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Relationship of soil characteristics to vegetation successions on a sequence of degraded and rehabilitated soils in Honduras

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Abstract

Land degradation and rehabilitation on hillsides are some of the most urgent natural resources management challenges in tropical and subtropical agriculture. Shifting cultivation is widespread in developing countries and after losing soil fertility the land is abandoned and a succession of different natural vegetation stages can be observed on the degraded soil. These successions can be used as autochthonous indicators of the degree of soil degradation as well as its recovery stage in the rehabilitation process. This study was carried out in the small La Lima watershed in Central Honduras on abandoned degraded hillside soils belonging to the Entisols order. Vegetation stages were classified by farmers and basic physical and chemical soil parameters were measured. Factor analysis of the data enabled the identification of three soil fertility indices, an Index of Soil Acidity and Aluminium Toxicity, an Index of Soil Protection and Macronutrient Availability, and an Index of Organic Reserve and Nutrient Retention, which along with other soil characteristics changed significantly with vegetation stages. Cause–effect relations between the fertility indices and other soil parameters were established and tested. Cluster analysis was used to group study plots by soil characteristics with similar vegetation associations, and the farmers' classification of vegetation stages were shown to be reasonable autochthonous indicators of soil degradation and rehabilitation. It was concluded that factors influencing organic matter content, nutrient supply, soil vegetation cover and soil compaction are critical for soil degradation and they must be managed appropriately for soil rehabilitation.

Keywords: Soil degradation and rehabilitation; Vegetation successions; Soil fertility indices; Honduras

1. Introduction

One of the major global environmental concerns is land degradation, as soil is a finite natural resource. Daily (1995) estimates that 43% of terrestrial vegetated land on earth is limited in its capacity to supply benefits to humans largely because of direct negative impacts of inappropriate land-use. This represents an estimated reduction of 10% in terms of potential direct economic benefits in the agricultural, forestry, industrial and medicinal products sectors (Daily, 1995). Also, land degradation in combination with population growth directly affects the living conditions of numerous rural households in developing countries.

The dominant types of soil degradation are discussed in the Global Assessment of Soil Degradation study (UNEP/ISRIC, 1991). The causative factors of soil degradation are well known: inappropriate con-

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version of native forests to agricultural land or its use for extensive livestock activities; forest over-exploitation; inappropriate agricultural production technologies; overgrazing; and industrial activities being the common factors. Hillside regions represent extremely fragile ecosystems. In Central America alone, hillsides account for 80% of the total land area, where up to 60% of the basic crops are produced for local consumption (CIAT/IICA/CATIE/CIMMYT, 1991). In Honduras, one of the poorest countries in Latin America, about 83% of the country is hillside, of which 75% has inclinations of greater than 25% (SECPLAN, 1989). Small-scale farmers produce mostly basic grains and coffee (*Coffea arabica* L.) on the hillsides, commonly through shifting cultivation with low fertilizer and pesticide inputs. These hillside-cultivated lands gradually decline in productivity and are eventually abandoned by farmers, thereby forest land is threatened as it is converted into new agricultural land. Currently, increased population pressure and increased demand for agricultural products are leading to an intensification of land-use with reduced fallow periods. In Honduras, only soil erosion has received some attention as it is known to threaten productivity of agricultural production and as well as the economic welfare of rural people (Valdés, 1994; Centro Internacional de Estudios sobre la Mujer/Vecinos Mundiales, 1995). Even less attention has been paid to the natural rehabilitation processes and vegetation succession of abandoned hillside plots, and there is no published literature on this subject. Understanding the dynamics of natural rehabilitation would provide a context for formulating recommendations for sustainable land-use and sustainable management practices. One important, but often ignored source of information is from the indigenous people who have a store of practical resource management knowledge. It is recognized that farmers perceive changes in soil fertility, and use the natural vegetation composition as an information source about soil and climate conditions to make decisions about land-use. As it is well known that certain soil characteristics, for example, acidity, aluminum and calcium contents, can determine species composition to some extent (Porta et al., 1994), farmers may well be correct in having an indirect knowledge about soil fertility on the basis of assessing plant composition and distribution in a region.

This study describes the soil degradation and rehabilitation vegetation succession stages as perceived by local farmers in a small but representative watershed for the central hillside region of Honduras. On the basis of their classification system, the principal physical and chemical soil characteristics were measured and statistically analyzed to determine correlations and establish indices of soil fertility. Cause and effect relations among different parameters were modeled and tested, using cluster analysis to compare the fertility characteristics of various plots as assessed by local farmers with their actual physical and chemical characteristics. This information was used to test our hypothesis that there is a substantive relationship between local knowledge of fertility based on vegetation-types as indicators for soil degradation and rehabilitation and the actual physical and chemical characteristics of soils.

2. Methods

2.1. Study location

This study was conducted in the small watershed of La Lima, which is part of the municipality of Tatumbla, 17 km southeast of Tegucigalpa, the capital of Honduras. The watershed area comprises about 9.5 km^2 and the altitude varies between 1200–1688 m above sea level. The site has a subtropical climate and two predominant seasons. The rainy season lasts from May–October, and almost no rain falls during the dry season from November–April. The mean annual precipitation is approximately 1180 mm, ranging from a low of 885 mm to a high of 1560 mm. The average temperature is 21.4°C, although it can be several degrees cooler at higher elevations.

The La Lima watershed is the source of two small creeks and it has steep, well-drained sandy loam slopes that end in a plain at its lower part, where soils are loamy and deep with reduced drainage properties. These soils belong to the Ojojona series in the order of Entisols. The natural vegetation is pine (*Pinus maximinoi* H.E. Moore and *Pinus oocarpa* Schiede) up to approximately 1600 m above sea level, after which a cloud forest of broadleaf species such as oaks (e.g. *Quercus penduncularis* Née and other species) prevail. In the cloud forest epiphytes are abundant, and include many species of mosses (Bryophyta), lichens (Lichenes), bromeliads (Family Bromeliaceae) and orchids (Family Orchidaceae).

The community of La Lima is the principal human settlement in the watershed, comprising 119 families in total, 62 of which are more centrally located, with the balance being more widely dispersed. The principal agricultural activity is the production of basic grains (*Zea mays* L. and *Phaseolus vulgaris* L.) for home consumption as well as some horticultural crop production for the Tegucigalpa market. Detailed information about study site selection and land-use dynamics in the area have been reported previously (Ardon et al., 1996; Kammerbauer and Ardon, 1996); the land being communally owned, but its use by individuals is private, although without formal title.

2.2. Workshops and interviews

As this research had a substantial participatory component, workshops were organized to allow interaction with the indigenous farmers and elicit their knowledge. The first workshop, which included men, women and children, was organized to discuss problems related to natural resources management in the community. A puppet theatre was performed to interest and motivate community members to participate actively in the subsequent discussions about land management, soil degradation and other related themes. After describing the research intentions, those farmers with an active interest in the study were identified. This was followed by a series of field trips in which their plots were visited and land-use practices and history were recorded. In a second workshop, the local farmers presented their perceptions and concepts about soil degradation processes and their use of vegetation succession stages as indicators of degraded soil and rehabilitation processes.

2.3. Selection of study plots

For site selection, the main factors looked for were a range in the types of plants growing on the plots, relative to the farmer's perceptions of degradation or rehabilitation. In addition, three important additional criteria were adopted: (a) that the plots had been abandoned for at least 2 years, (b) that the plots had slope inclinations of at least 10%, and (c) that the plots consisted of similar soil-type characteristics. Six random plots (replicates) of each of the identified five succession stages were selected, totalling 30 study plots with an average plot size of about 0.4 ha each. Their use history was recorded, a composite soil sample taken and in situ parameters measured for each plot.

Standard methods for soil sampling (Fundación Hondureña de Investigación Agrícola, 1995) and analysis (Schofield and Taylor, 1955; Jackson, 1958; Adams and Evans, 1962; Mehlich, 1973; Bremmer and Mulvaney, 1982; Escuela Agrícola Panamericana, 1991) were used, with approximately 12 sub-samples taken from the surface to a depth of 30 cm, these being used to prepare a composite sample of 0.5 kg. These composite soil samples were analyzed for: total nitrogen (Kjeldahl extraction), available phosphorus, potassium, calcium, magnesium, pH in water, pH in Adams and Evans buffer, exchangeable aluminium, organic matter, texture, and pore space by the Soil Laboratory of the Pan-American Agricultural School (Zamorano). From these data, cation exchange capacity, aluminum saturation, and lime requirement to elevate soil pH to 6.0 were determined. In situ, effective soil depth, bulk density, slope inclination and height above sea level were determined. Soil penetration resistance was measured with a cone penetrometer in two transects with 16 measurements in each plot under the same weather conditions (i.e. water regime). Differences in soil texture were also analyzed. To determine the degree of vegetation cover, the punctual intersection method described by Matteucci and Colma (1982) was used.

2.4. Statistical procedures

Multivariate analysis was used to consider all the variables simultaneously, each one being considered equally important at the start of analysis. First, principal component factor analysis (Pla, 1986; Norušis, 1993) was carried out to determine whether any correlation among the measured variables existed using the minimum possible number of factors to describe them. A conceptual name was given to each factor which comprised a description of the group of variables included. Based on the components identified as being significant by factor analysis, three composite indices were devised, (a) Soil Acidity and Aluminium Toxicity Index (SAATI), (b) Soil Protection and Macronutrient Availability Index (SPMAI), and (c) an Organic Reserve and Nutrient Retention Index (ORNRI). The objective of constructing these indices was to summarize the contribution of the 12 measured soil physico-chemical parameters to three and simplify the subsequent multivariate analysis. The original measured values of each variable were classified as high, medium or low relative to their absolute range, and each category was assigned a numeric value from 1–3, with the exception of pH, which was subdivided from 1–4. This approach has the benefit of all increases in values relating positively to improved soil fertility. The variables were also given a discretional weight depending on the intercorrelations between variables and their relative importance as limiting factors for plant growth. After the indices were calculated for each plot, a non-orthogonal variance analysis (Norušis, 1994) was carried out, considering as responses (dependent variables), the three composite indices and other key variables not included in the indices (soil penetration resistance and bulk density). With the independent variables defined by technical criteria, variance analysis provided a means by which to assess how much of the variability each independent variables accounted for the dependent variables. The Tukey test was then used for multiple mean comparisons to detect whether there were significant differences among the vegetation succession stages, considering only the soil fertility indices and the other variables which were shown to be statistically significant in the variance analysis. The last step was the use of cluster analysis (Crisci and López, 1983; Norušis, 1993) to identify plots having similar characteristics and to determine if these were related to the vegetation cover classification scheme devised by the La Lima farmers. In this analysis, soil fertility indices were included as well as four other relevant soil parameters, to determine if vegetation-type can indicate the state of soil degradation or rehabilitation.

3. Results and discussion

3.1. Degradation and natural rehabilitation stages

In the participatory discussions, farmers systematically classified abandoned agricultural land as having five vegetation-types that indicated to them different soil degradation stages. These were two different grass associations *jaraguá* grass and *grama* grass, a grass–shrub association *montecillo*, a shrub association *guamil* and finally a secondary mixed forest. The *jaraguá* grass plots, principally composed of *Hyparrhenia rufa* (Ness) Stapf, are considered highly degraded soils without any potential to reestablish agricultural crops. This grass establishes itself spontaneously after the abandonment of agricultural plots due to declining agricultural productivity. Plots with *grama* grass, a combination of two principal gramineas *Paspalum lividum* Trin. and *Sporobulus indicus* (L.) R. Br., are also considered degraded land, with some degree of soil fertility remaining, usually only used as pasture. In some cases this successional stage can be followed by a regeneration process to the stages of *montecillo* and *guamil*. The *montecillo* plots are composed of grasses and slow growing shrubs with low forage quality. These areas have usually been abandoned for at least 5 years, converting to *guamiles* in the medium term. The *guamil* plots, according to local knowledge, are considered to have recovered their fertility and are once again ready for agricultural production. In these plots, plant species similar to the early stages of a secondary forest are found, with small pines, oaks, a high shrub density, as well as spiny and climbing plants. The climax stage of the rehabilitation process is when a denser secondary forest, with mature pine, broadleaf species and shrubs, develops. Plots in this stage of regeneration were used as a reference by which to compare the more degraded soils.

3.2. Soil characteristics in the different vegetation succession stages

Table 1 shows the physical and chemical characteristics of the soils under the different succession stages of vegetation after abandonment of agricultural production. Average organic matter increased from the lowest level in the two grass associations through to *montecillo* and *guamil*, with the highest value in forest soil. While total nitrogen showed little change, consequently the C/N ratio behaved in a similar manner to organic matter. Soil organic matter is considered the single most important indicator of soil quality and a major component in the assessment of soil quality (Sikora et al., 1996). Soil acidity in all succession

Table 1
Means ($N = 6$) and standard deviations (SD) of physical and chemical soil parameters in the different vegetation succession stages of degraded and rehabilitated soils in the small La Lima watershed in the central region of Honduras

Soil parameter	Vegetation succession stages									
	Jaraguá grass		*Grama* grass		*Montecillo*		*Guamil*		Forest	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Chemical										
Organic matter (g kg^{-1})	28.7	8.7	29.8	10.3	33.6	17.4	36.6	14.5	46.4	18.6
Total nitrogen (g kg^{-1})	1.3	0.3	1.5	0.5	1.5	0.9	1.5	0.4	1.8	0.8
C/N relation	13	2	12	1	13	3	14	3	16	7
pH in water solution	5.34	0.53	5.12	0.33	5.29	0.28	5.29	0.43	5.09	0.44
Available phosphorus (mg kg^{-1})	12.8	13.2	10.4	19.1	13.3	11.0	5.1	4.3	10.2	17.2
Available potassium (mg kg^{-1})	180	36.4	164	55.2	193	73.7	244	189.5	246	149.2
Calcium (mg kg^{-1})	1951	752	1563	393	2141	377	1610	513	1975	825
Magnesium (mg kg^{-1})	378.3	139.9	240.8	89.3	303.3	79.8	286.7	80.5	399.2	106.6
(Ca + K)/Mg relation	6.85	4.37	7.44	1.07	8.12	2.16	6.71	2.42	5.54	2.10
Lime requirement (kg ha^{-1})	2263	1114	4567	3012	3013	1432	2494	1362	3891	2694
Aluminium (cmol kg^{-1})	0.39	0.72	1.42	2.72	0.10	0.03	0.61	1.25	1.32	2.42
Aluminium saturation (%)	3.2	6.1	10.5	17.3	0.7	0.2	6.7	14.3	11.5	23.0
Cation exchange capacity (cmol kg^{-1})	14	3	12	3	14	2	12	2	15	2
Physical										
Bulk density (Mg m^{-3})	0.80	0.09	1.03	0.22	1.18	0.25	0.83	0.06	0.82	0.15
Pore space (%)	54.0	7.8	49.1	10.5	41.9	8.1	55.5	6.8	58.0	9.3
Slope (%)	38	8.7	25	5.4	24	5.3	33	10.6	41	11.2
Effective soil depth (cm)	36	15.9	49	14.7	28	23.5	46	15.9	29	9.6
Soil penetration resistance (kPa)	300	12.7	310	25.5	260	45.2	277	40.8	243	33.9
Soil vegetation cover (%)	77.4	12.5	89.8	6.8	86.7	4.3	92.0	2.3	91.7	6.2

stages was high, with *grama* grass and forest showing the lowest pH values, which were associated with high aluminum concentration and aluminium saturation. Phosphorus contents are generally low in all vegetation successions, being especially low in *guamil*, reaching only half the concentration of the others while potassium reached the highest values in *guamil* and forest plots. The high available potassium concentrations are due to the natural contents in the original soil and probably a nutrient transfer by roots from the subsoil to the upper soil may occur in *guamil* and forest vegetation. The calculated ratios between (Ca + K)/Mg indicated a balanced soil–nutrient relationship in all vegetation stages. Cation exchange capacities remained at a relatively high level in all vegetation stages without major differences, not related directly with organic matter contents. Considering the physical characteristics, *Guamil* and forest plots showed the highest soil vegetation coverages, which provide more protection against soil erosion during the rainy season. A further important physical aspect was the soil penetration resistance as an indication of soil compaction. Soil penetration resistance generally declined from the grass stages to the *montecillo* and *guamil* stages and finally to the forest plots, coinciding with the increasing porosity measured, peaking at the forest stage. It can be supposed that the improved mechanical conditions were also related to improved soil water conditions but the latter were not analyzed in detail.

Data indicated that both *guamil* and forest vegetation showed improved soil conditions. The observed organic enrichment process is very slow and needs at least 10 years to take place, the time period being inadequate relative to the increasing rural population pressure which has increased demand for agricultural land in the area (Kammerbauer and Ardon, 1996). The recorded management history showed that most abandoned plots have been used for basic grain production or pasture which, as reported by farmers, resulted in soil erosion, compaction and invasion from aggressive weeds. Slash and burn of *guamil* and forest vegetation was a common management practice to enrich soils in nutrients for agricultural production in this area. Consequently, some of these soils used for agricultural activities in the La Lima watershed showed similar or higher concentrations of organic matter, nitrogen, phosphorus and potassium than those climax vegetation stages (data not shown).

3.3. Determination of soil fertility indices

Factor analysis generated three principal components (Table 2), with each component representing a series of variables, which simplified the analysis and interpretation. The first factor was defined as soil acidity and aluminium toxicity, the second as soil protection and macronutrient availability, and the third as organic reserve and nutrient retention. These three newly defined components explain 70% of the total variability (Table 2) with the explained variability of the parameters within the first principal component ranging from 53 to 88%; for the second principal component 52 to 61%, with exception of potassium (20%); and for the third component between 41–64%. It should be noted that organic matter is common to components II and III, which suggests strong correlations to different soil parameters. Factor analysis provides statistical evidence of the ability of the three indices to summarize the parameters within the components. The use of indices to estimate soil quality has been proposed and discussed by various authors (e.g. Doran and Parking, 1994; Rhoton and Lindbo, 1997; Wagenet and Hutson, 1997). Table 3 illustrates the construction of the three indices. Table 4 shows the value of each index in each vegetation succession stage, lower index values indicating a higher probability of soil degradation. Forest and *grama* grass

Table 2
Results from the principal component factor analysis using all soil parameters simultaneously[a]

Variables	Components			Variance explained by each variable
	I Acidity and aluminium toxicity	II Soil protection and macro nutrient availability	III Organic reserve and nutrient retention	
pH	53−	1	19+	73
Calcium (mg kg^{-1})	53−	1−	35+	89
Lime demand (kg ha^{-1})	71+	1+	0+	72
Aluminium (mg kg^{-1})	86+	2−	0+	88
Aluminium saturation (%)	88+	1−	1−	90
Total nitrogen (g kg^{-1})	4−	61+	15+	80
Soil coverage (%)	0+	60+	1−	61
Available phosphorus (mg kg^{-1})	14−	52−	0−	66
Available potasium (mg kg^{-1})	1−	20+	2−	23
Cation exchange capacity (cmol kg^{-1})	10−	2−	64+	76
Organic matter (g kg^{-1})	0−	46+	50+	96
Carbon/nitrogen relation	7+	0−	41+	48
Proportion of total variance that is explained				
Absolute	0.342	0.222	0.134	0.698
Cumulative	0.342	0.564	0.698	

Three principal components were identified and variables grouped to (I) soil acitity and aluminium toxicity, (II) soil protection and macronutrient availability and (III) organic reserve and nutrient retention. Percentages of the explained variability and sense of correlation (+ or −) of each variable in each component and percentages of the explained total variability of each variable by the three components are presented.

[a]The components were identified using an Equamax rotation. The calculated KMO = 0.531. Bartlett test of sphericity was highly significant: $\propto = 0.000005$.

Table 3
Construction of the indices of soil acidity and aluminium toxicity (SAATI), soil protection and macro nutrient availability (SPMAI) and organic reserve and nutrient retention (ORNRI)

Index	Variables	Weight	Levels			
			1	2	3	4
SAATI	Calcium (mg kg^{-1})	0.19	<800	800–1200	>1200	–
	Aluminium (cmol kg^{-1})	0.21	>2	1–2	<1	
	pH	0.15	<5.0	5.0–≤5.5	>5.5–≤6.0	>6.0
	Aluminium saturation (%)	0.24	>15	–	≤15	–
	Lime requirement (kg ha^{-1})	0.21	<2000	2000–3000	>3000	–
		Σ 1.00				
SPMAI	Total nitrogen (g kg^{-1})	0.25	<1.0	1.0–2.0	>2.0	–
	Available phosphorus (mg kg^{-1})	0.24	<15	15–30	>30	–
	Available potasium (mg kg^{-1})	0.12	<59	59–137	>137	–
	Soil coverage (%)	0.35	<80	80–95	>95	–
		Σ 1.00				
ORNRI	Cation exchange capacity (cmol kg^{-1})	0.31	<10	10–12	>12	–
	Carbon–nitrogen relation	0.24	<12	12–15	>15	–
	Organic matter (g kg^{-1})	0.45	<20	20–40	>40	–
		Σ 1.00				

For each parameter ranges were established and a value from 1 to 3 assigned (with the exception of pH). Further, each variable was weighted on technical criteria. Indices for each plot and replicate were calculated as the summary of parameter values multiplied by the weights.

Table 4
Means ($N = 6$) and standard deviations (SD) of the indices of SAATI, SPMAI and ORNRI for the different vegetation succession stages

Indices	Vegetation succession stages									
	Jaraguá grass		*Grama* grass		*Montecillo*		*Guamil*		Forest	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
SAATI	2.58	0.51	2.28	0.44	2.60	0.22	2.49	0.67	2.22	0.56
SPMAI	1.75	0.15	1.91	0.29	1.87	0.14	1.92	0.21	2.09	0.32
ORNRI	1.85	0.18	2.15	0.32	2.12	0.35	2.10	0.25	2.26	0.27

plots showed the lowest index values for SAATI compared with *guamil*, *montecillo* and *jaraguá*. In contrast, the SPMAI as well as the ONRI showed an increasing trend from soils with *jaraguá* vegetation to forest, although some deviations occurred among the different vegetation stages.

3.4. Discerning cause–effect relationships

The measured and calculated parameters of soil characteristics were arranged to establish cause–effect relations and a multiple variance analysis was made with results shown in Table 5. The generated variance analysis explains a high percentage of the variation of each response variable. Both SPMAI and ORNRI as well as soil penetration resistance and bulk density are statistically significant in explaining the succession stages, while SAATI is not. SPMAI itself is strongly influenced by plot location in the micro watershed, ORNRI, SAATI, slope inclination and effective soil depth. Furthermore, ORNRI is only determined by plot location in the micro watershed, and obviously, soil penetration resistance and bulk density are significantly influenced by different soil parameters (Table 5).

Table 6 shows multiple Tukey mean comparisons of the statistically relevant parameters for the different succession stages. There are significant differences in SPMAI among plots of forest and the other vegetation stages, but not within the other vegetation stages

Table 5
Variance analysis (non-orthogonal) for the selected response variables SPMAI, ORNRI, SAATI, soil penetration resistance and bulk density and different independent variables

Sources	SPMAI	ORNRI	SAATI	Soil penetration resistance (kPa)	Bulk density ($Mg\ m^{-3}$)
Succession stage	0.132[c]	0.24[c]	0.794	0.003[a]	0.084[b]
Height above sea level	0.023[a]	0.28[c]	0.060[b]	0.180[c]	0.527
SPMAI	–	0.446	nc	nc	nc
ORNRI	0.071[b]	–	0.285[c]	nc	nc
SAATI	0.234[c]	nc	nc	nc	nc
Texture	0.522	0.308	–	0.017[a]	0.232[c]
Slope (%)	0.046[b]	0.349	0.058[b]	0.058[b]	0.124[c]
Porous space (%)	nc	nc	0.435	nc	nc
Soil vegetation cover (%)	nc	nc	nc	nc	0.347
Bulk density ($Mg\ m^{-3}$)	nc	nc	nc	0.337	–
Effective soil depth (cm)	0.027[b]	0.357	nc	0.004[a]	nc
R^2	0.997	0.993	0.994	0.997	0.986
R^2 adjusted	0.993	0.984	0.988	0.993	0.971
Pr>F	0.0005	0.0005	0.0005	0.0005	0.0005

Significance levels: [a]highly significant $p \leq 0.05$; [b]significant $0.05 < p \leq 0.10$; [c]minimally significant $0.10 < p \leq 0.30$).
Model adjustment and model significance are presented; nc = not considered, relationship not included in the variance analysis model.

Table 6
Tukey test for multiple means comparisons for SPMAI, ORNRI, soil penetration resistance and bulk density as a function of the different succession stages

Succession stage	SPMAI	ORNRI	Soil penetration resistance (kPa)	Bulk density ($Mg\ m^{-3}$)
Jaraguá grass	1.750 a	1.850 a	300 b,c	0.81 a
Grama grass	1.907 a	2.148 a,b	310 c	1.03 b,c
Montecillo	1.865 a	2.115 a,b	260 a,b	1.18 c
Guamil	1.918 a	2.098 a,b	277 a,b,c	0.83 a,b
Forest	2.087 b	2.265 b	243 a	0.82 a

Means with the same letter in the same column indicate non-significant differences ($p < 0.25$).

themselves. This indicates that the forest plots have improved soil conditions in terms of nutrient supply and soil coverage compared with the other vegetation stages. ORNRI is significantly lower in the *jaraguá* plots than in the forest plots, the *jaraguá* plots showing reduced cation exchange capacity, higher C/N ratio and less organic matter. Soil penetration resistance data show significant differences between the forest plots and both the *jaraguá* and *grama* grass plots, which are differentiated from the *montecillo* and *grama* grass stages. There is a tendency toward increased soil compaction from forest, through to *montecillo*, *guamil*, *juarguá* and *grama* grass stages. Bulk densities were also significantly higher in *montecillo* relative to *jaraguá*, *guamil* and forest plots and also between *grama* grass compared with *jaraguá* grass and forest stages.

3.5. Identification of homogeneous plots

With the procedures and indices developed, homogeneous plots were identified to verify if there was a grouping tendency using the soil parameters relative to the succession stages, when used as autochthonous indicators to determine the status of the soils. Selecting the appropriate variables to include in this analysis was crucial and based on the significance of the data discussed above, the following parameters were

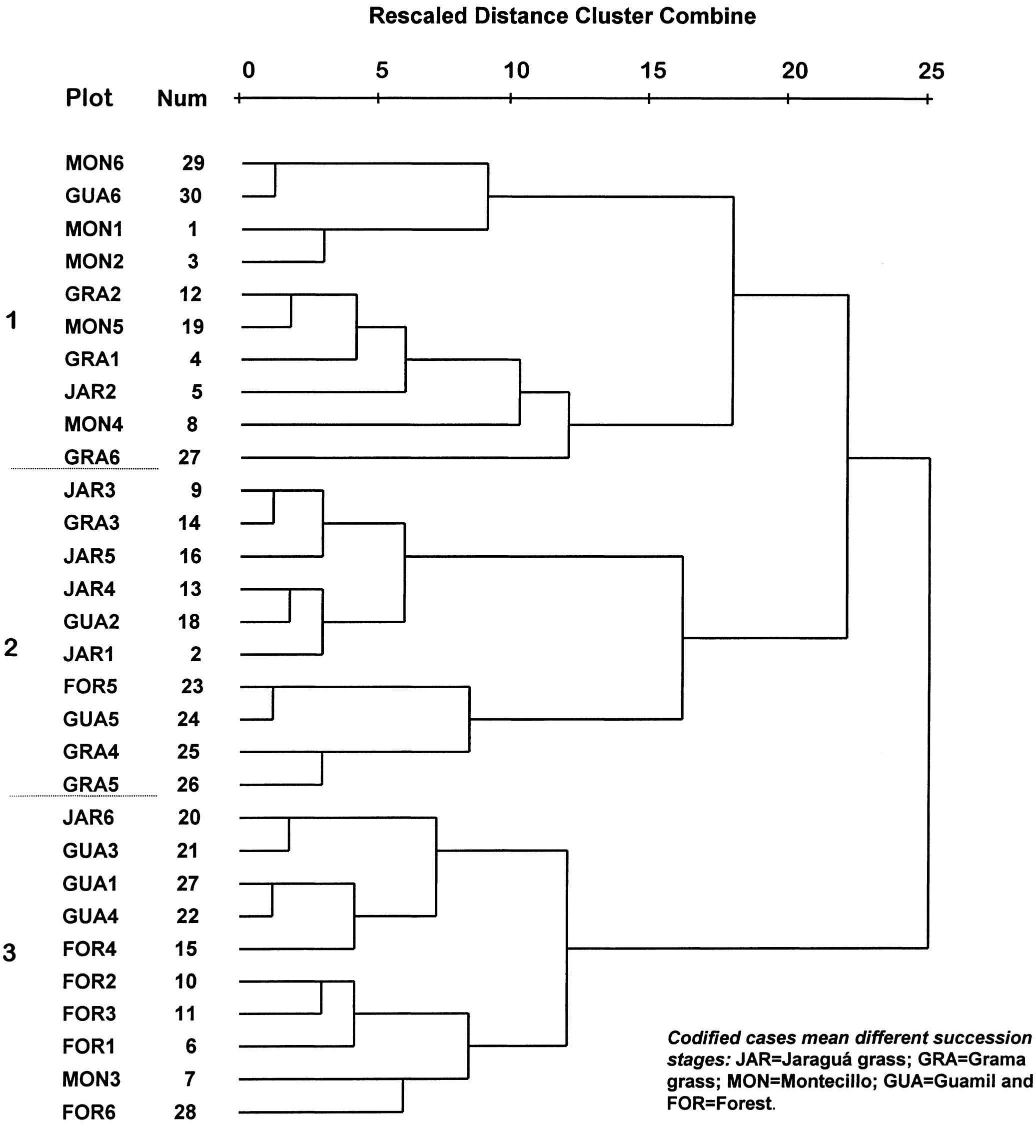

Fig. 1. Dendrogram of vegetation succession stages on degraded and rehabilitated agricultural plots (Num = Number 1–30), using the Ward method, Euclidean distance and Z-score transformation. Three principal groups were formed: 80% of the plots inside the first group are *montecillo* and *grama* grass stages, 70% of the plots in the second group are *jaraguá* and *grama* grass stages and 80% of the plots in the third group are *guamil* and forest stages.

selected for cluster analysis: the three indices, soil bulk density, soil penetration resistance, pore space and effective soil depth. The results of cluster analysis are presented in Fig. 1. Three groups of homogenous plots could be identified from the resulting dendrogram. In the first group, 80% of plots had *montecillo* and *grama* grass stages, while in the second group 70% of the plots had *jaraguá* and *grama* grass stages. The third group had *guamil* and forest vegetation in 80% of the plots. It should be noted that half of the plots with *grama* grass have characteristics similar to *montecillo* vegetation and there is a strong tendency to group the plots into three vegetation succession stages rather than five, as originally determined by local farmers. However, in general, the data obtained supported the local perceptions regarding soil fertility status based on the vegetation classification.

4. Conclusions

Soil degradation and rehabilitation are very complex biophysical processes further influenced by economic and social conditions. Land degradation is largely induced by human behavior and low soil fertility is the main reason for abandoning agricultural plots in the shifting cultivation process. There is an increasing need for simple soil quality indices to describe soils in terms of the land sustainability and management (Halvorson et al., 1997; Sims et al., 1997). Farmers use vegetation succession stages as indicators of soil status, both for its degree of degradation and rehabilitation. In the small La Lima watershed they classified *jaraguá* grass plots as highly degraded, *grama* grass as degraded land but with some residual fertility and *guamil* and *montecillo* plots as somewhat improved soils. Mixed forest plots were considered the climax stage in vegetation succession. Cluster analysis supported the link between vegetation stages and the respective soil characteristics. This system of determining the potential degree of fertility and infertility by vegetation successions appears quite workable and it was supported by physico-chemical analysis of the soils. The information derived from factor analysis allowed the development of simplified soil fertility indicators that are capable of representing more complex physical and chemical data. It was further illustrated that a natural restoration process of degraded soils occurs, albeit slowly.

For practical purposes it can be concluded that it is critical that factors influencing organic matter content, nutrient supply, soil coverage and soil compaction are managed appropriately by farmers. It is likely that these results are representative for this soil-type on hillsides in the central region of Honduras, as similar vegetation succession patterns and classifications from grass, through grass–shrub combinations to shrubs and mixed forests can be observed on many sites after agricultural abandonment. The indices developed would be useful to apply and also validate for other soil-types and conditions to determine the status of soil degradation and natural rehabilitation processes. The study supports the perception of the farmers about soil degradation and rehabilitation and gives additional information about the underlying physical and chemical dynamics. Although shifting agriculture can be used successfully in circumstances where population and time pressures are not a problem (Kleinmann et al., 1995), abandonment of degraded land, where land as a finite resource, is under the current context (space and time constraints) a non-sustainable agricultural management practice. Consequently, further research on soil degradation and rehabilitation will be necessary to find effective and more rapid methods for determining and improving soil fertility in tropical and sub-tropical regions to ensure that agricultural production systems are sustainable.

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