended dose of NPK (100%) used in jute (*Corchorus capsularis*) was 60:13:50 kg ha^{-1} and for rice (*Oryza sativa*) and wheat (*Triticum aestivum*) it was 120 26:50 kg ha^{-1}. The size of each plot was 20 m × 10 m. Fertilizers were applied to jute, rice, and wheat each year according to the treatments. Source of N up to 1989 was ammonium sulfate; after that, NPK were supplied through urea, single super phosphate, and muriate of potash, respectively. FYM was added at 10 t ha^{-1} before sowing of jute each year. Puddling was carried out by a tractor-drawn disc plow. The 30-day-old paddy seedlings were transplanted during August. The spacing was maintained at 10 cm between plants and 20 cm between rows. Nitrogen was applied as urea in three equal split doses. First dose was applied at the time of sowing, second and last doses were top dressed at 25–30 days after transplanting (DAT) and 45–50 DAT, respectively. Phosphorus and K were applied as basal every time at the time of transplanting. Regular irrigation at 5 to 6-day intervals was applied, except on rainy days. Interculture operation, such as hand weeding, was carried out from time to time. The crop was harvested at the end of November. After the harvest of paddy, the field was plowed thoroughly with tractor-drawn disc plow followed by harrowing and planking. The wheat crop used to sow in the first fortnight of December keeping a distance of 20 cm between rows and seeds were sown at a distance of 5 cm. Nitrogen was applied as urea in three equal split doses at the time of sowing 25–30 DAS and 55–60 DAS. Phosphorus and K were applied as a basal at the time of sowing. Irrigation was applied at critical stages of crop growth considering the availability of soil moisture. The crop was harvested in the last week of March. Jute used to sow in the second fortnight of April after plowing the soil with tractor-drawn disc plow followed by harrowing and planking. Nitrogen was applied as urea in two equal split doses first after intercultural operations like weeding and thinning at 30 DAS and the second application was completed within 45 DAS. Phosphorus and K were used to apply as a basal at the time of sowing. Jute is mainly a rainfed crop, but one or two lifesaving irrigations were given during April–May. The crop was harvested in the first week of August.

Soil Sampling, Processing, and Analysis

Soil samples were collected from 0- to 15-cm soil depth after the harvest of rice in 2002 and were analyzed for various soil physical, chemical, and biological variables. The physical variables included mean weight diameter of soil aggregates (wet sieving method) and bulk density. Bulk density and soil texture were measured by the core method (Blake and Hartge 1986) and bouyoucos hydrometer method (Gee and Bauder 1986), respectively. The aggregate size distribution was determined by wet sieving (Yoder 1936), and the values were expressed as mean weight diameter (MWD) after oven drying (van Bevel 1949).

A part of the representative soil samples was air dried, ground, and passed through 0.2-mm sieve for determination of organic carbon by Walkley and Black's method (Jackson 1967a). Total Kjeldahl nitrogen was determined by using standard digestion system and Kjeltec Auto 1030 Analyzer of Tecator made of Sweden based on the principle of modified Kjeldahl method (Bremner 1965; Jackson 1967b). Available soil nitrogen was determined by alkaline-$KMnO_4$ method given by Subbaiah and Asija (Subbaiah and Asija 1956), which takes care of easily oxidizable N. Available P (Olsen P) was determined by sodium bicarbonate ($NaHCO_3$) extraction and subsequent colorimetric analysis (Olsen et al. 1954). Exchangeable K (Hanway and Heidel 1952) and available Zn, Fe, Cu, and Mn were determined by using the DTPA (diethylene triamine penta acetic acid) micronutrient extraction method developed by Lindsay and Norvell (Lindsay and Norvell 1978). The micronutrient concentrations in the DTPA extract were measured by using inductively coupled plasma (ICP) spectrometer (ICP-XP model, simultaneous system of GBC Australia). Electrical conductivity (Rhoades 1982) and pH of water-saturated pastes were measured by using conductivity and pH meter, respectively. Microbial biomass carbon (MBC) determinations were made by using chloroform fumigation technique as described by Jenkinson and Powlson (Jenkinson and Powlson 1976) and Jenkinson and Ladd (Jenkinson and Ladd 1981). The dehydrogenase activity (DHA) was measured by using tri-phenyl tetrazolium chloride (Tabatabai 1982), which was reduced to triphenyl formazan (TPF).

Soil Quality Index Demonstration

To determine the soil quality index, four main steps were followed: 1) define the goal, 2) select a minimum data set (MDS) of indicators that best represent soil function, 3) score the MDS indicators based on their performance of soil function, and 4) integrate the indicator score into a comparative index of soil quality.

Crop yield can be an important indicator of soil quality, because it serves as a plant bioassay of the interacting soil characteristics. The sustainable yield index computed on the basis of the yield obtained from 1972 to 2002 (Table 2) for each treatment were considered as goal, because the farmers like to get more consistent productivity from the unit land.

Table 2. Average yield (t ha^{-1}) and sustainable yield index (SYI) of jute, rice, and wheat from 1971 to 2002

	Jute		Rice		Wheat		
Treatment	Average yield	SYI	Average yield	SYI	Average yield	SYI	Overall SYI
100% N	1.627	0.479	3.094	0.379	1.9	0.4	0.419
100% NP	1.721	0.528	3.501	0.433	2.175	0.478	0.480
100% NPK	1.957	0.641	3.797	0.439	2.257	0.529	0.536
100% NPK + FYM	2.063	0.662	3.856	0.538	2.34	0.537	0.579
Control	0.874	0.255	1.546	0.363	0.736	0.312	0.310

The sustainable yield index (SYI) (Singh et al. 1990) is defined as

$$\mathrm{SYI} = \frac{\bar{\mathrm{Y}} - \sigma}{\mathrm{Y}_{\max}}$$

where $\bar{\mathrm{Y}}$ is the estimated average yield of a practice over years, σ is its estimated standard deviation, and $\mathrm{Y}_{\max}$ is the observed maximum yield in the experiment over the years of cultivation.

The data were reduced to a minimum data set through a series of uni- and multivariate statistical methods using SPSS software (SPSS 1998). The nonparametric statistics (Kruskal-Wallis χ^2) were used to identify indicators with significant treatment differences. The nonparametric methods were chosen because it did not require assumptions of normality and homoscedasticity, thereby avoiding any need to transform the data (Andrews and Carroll 2001). Only variables with significant differences between treatments ($p < 0.05$) were chosen for the next step in MDS formation. The standardized principal component analysis (PCA) was performed for each statistically significant variables (Andrews and Carroll 2001; Andrews et al. 2002). Principal components (PC) for a data set are defined as linear combinations of variables that account for maximum variance within the set by describing vectors of closet fit to the n observation in p-dimensional space, subject to being orthogonal to one another. The principal components receiving high eigen values and variables with high factor loading were assumed as the variables that best represent system attributes (Brejda et al. 2000). Therefore, only the PCs with eigen values 0.5 or greater, which explained at least 5% of the variation in the data (Wander and Bollero 1999) were examined. Within each principal component, only highly weighted factors (i.e., those with absolute values within 10% of the highest weight) were retained for the MDS. To reduce redundancy and to rule out spurious groupings among the highly weighted variables within PCs, multivariate correlation matrix were used to determine the strength of the relationships among variables. As a check of how well the MDS represented the management system goals, multiple regression was run by using the final MDS indicators as independent variable and measure representing management goal as dependent variables.

After determining the MDS indicators, each of the MDS variables was scored on the basis of the performance of soil function, considering soil type and variation of values within treatments (Table 3). Each variable was transformed or standardized to a value between 0 (least favorable soil function) and 1 (most favorable soil function) scoring functions (Andrews et al. 2002). Once transformed, the MDS variables for each observation were weighted by using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage, divided by the total percentage of variation explained by all PCs with eigenvectors greater than 0.5, provided the weighted factor for variables chosen under a given PC. The final formula

$$\mathrm{SQI} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{Wi\ X\ Si}$$

where W is the PC weighting factor and S is the indicator score. Here, the assumption is that higher index scores meant better soil quality or greater performance of soil functions.

Apart from the PCA approach, another method was also followed to compute soil quality index. In this approach, one undisturbed fallow soil (minimum human interference) adjoining to experimental area was analyzed to compare if long-term agricultural farming is deteriorating the soils or not, with reference to undisturbed fallow field. Here, the basic objective was to judge if there is any aggradation or degradation due to agriculture. Sample from undisturbed fallow area was considered as reference. First, the percent deviation of each parameter over the undisturbed samples was measured. The positive (+) and negative (−) signs were assigned to the percent deviation based on the assumptions of the degradation or aggradation effect of the parameters. Positive sign was assigned for the parameters microbial biomass carbon, dehydrogenase activity, organic carbon, total N, available N, available P, and available K when there was an increase of values over undisturbed fallow, and for bulk density, it is a decrease of values over undisturbed fallow and vice versa. Any change of pH over undisturbed fallow is considered negative. The parameters were ranked from 1 to 10, depending on their importance and responsiveness toward aggradation or degradation (Table 4) (Dalal and Moloney 2000). Then, percent deviation was multiplied by the respective rank. The weighted mean was calculated by dividing the summation with the sum total of the rank, and the weight mean value was considered as also soil quality index.

Table 3. Scoring chart used for selected soil variables/indicators based on the soil type and the variation of values within the treatments

Available phosphorus		Total nitrogen		Dehydrogenase activity		Mean weight diameter	
Kg ha^{-1}	Score	%	Score	μg TPF 24 h^{-1} g^{-1}	Score	mm	Score
0–25	0–0.4	<0.025	0.1	<10	0.1	<0.10	0.1
25–50	0.4–0.6	0.025–0.05	0.1–0.5	10–30	0.1–0.4	0.1–0.2	0.1–0.3
50–75	0.6–0.75	0.05–0.075	0.5–0.75	30–50	0.4–0.8	0.2–0.4	0.3–0.5
75–100	0.75–1.0	0.075–0.1	0.75–1	50–75	0.8–1	0.4–0.5	0.5–0.75
>100	1	>0.1	1	>75	1	0.5–0.75	0.75–1.0
						>0.75	1

Table 4. Scoring for ranking some physical, chemical, and biological indicators of soil quality (Dalal and Moloney 2000)

Serial no.	Selection criteria	pH	Organic carbon	Available nutrients	Aggregate stability	Bulk density	Microbial biomass carbon	Enzyme activity
1	Responsiveness	7	7	8	8	7	9	8
2	Ease of capture	8	7	6	5	7	3	8
3	Interpretation	8	8	8	7	5	5	6
4	Measurement error	7	8	7	5	5	4	5
5	Stable to measure	9	10	7	6	7	7	4
6	Frequency	8	8	6	7	7	5	4
7	Cost	8	6	5	5	6	2	6
8	Aggregation	6	9	5	5	7	3	4
9	Mappable	9	9	5	6	7	3	4
10	Acceptance	9	10	9	7	8	5	4
	Total score	79	82	66	61	66	46	53

Ranking of the parameters as follows: bulk density = 6.6; mean weight diameter = 6.1; pH = 7.9; organic carbon = 8.2; available nitrogen = 6.6; available P = 6.6; available K = 6.6; microbial biomass carbon = 4.6; dehydrogenase activity = 5.3.

RESULTS AND DISCUSSION

Soil Analysis Results

By comparing the initial soil properties of experimental site at the time of start of the experiment during 1972 (Table 1) with those after the harvest of rice during 2002 (Table 5), it was observed that there has been considerable reduction in organic carbon content of soil even in the treatment where farmyard manure (FYM) was added. There were few changes of pH and EC, even after continuous addition of fertilizer. The pH and EC in all the treatments were in optimum range of soil. The total soil nitrogen was highest in the treatment with 100% NPK + FYM (T4) followed by 100% N (T1), 100% NPK (T3), 100% NP (T2), and control (T5), respectively. The higher amount of total N in 100% N treatment may be due to less uptake of nitrogen by plant due to the imbalance nutrients application in this treatment. The available N, P, and K are in the order of 100% NPK + FYM followed by 100% NPK, 100% NP, 100% N and control, respectively. There was considerable buildup of phosphorus in the plots, which received P application continuously. Among the soil physical properties, no significant changes were observed in bulk density. The mean weight diameter of aggregates was highest in 100% NPK + FYM followed by 100% NPK, 100% NP, 100% N and control, respectively. The increase in soil aggregates due to the incorporation of organic matter is supported by the fact that organic substances added to soil through FYM are capable of binding the soil particles together) (MacRae and Mehuys 1985). The improvement of soil structure in balance fertilizer treatments might have resulted from increased root residues of crops (Latif et al. 1992). The soil biological properties like microbial biomass carbon and dehydrogenase activity were highest in 100% NPK + FYM followed by 100% NPK, 100% NP, 100% N and control, respectively. There is strong relationship between soil organic matter content and enzyme activities (Gracia, Hernandez, and Costa 1994). Addition of organic matter in T4 treatment might have increased the biological activity of the soil (Min et al. 2003). The micronutrients Cu, Mn, Fe, and Zn were not limited in all the treatments, and the plants did not show any deficiency symptoms of micronutrients. One undisturbed fallow soil near the experimental plot was also analyzed. There was difference of results of soil properties between the initial soil properties during 1972 and the soil of undisturbed fallow plot. This may be due to natural weathering of soil as well as erosion effect. In most cases, undisturbed fallow soil have properties between T2 and T3 treatments.

Minimum Data Set (MDS) Formulation for Soil Quality Indicators

The nonparametric χ^2 test of treatment means revealed that of 15 soil properties (or variables), 5 properties did not have significant difference between

Table 5. Treatment effects on selected soil quality indicators to a depth of 0–15 cm after the harvest of rice in 2002

Treatment	pH	EC (dS m^{-1})	Organic carbon (%)	Total N (%)	Avl. N (kg ha^{-1})	Avl. P (kg ha^{-1})	Avl. K (kg ha^{-1})	MBC (μg g-1 of soil)	DHA (μg TPF 24 h^{-1} g^{-1})	Bulk density (Mg m^{-3})	MWD (mm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	Zn (ppm)
100% N	7.11	0.15	0.481	0.086	208.33	15.67	210.33	151.37	19.90	1.41	0.45	4.185	10.35	33.33	0.69
100% NP	7.10	0.18	0.489	0.078	246.67	73.00	227.33	248.17	26.68	1.36	0.62	3.961	9.11	33.24	0.75
100% NPK	6.97	0.21	0.564	0.084	274.33	94.67	247.33	412.33	32.89	1.43	0.65	4.107	9.61	47.73	0.72
100% NPK +FYM	6.98	0.21	0.627	0.099	281.00	115.67	248.67	479.20	39.11	1.33	0.72	5.542	12.44	48.70	1.12
Control	7.12	0.15	0.469	0.076	182.67	11.00	208.33	140.21	21.18	1.42	0.35	3.915	7.71	35.27	0.78
$P <$ [a]	0.036	0.020	0.022	0.015	0.014	0.011	0.084	0.010	0.011	0.187	0.017	0.287	0.02	0.064	0.088
Undisturbed fallow soil	6.85	0.17	0.478	0.076	248.00	63.33	226.67	237.75	34.69	1.36	0.66	5.79	12.99	50.22	0.74
	(0.04)	(0.01)	(0.02)	(0.01)	(6.431)	(2.400)	(5.077)	(7.33)	(1.972)	(0.029)	(0.027)	(0.14)	(1.98)	(2.68)	(0.08)

In undisturbed fallow soil, values in the parentheses is standard deviation between replicated values.

[a] Significance of ANOVA comparison of Kruskal-Wallis test between treatments.

treatments. Soil Available K, extractable Cu, Fe, Zn, and bulk density showed no significant difference between treatments at $p < 0.05$ level (Table 5). In principal component analysis, these 5 variables were dropped, and the remaining 10 variables having significant difference with treatments were used. In the PCA of variables with significant differences between treatments greater than 95% of the variance in the data were explained by the first three principal components (Table 6) having eigen values greater than 0.5. Highly weighted variables under PC1 included dehydrogenase activity, microbial biomass carbon, organic carbon, available P, EC, available N, mean weight diameter of aggregates. Under PC2 pH and total N, and for PC3, pH was found to be the highly weighted variables. Because the soil pH in all the treatments was within the optimum range, it was not included in the MDS and total N from PC2 was included in MDS. All seven highly weighted variables under PC1 were also highly correlated (Table 7). The dehydrogenase activity had the highest correlation sums as well as highest factor loading value in PC1 and because of its simple and inexpensive test, it was retained under MDS. Mean weight diameter was the only physical parameter of soil having high factor loading that was also retained under MDS. Organic carbon has the lowest correlation coefficient, but it had high correlation coefficient with DHA (0.93), and so it was dropped. Available N is the next lowest correlation coefficient, but because total N was taken under MDS, it was dropped. From the soil chemical properties, available P having higher correlation coefficient with available N (0.91) was included into MDS. Because the EC and soil

Table 6. Results from the principal components analysis of statistically significant variables ($p < 0.05$)

Statistic or variable	PC1	PC2	PC3
Eigenvalue	7.595	1.326	0.589
Percentage of variance explained	75.950	13.259	5.890
Cumulative percentage	75.950	89.209	95.099
Eigenvectors			
PH	−0.605	$\underline{0.603}$	$\underline{0.489}$
EC	$\underline{0.899}$	0.297	−0.117
Organic carbon	$\underline{0.959}$	−0.153	−0.0552
Total N	0.765	$-\underline{0.563}$	0.232
Available N	$\underline{0.897}$	0.324	0.085
Available P	$\underline{0.942}$	0.263	−0.0005
Microbial biomass carbon	$\underline{0.967}$	0.107	−0.107
Dehydrogenase assay	$\underline{0.969}$	0.101	−0.200
Mn	0.750	−0.479	0.422
Mean weight diameter	$\underline{0.888}$	0.331	0.206

Underline factor loadings are considered highly weighted.

Table 7. Correlation matrix for highly weighted variables under PC with high factor loading

Variables	EC	Organic carbon	Available N	Available P	MBC	DHA	MWD
EC	1.000	0.837	0.860	0.902	0.901	0.922	0.840
Organic carbon	0.837	1.000	0.773	0.853	0.915	0.933	0.778
Available N	0.860	0.773	1.00	0.911	0.893	0.884	0.910
Available P	0.902	0.853	0.911	1.000	0.946	0.934	0.930
MBC	0.901	0.915	0.893	0.946	1.000	0.957	0.856
DHA	0.922	0.933	0.884	0.934	0.957	1.000	0.854
MWD	0.840	0.778	0.910	0.930	0.856	0.854	1.000
Total	6.262	6.088	6.231	6.475	6.468	6.485	6.168

pH values were within the optimum range in all the treatments, EC along with pH were dropped from MDS. Using the similar procedure, Andrews et al. (2002) and Andrews and Carrol (Andrews and Carroll 2001) also reported that soil aggregates and total N were important variables to be included in the MDS while computing soil quality index. Enzyme activity was also considered an effective indicator of soil quality changes resulting from environmental stress or management practices (Quilchano and Maranon 2002). A multiple regressions was computed by using the four MDS indicators (i.e., MWD, DHA, total N and available P) as independent variables and the end point measures representing management goals (i.e., overall sustainable yield index as dependent variables). The coefficient of determination (r^2) is 0.69 with level of probability of significance is 0.013. This indicates that the MDS was responsive to management goals (SYI) in this cropping system.

Soil Quality Index Interpretation

The MDS variables for each treatment were transformed by using scoring functions (Table 3). The SQI was calculated by using weighing factors for each scored MDS variable according to the formula:

$$\mathrm{SQI} = \Sigma\, 0.799\,\mathrm{X}\ \mathrm{S}\ (\mathrm{DHA}) + 0.799\,\mathrm{X}\ \mathrm{S}\ (\mathrm{Available\ P}) + 0.799\,\mathrm{X}\ \mathrm{S}\ (\mathrm{MWD}) + 0.139\,\mathrm{X}\ \mathrm{S}\ (\mathrm{total\ N})$$

where S is the score for the variable and the coefficients are the weighing factors derived from the PCA. The organic system along with chemical fertilizer received the highest SQI value (Figure 1). The mean weight diameter of aggregates contributed maximum to the soil quality index (42.2%) followed

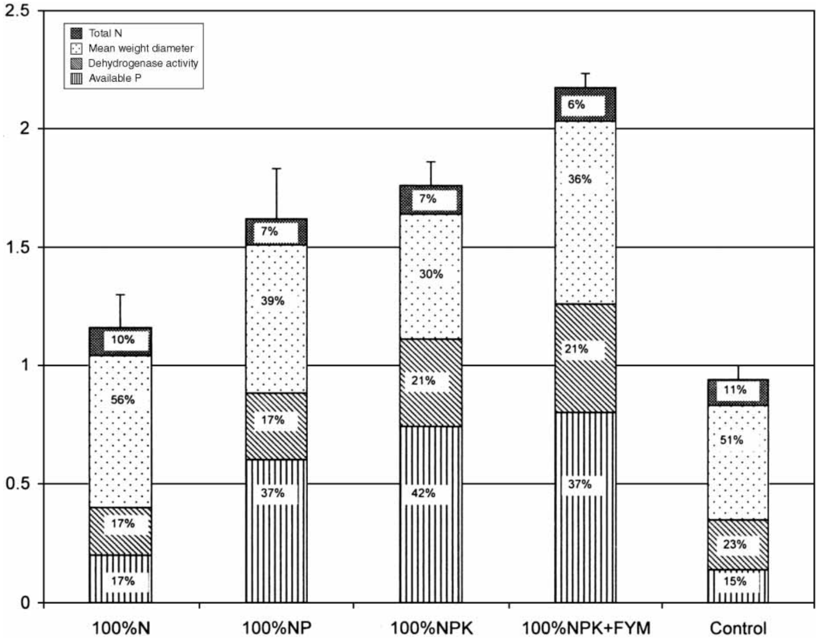

Figure 1. Soil quality index (SQI) for each treatment. Stacked bars show the component (scored and weighted) indicators means added to derive the overall index values. Error bars denote standard deviation of overall index values. $LSD_{0.05}$ for SQI between treatments = 0.205.

by available P (29.6%), DHA (19.9%), and total N (8.3%), respectively. By considering 100% NPK + FYM as ideal treatment (SQI = 100), the relative soil quality (Figure 2) explained that if there were exclusion of FYM, the soil quality (SQ) would decline by 19.35%. Furthermore, if FYM and potassium fertilizer were excluded, the SQ would decline to 25.81%; similarly, if FYM, potash, and phosphorus fertilizer were excluded, SQ would decline by 46.54%; and if no fertilizer as well as manure was applied, the SQ would decline by 56.68%. In the same way, if no manures were applied, sustainability of yield (SY) would be reduced by 7.37%; if manures and potassium fertilizer were excluded, 17.16% of SY would be reduced. Furthermore, if manures, potassium, and phosphate fertilizer were excluded, SY would go down by 27.58%, and if no fertilizer as well as manures were applied, SY would be reduced by 46.46%. The variation of results between sustainable yield index and soil quality index may be due to other biophysical factors like climate crop variety that govern the yield in rice-wheat-jute cropping system.

Another approach taking the undisturbed fallow as benchmark soil was also used to compare the fragility of the production system caused by the

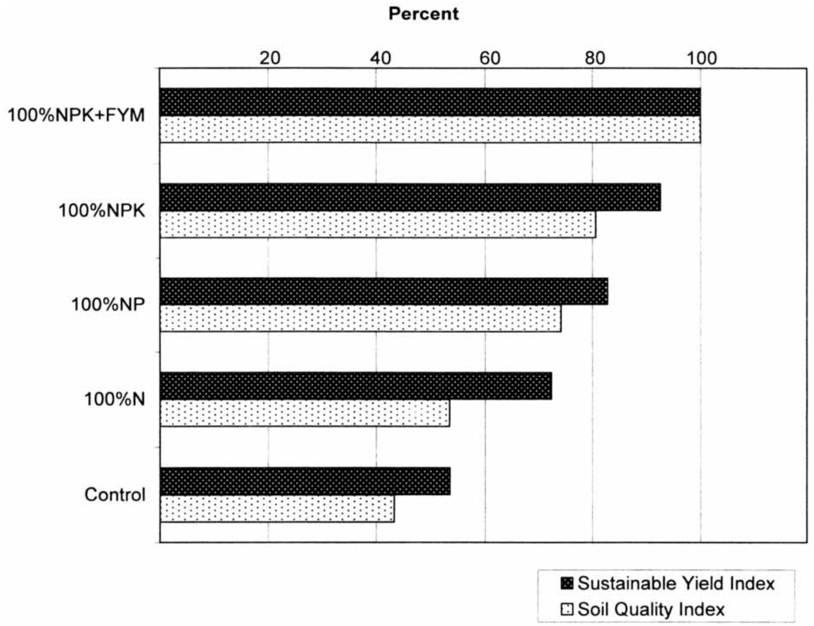

Figure 2. Relative soil quality and sustainable yield index among the treatments considering 100% NPK + FYM as 100.

traditional system of farming. The soil parameters of pH, organic carbon, total N, Available N, P, K, MBC, DHA, bulk density, MWD were used, and the percent deviation of each variables for each treatment with reference to the undisturbed fallow are presented in Table 8. The two treatments (i.e., 100 NPK + FYM and 100% NPK) showed aggradation of soil quality, but the other three treatments, 100% N, 100% NP, and control, where no fertilizer and manures were applied showed negative change of soil quality in reference to undisturbed fallow and indicated degradation of the system.

CONCLUSIONS

The balance fertilization along with manures improves the soil aggregation as well as biological activity of soil and maintains soil quality and sustainability of productivity. The multivariate statistical method effectively selected a minimum data set from large existing data sets. The use of this approach has the potential to integrate biological, chemical, and physical data for ecological management applications where such integration is often lacking. The indexing approach can be used as a tool for adaptive land management for monitoring the effects of management practices on soil functions that best meet the goal. The undisturbed fallow soil can be used as reference in

Table 8. Percent changes in the soil properties as influenced by management practices with reference to undisturbed fallow samples

Treatments	pH	Organic carbon	Total N	Available N	Available P	Available K	MBC	DHA	Bulk density	MWD	SQI
100% N	−3.69	0.76	13.60	−16.00	−75.26	−7.21	−36.34	−42.63	−3.67	−33.82	−18.54
100% NP	−3.60	2.44	2.19	−0.54	15.26	0.29	4.38	−23.08	0.24	−8.82	−0.76
100% NPK	−1.70	18.00	10.96	10.62	49.47	9.12	73.42	−5.19	−4.89	−4.41	14.05
100% NPK +FYM	−1.75	31.26	29.82	13.31	82.63	9.71	101.54	12.74	2.69	5.88	26.50
Control	−3.89	−1.88	0.439	−26.34	−82.63	−8.09	−41.03	−38.94	−4.40	−48.53	−23.60

case of nonavailability of benchmark spot. This approach of soil quality indexing may have even broader applications for soil restoration than for agriculture. Certainly, MDS indicators and scoring functions may need to be changed with differing management, climate, soil type, or even time. But this case study emphasizes that soil quality assessment is a tool that can be used to evaluate the effects of land management practices on soil function.

ACKNOWLEDGMENTS

We thank Director CRIJAF, Barrackpur and all the project investigators under All India Coordinated Research Project on Long-Term Fertilizer Experiment for effectively maintaining the experiment since 1972. We also thank Agro Ecosystem Directorate (Rainfed) under National Agricultural Technology Project for supporting the project financially since 2000.

REFERENCES

Acton, D.F. and Gregorich, L.J. (1995) Understanding Soil Health. In *The Health of Our Soils: Toward Sustainable Agriculture in Canada*; Acton, D.F. and Gregorich, L.J., eds.; ZCentre for Land and Biological Resources Research: Ottawa, Ontario, Canada, Research Branch, Agriculture and Agri-Food Canada, 5–10.

Andrews, S.S. and Carroll, C.R. (2001) Designing a Soil Quality Assessment Tool for Sustainable Agroecosystem Management. *Ecological Applications*, 11: 1573–1585.

Andrews, S.S., Mitchell, J.P., Mancinelli, R., Larlen, D.L., Hartz, T.K., Horwarth, W.R., Pettygrove, G.S., Scow, K.M., and Munk, D.S. (2002) On Farm Assessment of Soil Quality in California's Central Valley. *Agronomy Journal*, 94: 12–23.

Bhardwaj, K.K.R. (1982) Effect of the Age and Decomposition Period of Dhaincha on the Yield of Rice. *Indian Journal of Agronomy*, 27: 284–285.

Blake, G.R. and Hartge, K.H. (1986) Bulk Density. In *Methods of Soil Analysis. Part 1. Physical and Minerological Methods,* 2nd ed.; and Klute, A., eds.; American Society of Agronomy: Madison, Wisconsin; Agron. Monogr. 9, 364–367.

Brejda, J.J., Moorman, T.B., Karlen, D.L., and Dao, T.H. (2000) Identification of Regional Soil Quality Factors and Indicators. I. Central and Southern High Plains. *Soil Science Society of America Journal*, 64: 2115–2124.

Bremner, J.M. (1965) Organic Forms of Soil Nitrogen. In *Methods of Soil Analysis, Part 2*; Black, C.A., ed.; American Society of Agronomy: Madison, Wisconsin; Agron. 9, 1238–1255.

Dalal, R.C. and Moloney, D. (2000) Sustainability Indicators of Soil Health and Biodiversity. In *Management for Sustainable Ecosystems*; Hale, P., Petrie, A., Moloney, D. and Sattler, P., eds.; Centre for Conservation Biology, The University of Oueensland: Brisbane.

Doran, J.W. and Parkin, T.B. (1994) Defining and Assessing Soil Quality. In *Defining Soil Quality for a Sustainable Environment*; Doran, J.W., Coleman, D.C., Bezdicek, D.F. and Stewart, B.A., eds.; 3–21, SSSA Spec. Publ. No. 35, Soil Science Society of America: Madison, Wisconsin.

Doran, J.W., Sarrantonio, M., and Lieberg, M.A. (1996) Soil Health and Sustainability. *Advances in Agronomy*, 56: 1–54.

Ericksen, P.J. and McSweeney, K. (1999) Fine Scale Analysis of Soil Quality for Various Land Uses and Landforms in Central Honduras. *American Journal of Alternative Agriculture*, 14: 146–157.

Gee, G.W. and Bauder, J.W. (1986) Particle Size Analysis. In *Methods of Soil Analysis. Part 1. Physical and Minerological Methods,* 2nd ed.; and Klute, A., eds.; American Society of Agronomy: Madison, Wisconsin; Agron. Monogr. 9, 404–408.

Ghai, S.K., Rao, D.L.N., and Batra, L. (1988) Nitrogen Contribution to Wetland Rice by Green Manuring with *Sesbania* Spp. in an Alkaline Soil. *Biology and Fertility of Soils*, 6: 22–25.

Gracia, C., Hernandez, T., and Costa, F. (1994) Microbial Activity in Soils Under Mediterranean Environmental Conditions. *Soil Biology and Biochemistry*, 26: 1185–1191.

Granatstein, D. and Bezdicek, D.F. (1992) The Need for a Soil Quality Index: Local and Regional Perspectives. *American Journal of Alternative Agriculture*, 7: 12–16.

Hanway, J.J. and Heidel, H. (1952) Soil Analyses Methods as Used in Iowa State College Soil Testing Laboratory. *Iowa Agriculture*, 57: 1–31.

Hobbs, P.R., Hettel, G.P., Singh, Y., Harrington, L., and Fujisaka, S. (1990) *Diagnostic Survey of Farmers' Practices and Problems and Needs for Future Research: Rice-Wheat Cropping System in Tarai Areas of Nainital, Rampur and Pilibhit Districts in Uttar Pradesh*; Indian Council of Agricultural Research: New Delhi, India, 35–38.

Howard, P.J.A. (1933) Soil Protection and Soil Quality Assessment in the EC. *Science of the Total Environment*, 129: 219–239.

Islam, K.R. and Weil, P.R. (2000) Soil Quality Indictor Properties in Mid-Atlantic Soils as Influenced by Conservation Management. *Journal of Soil Water Conservation*, 55: 69–78.

Jackson, M.L. (1967a) Organic Matter Determinations for Soils. In *Soil Chemical Analysis*; Prentice Hall of India Private Limited: New Delhi, India, 205–225.

Jackson, M.L. (1967b) Nitrogen Determinations for Soils and Plant Tissue. In *Soil Chemical Analysis*; Prentice Hall of India Private Limited: New Delhi, India, 183–192.

Jenkinson, D.S. and Powlson, D.S. (1976) The Effects of Biocidal Treatments on Metabolism in Soil: V.A. Method for Measuring Soil Biomass. *Soil Biology and Biochemistry*, 8: 209–213.

Jenkinson, D.S. and Ladd, J.N. (1981) Microbial Biomass in Soil: Measurement and Turnover. In *Soil Biochemistry*; Paul, E.A. and Ladd, J.N., eds.; Marcel Dekker, Inc.: New York; Vol. 5, 415–457.

Karlen, D.L. and Stott, D.E. (1994) A Framework for Evaluating Physical and Chemical Indicators of Soil Quality. In *Defining Soil Quality for a Sustainable Environment*; Doran, J.W., Coleman, D.C., Bezdicek, D.F. and Stewart, B.A., eds.; Soil Science Society of America: Madison, Wisconsin, 53–72, SSSA Spec. Publ. No. 35.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., and Jordahl, J.L. (1994) Crop Residue Effects on Soil Quality Following 10-years of No-till Corn. *Soil Tillage Research*, 31: 149–167.

Karlen, D.L., Parkin, T.P., and Eash, N.S. (1996) Use of Soil Quality Indicators to Evaluate Conservation Reserve Program Sites in Iowa. In *Methods for Assessing Soil Quality*; Doran, J.W. and Jones, A.J., eds.; Soil Science Society of America: Madison, Wisconsin, 345–355.

Kennedy, A.C. and Papendick, R.I. (1995) Microbial Characteristics of Soil Quality. *Journal of Soil and Water Conservation*, 50: 243–248.

Kumar, A. and Tripathi, R.P. (1990) Effect of Continuous Use of Manures and Fertilizers on Physical Properties of Soil Under Paddy-Wheat-Cowpea Cropping System. *Crop Research*, 3: 7–13.

Lal, R. (1985) Tillage in Lowland Rice Based Cropping Systems. In *Soil Physics and Rice*; International Rice Research Institute: Los Banos, Philippines, 283–307.

Lal, S. and Mathur, B.S. (1989) Effect of Long-Term Fertilization Manuring and Liming of an Alfisol of on Maize, Wheat and Soil Properties. I. Maize and wheat. *Journal of Indian Society of Soil Science*, 37: 717–724.

Larson, W.F. and Pierce, F.J. (1991) Conservation and Enhancement of Soil Quality. In *Evaluation for Sustainable Land Management in the Developing World*; Proceedings of the 12 International Board for Soil Resource and Management: Bangkok, Thailand; Vol. 2.

Larson, W.E. and Pierce, F.J. (1994) The Dynamics of Soil Quality as a Measure of Sustainable Management. In *Defining Soil Quality for a Sustainable Environment*; Doran, J.W., Coleman, D.C., Bezdicek, D.F. and Stewart, B.A., eds.; Soil Science Society of America: Madison, Wisconsin, 37–51, SSSA Spec. Publ. No. 35.

Latif, M.A., Mehuys, G.R., Mackenzie, A.F., Alli, I., and Faris, M.A. (1992) Effects of Legumes on Soil Physical Quality in a Maize Crops. *Plant Soil*, 140: 15–23.

Lewandowski, A., Zumwinkle, M., and Fish, A. (1999) Assessing the Soil System: A Review of Soil Quality Literature. Minnesota Department of Agriculture, Energy and Sustainable Agriculture Program: St. Paul, Minnesota.

Lindsay, W.L. and Norvell, W.A. (1978) Development of a DTPA Soil Test for Zinc, Iron, Manganese and Copper. *Soil Science Society of America Journal*, 42: 421–428.

MacRae, R.J. and Mehuys, G.R. (1985) The Effect of Green Manuring on the Physical Properties of Temperate Area Soils. *Advances in Soil Science*, 3: 71–94.

Mahapatra, I.C., Singh, K.N., Pillai, K.G., and Bapat, S.R. (1985) Rice Soils and Their Management. *Indian Journal of Agronomy*, 30: 1–40.

Mandal, U.K., Singh, G., Victor, U.S., and Sharma, K.L. (2003) Green Manuring: Its Effect on Soil Properties and Crop Growth Under Rice-Wheat Cropping System. *European Journal of Agronomy*, 19: 225–237.

Min, D.H., Islam, K.R., Vough, L.R., and Weil, R.R. (2003) Dairy Manure Effects on Soil Quality Properties and Carbon Sequestration in Alfalfa-Orchardgrass Systems. *Commununications in Soil Science and Plant Analysis*, 34: 781–799.

Nambiar, K.K.M. and Abrol, I.P. (1989) Long-Term Fertilizer Experiments in India: An overview. *Fertilizer News*, 34: 11–20.

Olsen, S.R., Cole, C.U., Watanabe, F.S., and Deen, L.A. (1954) *Estimation of Available Phosphorus in Soil by Extracting with Sodium Bicarbonate*; U.S. Government Printing Office: Washington, DCUSDA Circ. 939.

Painuli, D.K., Woodhead, T., and Pagliai, M. (1988) Effective use of Energy and Water in Rice-Soil Puddling. *Soil Tillage Research*, 12: 149–161.

Palm, C.A., Swift, M.J., and Woomer, P.L. (1996) Soil Biological Dynamics in Slash-and-Burn Agriculture. *Agricultural Ecosystems and Environment*, 58: 61–74.

Quilchano, C. and Maranon, T. (2002) Dehydrogenase Activity in Mediterranean Forest Soils. *Biology and Fertility of Soils*, 35: 102–107.

Rhoades, J.D. (1982) Soluble Salts. In *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*, 2nd ed.; Page, A.L., Miller, R.H. and Keeney, D.R., eds.; American Society of Agronomy: Madison, Wisconsin; Agron. Monogr, 9, 167–178.

SPSS (1998) *SigmaPlot 5.0 Programming Guide*. Chicago, Illinois: SPSS.

Singh, N.T. (1994) Green Manures as Sources of Nutrients in Rice Production. In *Organic Matter and Rice*; Banta, S., ed.; International Rice Research Institute: Manila, Philippines, 217–228.

Singh, R.P., Das, S.K., Rao, U.M.B., and Reddy, M.N. (1990) *Towards Sustainable Dryland Agricultural Practices*; Central Research Institute for Dryland Agriculture: Hyderabad, India.

Subbaiah, B.V. and Asija, G.C. (1956) A Rapid Procedure for Determination of Available Nitrogen in Soils. *Current Science*, 25: 259–260.

Swarup, A. (1987) Effect of Pre-Submergence and Green Manuring (*Sesbania aculeata*) on Nutrition and Yield of Wetland Rice (*Oryxa sativa* L.) on a Sodic Soil. *Biology and Fertility of Soils*, 5: 203–208.

Tabatabai, M.A. (1982) Soil Enzymes. In *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties* 2nd ed.; Page, A.L., Miller, R.H. and Keeney, D.R., eds.; American Society of Agronomy: Madison, Wisconsin; Agron. Monogr, Vol. 9, 937–940.

van Bevel, C.H.M. (1949) Mean Weight Diameter of Soil Aggregates as a Statistical Index of Aggregation. *Soil Science Society of America Proceedings*, 14: 20–23.

Wander, M.M. and Bollero, G.A. (1999) Soil Quality Assessment of Tillage Impacts on Illinois. *Soil Science Society of America Journal*, 63: 961–971.

Yaduvanshi, N.P.S. (2003) Substitution of Inorganic Fertilizers by Organic Manures and the Effect on Soil Fertility in a Rice-Wheat Rotation on Reclaimed Sodic Soil in India. *Journal of Agricultural Science*, 140: 161–168.

Yoder, R.E. (1936) A Direct Method of Aggregate Analysis and Study of the Physical Nature of Erosion Losses. *Journal of American Society of Agronomy*, 28: 337–351.