Soil Quality under Different Land Uses in Kaligarang Watershed, Indonesia

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Abstract

For a small agricultural watershed in Java, Indonesia, land use specific soil quality is described. The objectives of this study were to determine statistically significant soil quality indicators using a minimum data set (MDS) and calculate soil quality indexes for different land units in a typical agricultural watershed. Field surveys were conducted to identify the biophysical conditions and to compile an inventory of land use. On the basis of ground slope, soil type, and land use, land units have been identified, which are assumed to represent typical soil quality conditions. Soil sampling for the determination of soil chemical and physical characteristics was based on these land units. Principal components' analysis (PCA) was used to identify the overall soil quality attributes for the area. Generally, the soil fertility status of the watershed is low, especially for land planted to annual food crops. Five statistically significant soil quality indicators (i.e. soil attributes) have been identified for the watershed, i.e. texture (silt), total N, water stable aggregates (WSA), soil organic carbon (SOC), and bulk density.

The study revealed that low soil quality is a major problem in the area. To address declining land productivity in the context of land degradation and sustainability of land use, land use systems and practices in the area should be examined in more detail. Locally appropriate soil fertility enhancement measures should be identified to build up overall soil quality – and hence fertility – in the area, leading to better and more sustainable land productivity under smallholder land use.

Introduction

Soil is a critically important component of the earth's biosphere, not only for the production of food and fiber but also for the maintenance of local, regional, and global environmental quality (Doran and Parkin, 1994). In Indonesia, about 20 million ha (33 percent) of arable land have been degraded into marginal land, due to inappropriate land use practices that have led to a loss of soil quality and, hence, land productivity. Because of its importance, in 1993, the US National Research Council recommended that protecting soil quality should be a fundamental goal of any national environmental program (Brejda *et al.*, 2000). The term soil quality has been defined by the Soil Science Society of America (SSSA) as "Soil quality is inherent attributes of soil that are inferred from soil characteristics or indirect observations (e.g. compactibility, erodibility, and fertility)" (Doran and Parkin, 1994). Larson and Pierce

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(1991) suggested a definition of soil quality as the "capacity of a soil to function within the ecosystem boundaries and interact positively with the environment external to that ecosystem". Several other similar definitions of soil quality have been proposed (Doran and Parkin, 1994; Diack and Stott, 2001). A more comprehensive definition of soil quality was proposed by Karlen *et al.* (1997) stating that "soil quality is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation".

Soil quality has become an important issue. Research on soil quality has notably increased within the last decade, but there is still a significant need to develop appropriate soil quality indexes. A soil quality index helps to assess the soil quality of a given site or ecosystem and enables comparisons between the conditions at the plot, field, or watershed levels under different land use and management practices.

The objectives of this study were to identify important soil quality indicators and develop soil quality indexes for different land uses and land management practices in a typical agricultural watershed in Java, Indonesia

Materials and Methods

Description of the Site

The study was conducted at Babon sub-catchment, Kaligarang Watershed, Java, Indonesia. The altitude of the area ranges between 400 and 550 m above sea level. The research sites were on two soil orders – Alfisols and Inceptisols – that were formed by Central Ungaran ashes and volcanic rocks and originated from the Pleistocene-Holocene (quaternary) age (MSEC, 2000). The soils are well-drained, very deep (>150 cm), dark reddish brown to very dark brown friable clays. The average topsoil bulk density is 1.17 g cm^{-3}.

The area has a humid climate with tropical rainforest vegetation. According to the Schmidth–Ferguson Classification, the study area falls into climate type B (Schmidth and Ferguson, 1951). The average rainfall of the two driest months is less than 60 mm, while the average rainfall of the nine wettest months is more than 100 mm. The dry months fall between July and August, while the wet months usually fall between October and June. The mean annual rainfall of the research site is 3,181 mm (12 years of available data).

The watershed has an area of 30.7 ha, of which 17.4 ha are terraced paddy rice fields in the valley bottom. Only the remaining 13.3 ha of sloping rainfed lands are included in the study. The watershed is subdivided into three catchments with distinct land uses, i.e. (i) Kalisidi Catchment (11.2 ha) is dominated by rambutan and mixed garden cultivation; (ii) Rambutan Catchment (1.1 ha) is dominated by rambutan cultivation and some bush, which is not used; (iii) Tegalan Catchment (1.0 ha) is cultivated for annual food crops of cassava, groundnut, and maize, and also has some grassland. To reduce soil erosion in the upland crop areas, the farmers constructed forward-sloping bench terraces. These terraces are irregularly shaped. For their annual food crops, especially maize and groundnut, most farmers apply only urea (50-120 kg ha^{-1}) and farmyard manure (cattle and buffalo dung at a rate of approximately 5 t ha^{-1}), but some farmers only apply manure. For cassava, most farmers do not use fertilizers at all. For the rambutan orchards, since 1997, the manager decided to reduce the level of management of the plantation due to rising insecurity of the land holding. Therefore, no fertilizers and other chemicals were applied, leading to a reduction of yields. Previously, urea, TSP, and KCl, were applied two times a year, usually at the beginning and the end of the rainy season. For each tree, 4 kg urea, 2.5 kg TSP, and 1.25 kg KCl used to be applied.

Field Survey and Identification of Land Units

A field survey was conducted to identify the biophysical conditions of the study area and develop an inventory of land management practices, rainfall pattern, and the natural land resources. On the basis of slope, soil type, and land use, land units were identified by overlaying existing base maps. In total, 11 distinct land units have been identified in the area, i.e. three for Tegalan, three for Rambutan, and five for Kalidisi. Table 1 shows the distribution of land units and their determinants.

Table 1. Distribution of land units and their determinants

Catchment	Land unit	Total area	Slope (score*), % slope)	Description Soil type with subgroup *)	Land use
Tegalan	1	0.51	V (30-45)	Inceptic Hapludalfs	Cultivated land. Crops: cassava, maize, and groundnut.
	2	0.34	VI (45-65)	Inceptic Hapludalfs	Grasses
	3	0.13	VI (45-65)	Vertic Hapludalfs	Cultivated land. Crops: cassava, maize, and groundnut.
Rambutan	4	0.12	VI (45-65)	Vertic Paleudalfs	Bushes
	5	0.24	VI (45-65)	Typic Hapludalfs	Rambutan orchard
	6	0.76	V (30-45)	Typic Hapludalfs	Rambutan orchard
Kalidisi	7	2.69	VI (45-65)	Humic Eutrudepts	Rambutan orchard
	8	1.31	V (30-45)	Humic Eutrudepts	Rambutan orchard
	9	2.05	VI (45-65)	Ruptic-alfic Eutrudepts	Rambutan orchard
	10	1.21	V (30-45)	Ruptic-alfic Eutrudepts	Rambutan orchard
	11	3.97	V (30-45)	Humic Eutrudepts	Mixed gardens: coffee, mahogany, bamboo, banana, hibiscus, cloves, mangoes, rambutan, bushes, and grasses.

*) USDA classification system (Soil Survey Staff, 1996)

Soil Sampling and Determination of the Soil Properties

Based on the identified land units, 11 soil profiles were made. Each profile was selected on the basis of five auger holes. For each profile, composite topsoil samples were taken, air-dried, sieved through a 2 mm screen and analyzed for physical and chemical properties. For the analysis, the methods described by Westerman (1990) were used. The physical properties determined were particle-size distribution (pipette method), saturated hydraulic conductivity (double Haube permeameter), aggregate stability (dry and wet sieving method), and bulk density (core method); the chemical characteristics determined were pH in H_2O (1: 2.5 soil/water), soil organic carbon (SOC) (Walkley-Black method), total N, C/N ratio, available-P (Bray-I method), exchangeable cations K, Ca, Mg, and Na (ammonium acetate extraction at pH 7), CEC (ammonium acetate extraction at pH 7), and base saturation. From the particle-size distribution data and the soil organic matter content, the soil erodibility index (*K*-index) was calculated for each land unit using the formula developed by Kirkby and Morgan (1980).

Statistical Analysis

We used the technique proposed by Wander and Bollero (1999) and Andrews *et al.* (2002) to construct a soil quality index (SQI). The three main steps of this technique are to (i) select a minimum data set (MDS) of indicators that best represent the soil functions; (ii) score the MDS indicators based on their performance of soil functions; and (iii) integrate the indicator scores into a comparative index of soil quality (Andrews *et al.*, 2002).

To select a representative MDS for the three catchments, a principal components' analysis (PCA) of selected soil attributes was made (Doran and Parkin, 1994). Principal components (PCs) for a data set are defined as linear combinations of the variables that account for maximum variance. It was assumed that PCs receiving high values best represent system attributes (Andrews *et al.*, 2002). Therefore only the PCs with eigenvalues ≥ 1 were examined. Eigenvalues are the amount of variance explained by each factor, while communalities estimate the portion of variance in each soil attribute explained by the factors (Brejda *et al.*, 2000). Factor analysis was used to group the initially identified 18 soil attributes into statistical factors based on their correlation structure. The correlation structure of soil attributes was analyzed using bivariate correlation. Principal components' analysis was used for the factor extraction using the factor-data reduction procedure in the SPSS 10.0 (SPSS Inc.) Software.

In this PCA, each variable received a weight or factor loading that represents its contribution to the PC. As suggested by Andrews *et al.* (2002), we retained only the highly weighted variables from each PC. Highly weighted variables were defined as those within 10 percent of the highest factor loading. When more than one variable was retained within a PC, we observed their significance correlation. If these weighted variables were not correlated (i.e. $r < .60$), then each was considered important and was retained in the MDS. If the variables were significantly correlated, one of the variables could be considered redundant and, therefore, eliminated from the MDS. Among the significantly correlated variables within a PC, the variable with the highest sum of correlation coefficients was chosen for the MDS (Andrews *et al.*, 2002).

The second step was to score the MDS indicators and the conversion of the selected soil data into a 0 to 1 scale. We used two equations proposed by Diack and Stott (2001). These equations are:

$$y = (x\text{-}s)/(1.1t\text{-}s) \qquad \text{for “more is better”} \qquad [1]$$

and,

$$y = 1\text{-}\{(x\text{-}s)/(1.1t\text{-}s)\} \qquad \text{for “less is better”,} \qquad [2]$$

where, y is the score of the soil data; x is the value of the soil property converted into a 0 to 1 scale value; s is the lowest possible value of the soil property, we have decided that s = 0; and t is the highest value for that soil property.

The third step was to calculate the soil quality index (SQI) using the formula described by Andrews *et al.* (2002):

$$\mathrm{SQI} = \underset{\mathrm{I}=1}{\overset{n}{\mathrm{S}}}\ \mathrm{Wi \times Si} \qquad [3]$$

where W is the PC weighting factor and S is the indicator score (named *y* in Eq. 2). The weighting factor (i.e. the weight of the PC) is determined by the percent of variation in the data set explained by the PC that contributes the indicator variable (i.e. the soil attribute), divided by the total percentage of variation explained by all PCs' eigenvectors >1.

We also compared the 11 land unit means using one-way ANOVA. Treatment means' separations were interpreted from the LSD results.

Results and Discussion

Soil Properties

The soil physical and chemical properties of the different land units in the study area are shown in Table 2. To assess the levels of the chemical properties, the scales provided by Landon (1991) and Black (1965a and 1965b) were used. The soils of the watershed can generally be considered to be of low fertility. Soil pH is rated low; soil organic carbon very low; total-N low; available-P slightly low to low; exchangeable K slightly low; the levels of exchangeable Ca medium; exchangeable Mg high, and the CEC medium.

Matrix Correlation and Soil Quality Index

Significant ($p = 0.05$) to highly significant ($p = 0.01$) correlations were shown by 49 (about 32 percent) out of 153 soil attribute pairs (Table 3). These can be used for grouping soil attributes into factors based on their correlation pattern.

Table 3 shows highly significant correlations between silt content and sand content, pH, exchangeable Ca, Mg, total exchangeable bases, base saturation, and the *K*-index. It also shows that total N is highly correlated with sand content, available P, and CEC. These observations can be used to refine the factors of the PCs (see Table 4).

The principal components' analysis (PCA) identified five soil attributes contained in six PCs with an overall cumulative variance of about 88 percent. The order of significance of these soil characteristics was determined by the magnitude of their eigenvalues. These five soil attributes constitute the soil quality indicators for the MDS, which can be used to construct soil quality indexes (SQI) for the different land units. The five soil quality indicators that make up the MDS for the study area are silt content (representing texture), total N, WSA, SOC, and bulk density. The indicators and their factor loadings within their respective PCs are shown in Table 4.

The computed factor weightings were 0.38 for PC1, 0.22 for PC2, 0.14 for PC3, 0.11 for PC4, 0.09 for PC5, and 0.06 for PC6. After weighting, we scored the attributes of each principal component using Eq. [1] and [2] (Diack and Stott, 2001). We used Eq. [1] i.e. the "more is better" scoring function, for total N, WSA, and SOC, because of their positive effect on soil fertility, water partitioning, and structural stability (Andrews *et al.*, 2002). We used Eq. [2], i.e.

Table 2. Soil properties of the different land units in the study area.

	Land unit										
Parameters	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Sand (%)	14 ± 1.0 bc*	21 ± 2.5 d	17 ± 3.0 cd	10 ± 1.7 ab	11 ± 2.5 ab	11 ± 2.7 ab	18 ± 1.5 cd	10 ± 1.5 ab	9 ± 1.5 a	19 ± 3.1 d	17 ± 3.5 cd
Silt (%)	39 ± 4.5 e	33 ± 2.7 d	39 ± 3.6 e	6 ± 2.1 a	3 ± 0.6 a	16 ± 3.5 b	28 ± 2.1 d	20 ± 2.0 bc	21 ± 2.7 bc	22 ± 3.1 c	30 ± 2.7 d
Clay (%)	47 ± 4.2 ab	46 ± 1.2 ab	44 ± 5.3 a	84 ± 2.3 e	86 ± 2.7 e	73 ± 5.6 d	54 ± 3.6 c	70 ± 1.5 d	70 ± 4.0 d	59 ± 5.3 c	53 ± 1.2 bc
pH (in H_2O)	5.4 ± 0.2 def	5.5 ± 0.1 ef	5.7 ± 0.2 f	5.2 ± 0.2 bcd	5.0 ± 0.1 abc	4.9 ± 0.2 ab	5.2 ± 0.2 cde	4.7 ± 0.3 a	5.1 ± 0.1 bc	5.2 ± 0.1 cde	5.1 ± 0.2 bcd
SOC (%)	1.35 ± 0.13 b	1.54 ± 0.14 c	1.27 ± 0.03 b	1.78 ± 0.11 d	1.01 ± 0.09 a	1.82 ± 0.15 d	2.28 ± 0.06 f	1.99 ± 0.12 e	0.99 ± 0.09 a	2.28 ± 0.05 f	1.37 ± 0.03 b
N (%)	0.15 ± 0.03 abc	0.23 ± 0.03 de	0.16 ± 0.01 bc	0.11 ± 0.03 a	0.16 ± 0.03 bc	0.17 ± 0.02 bc	0.14 ± 0.02 ab	0.17 ± 0.02 bc	0.18 ± 0.02 bc	0.27 ± 0.02 e	0.20 ± 0.04 cd
C/N	9.0 ± 2.4 bcd	6.7 ± 0.8 ab	7.9 ± 0.6 abc	16.4 ± 3.8 e	6.3 ± 1.3 ab	10.7 ± 1.1 cd	16.3 ± 2.9 e	11.7 ± 1.6 d	5.5 ± 0.1 a	8.4 ± 0.8 abc	6.9 ± 0.7 ab
Available P (cmol kg^{-1})	9.7 ± 2.1 ab	20.3 ± 2.1 de	15.3 ± 3.8 bcd	8.0 ± 2.0 a	13.0 ± 2.7 abc	17.0 ± 2.0 cd	12.3 ± 2.1 abc	17.3 ± 3.8 cd	16.3 ± 3.8 cd	24.7 ± 4.5 e	18.0 ± 4.6 cd
Exch. Ca (cmol kg^{-1})	12.6 ± 0.9 ef	8.4 ± 0.7 abc	10.1 ± 0.4 bcd	6.2 ± 0.2 a	6.6 ± 0.8 a	7.9 ± 0.4 ab	13.4 ± 1.6 f	6.7 ± 1.0 a	10.7 ± 1.9 cde	7.8 ± 1.2 ab	11.2 ± 3.3 def
Exch. Mg (cmol kg^{-1})	2.4 ± 0.2 e	2.1 ± 0.2 e	2.1 ± 0.2 e	1.1 ± 0.1 bc	1.1 ± 0.4 bc	1.1 ± 0.4 bc	1.5 ± 0.1 d	0.4 ± 0.1 a	1.2 ± 0.2 cd	0.8 ± 0.2 b	1.5 ± 0.2d
Exch. K (cmol kg^{-1})	0.28 ± 0.01 b	0.28 ± 0.03 b	0.31 ± 0.02 bc	0.13 ± 0.03 a	0.18 ± 0.02 a	0.42 ± 0.05 de	0.35 ± 0.03 cd	0.25 ± 0.04 b	0.48 ± 0.09 e	0.28 ± 0.02 b	0.59 ± 0.04 f
Total exch. cations (cmol kg^{-1})	15.5 ± 0.9 e	10.9 ± 1.0 bc	12.7 ± 0.4 cd	7.9 ± 0.4 a	8.2 ± 0.7 ab	9.6 ± 0.8 ab	15.6 ± 1.6 e	7.5 ± 1.0 a	12.6 ± 2.17 cd	9.1 ± 1.0 ab	13.7 ± 3.3 de
CEC (cmol kg^{-1})	18.4 ± 1.0 abc	23.6 ± 3.4 de	20.9 ± 0.4 bcde	15.5 ± 0.4 a	19.0 ± 1.9 abcd	22.4 ± 2.8 cde	19.6 ± 2.4 abcd	17.0 ± 2.3 ab	21.7 ± 2.5 cde	24.8 ± 4.5 e	25.3 ± 2.3 e
Base saturation, BS (%)	84.4 ± 5.7 e	46.3 ± 3.7 abc	60.8 ± 1.4 d	51.1 ± 1.3 bcd	43.4 ± 2.5 ab	43.0 ± 5.5 ab	79.7 ± 9.2 e	43.9 ± 3.7 ab	58.9 ± 16.5cd	37.2 ± 6.11 a	53.7 ± 8.0 bcd
Bulk density (g cm^{-3})	1.14 ± 0.02 a	1.16 ± 0.04 ab	1.14 ± 0.03 a	1.13 ± 0.03 a	1.12 ± 0.02 a	1.10 ± 0.11 a	1.20 ± 0.05 ab	1.15 ± 0.05 a	1.26 ± 0.08 b	1.18 ± 0.05 ab	1.10 ± 0.06 a
WSA (%)	84.5 ± 8.3 b	64.1 ± 7.5 a	56.5 ± 26.2 a	88.8 ± 2.9 b	84.9 ± 2.94 b	59.4 ± 2.5 a	83.0 ± 15.2 b	58.4 ± 1.7 a	83.8 ± 11.8 b	85.4 ± 2.4 b	84.2 ± 5.3 b
Hydraulic conductivity (cm h^{-1})	1.89 ± 0.11 cde	1.98 ± 0.57 de	1.53 ± 0.17 bcd	0.97 ± 0.30 ab	1.62 ± 0.37 bcd	23.5 ± 0.31 e	1.38 ± 0.57 bcd	1.17 ± 0.36 b	0.54 ± 0.10 a	1.26 ± 0.41 bc	1.53 ± 0.14 bcd
K-index	0.21 ± 0.05 ef	0.18 ± 0.04 de	0.26 ± 0.04 f	0.09 ± 0.03 abc	0.09 ± 0.04 abc	0.08 ± 0.05 a	0.13 ± 0.05 abcd	0.09 ± 0.04 abc	0.15 ± 0.02 bcde	0.16 ± 0.01 cde	0.09 ± 0.02 ab

Notes: SOC = soil organic carbon; CEC = cation exchange capacity; WSA = water-stable aggregates

* Values within each row, followed by the same letter, are not significantly different (Duncan's multiple range test at $P = 0.05$)

‹ Significance of ANOVA comparisons between land units

Table 3. Pair-wise correlations between soil characteristics (attributes) in the study area [1]

Soil attributes	Sand	Silt	Clay	pH H_2O	SOC	Total N	C/N ratio	Available P	Exch. Ca	Exch. Mg	Exch. K	Total exch. bases	CEC	BS	Bulk density	WSA	Hydraulic conductivity
Silt	0.584(**)																
Clay	-0.764(**)	-0.970(**)															
pH H_2O	0.556(**)	0.603(**)	-0.646(**)														
SOC	0.227	-0.029	-0.045	-0.161													
Total N	0.454(**)	0.204	-0.298	0.054	0.159												
C/N ratio	-0.137	-0.194	0.195	-0.148	0.653(**)	-0.601(**)											
Available P	0.284	0.168	-0.219	-0.060	0.207	0.699(**)	-0.361(*)										
Exch. Ca	0.238	0.635(**)	-0.576(**)	0.321	-0.079	-0.017	-0.059	-0.145									
Exch. Mg	0.452(**)	0.678(**)	-0.674(**)	0.757(**)	-0.389(*)	-0.113	-0.204	-0.245	0.570(**)								
Exch. K	0.168	0.352(*)	-0.330	-0.092	-0.179	0.191	-0.321	0.293	0.497(**)	0.125							
Total exch. bases	0.297	0.678(**)	-0.628(**)	0.426(*)	-0.148	-0.049	-0.085	-0.181	0.986(**)	0.691(**)	0.483(**)						
CEC	0.493(**)	0.293	-0.381(*)	0.124	-0.057	0.709(**)	-0.546(**)	0.537(**)	0.255	0.104	0.507(**)	0.249					
BS	0.053	0.509(**)	-0.421(*)	0.375(*)	-0.077	-0.424(*)	0.238	-0.486(**)	0.816(**)	0.629(**)	0.162	0.834(**)	-0.310				
Bulk density	-0.035	0.076	-0.050	0.098	-0.026	0.177	-0.132	0.115	0.226	-0.062	0.089	0.175	0.113	0.136			
WSA	-0.154	-0.254	0.248	-0.070	-0.052	-0.011	0.031	-0.183	0.249	-0.010	-0.052	0.222	0.015	0.226	0.083		
Hydraulic conductivity	0.187	0.242	-0.249	0.124	0.052	-0.006	0.019	0.196	-0.013	0.305	0.041	0.046	0.085	0.012	-0.423(*)	-0.327	
***K*-index**	0.410(*)	0.695(**)	-0.675(**)	0.761(**)	-0.247	0.076	-0.231	0.035	0.343	0.633(**)	-0.081	0.405(*)	0.093	0.375(*)	0.248	-0.241	0.102

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[1] Significance levels: (*) p = 0.05; (**) p = 0.01

the "less is better" scoring function, for silt content and bulk density, because of the significant influences of silt content on soil erodibility and of bulk density on the porosity of soils (Lal, 1988).

Table 4. Component matrix for the first 6 principal components

PCs‹	PC1	PC2	PC3	PC4	PC5	PC6	
Eigenvalue:	6.02	3.46	2.15	1.73	1.46	1.02	
Percent of variance:	33.42	19.21	11.97	9.59	8.10	5.66	
Cumulative percent:	33.42	52.62	64.59	74.18	82.28	87.94	Communalities
Eigenvectors:Œ							
Sand (%)	0.64	0.38	-0.33	0.22	0.15	0.28	0.81
Silt (%)	0.91§	0.06	-0.17	0.10	-0.01	-0.17	0.91
Clay (%)	-0.92	-0.16	0.24	-0.15	-0.04	0.05	0.95
pH H_2O	0.73	-0.10	-0.33	-0.28	0.31	0.20	0.85
SOC (%)	-0.18	0.09	-0.34	0.86	0.27	0.04	0.97
Total N (%)	0.20	0.86	0.14	0.08	0.20	0.19	0.88
C/N ratio	-0.30	-0.57	-0.37	0.61	0.12	-0.04	0.93
Available P (cmol kg^{-1})	0.07	0.84	-0.02	0.18	0.02	-0.13	0.76
Ca (cmol kg^{-1})	0.77	-0.30	0.43	0.29	-0.09	-0.03	0.96
Mg (cmol kg^{-1})	0.83	-0.29	-0.15	-0.28	-0.13	0.19	0.92
K (cmol kg^{-1})	0.40	0.27	0.50	0.23	-0.47	-0.30	0.86
TEB (cmol kg^{-1})	0.83	-0.32	0.35	0.21	-0.12	0.02	0.98
CEC (cmol kg^{-1})	0.40	0.73	0.29	0.08	-0.11	0.18	0.83
BS (%)	0.61	-0.72	0.16	0.17	-0.02	-0.06	0.95
Bulk density (g cm^{-3})	0.15	0.05	0.44	-0.02	0.66	-0.42	0.83
WSA (%)	-0.07	-0.26	0.58	0.11	0.15	0.67	0.89
Hydraulic conductivity (cm h^{-1})	0.21	0.12	-0.54	0.04	-0.60	0.03	0.71
K-index	0.72	-0.05	-0.28	-0.35	0.35	-0.15	0.87

‹ PC, principal component

ŒSOC, soil organic carbon; TEB, total exchangeable bases; CEC, cation exchange capacity; BS, base saturation; WSA, water stable aggregates *K*-index, soil erodibility index

§ Underlined factor loadings correspond to the indicators included in the MDS

Then, the soil quality indexes (SQI) were determined for all land units in the study area using the formula proposed by Andrews *et al.* (2002) [Eq. 3]. The soil quality indexes of all land units and their significant differences are shown in Table 5. The lowest SQI (0.37) was found on Land Unit 3, which is characterized by Vertic Hapludalfs and cultivation of annual rainfed crops (i.e. cassava, maize, and groundnut). The highest SQI (0.70) was found on Land Unit 5, which is characterized by Typic Hapludalfs and perennial crops (i.e. rambutan orchards). Both land units are on very steep land (slope class VI, 45-65 percent).

Table 5. Soil quality index of each land unit

Land unit	SQI
1	0.42 ± 0.05 ab
2	0.49 ± 0.04 bc
3	0.37 ± 0.07 a
4	0.68 ± 0.04 e
5	0.70 ± 0.02 e
6	0.59 ± 0.03 d
7	0.53 ± 0.06 cd
8	0.56 ± 0.03 cd
9	0.56 ± 0.04 cd
10	0.67 ± 0.01 e
11	0.50 ± 0.06 c

Note: SQI = soil quality index
‹ Significance of ANOVA comparisons between land units.

Conclusions

Five significant soil attributes (indicators) have been identified, which reliably explain soil quality in the study area, i.e. texture (percentage silt), total N, WSA, SOC, and bulk density. Overall, soil quality in the study area can be described as low to medium. The indicator with the highest weight was texture (expressed in terms of silt content). This soil attribute cannot be changed by land management practices, and is therefore considered inherent.

However, the overall soil quality can undoubtedly be improved considerably by enhancement of the other identified soil attributes through better land management practices and the introduction of more appropriate cropping systems.

An example for Land Unit 3 in Tegalan Catchment would be to replace the low-value annual food crops with high-value crops, such as fruits (e.g. rambutan, longan, mangoes) or with grass cultivation for cattle and buffalo grazing. Also, soil fertility conservation needs should receive more attention, such as the application of organic matter and more appropriate fertilizer usage.

To address declining land productivity in the context of land degradation and sustainability of land use, land use systems and practices in the area should be examined in more detail. Locally appropriate soil fertility enhancement measures should be identified to build up overall soil quality – and hence fertility – in the area. The study clearly confirms the general wisdom that in tropical steeplands, which are subjected to high risks of soil degradation – especially soil erosion – minimum soil disturbance will contribute significantly to the maintenance of soil quality, and hence soil productivity and the sustainability of land use.

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