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Selection and interpretation of soil quality indicators for forest recovery after clearing of a tropical montane cloud forest in Mexico

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ABSTRACT

Through slash-and-burn techniques, vast areas formerly occupied by tropical montane cloud forest (TMCF) in Mexico have been converted into croplands and secondary forest of different ages. Despite the dramatic changes in soil properties and processes detected during cropping and forest regeneration, no attempts have been made to develop soil quality indicators (SQI) to assist in the assessment of soil conditions during such changes. SQI are considered to be essential in evaluating plans of forest restoration or management; as such, the objectives of this study were to (i) select soil properties that can be used as SQI during forest regeneration for abandoned crop fields in a TMCF area managed under the slash-and-burn method; and (ii) examine the ecological significance of stand age for function-based interpretations of the selected SQI. To this end, the soil properties of three adjacent chronosequences in El Rincón, Sierra Norte, Southern Mexico were analyzed. Each chronosequence consisted of ordered series of five stands of different age after abandonment: a cornfield and adjacent forests of ~15 (incipient forest), ~45 (young forest), ~75 (mature forest), and ⩾100 (old-growth forest) years after abandonment. The soil properties of undisturbed old-growth forest stands were used as a reference. After inspection of principal component analysis results and control charts, the following soil properties were chosen as SQI in TMCF areas: soil organic carbon, pH, plant-available P, O horizon thickness and exchangeable Al^{3+}. The selected SQI displayed different rates of change during forest regeneration. Soil organic carbon had a fast recovery rate and, therefore, a greater ability to return to its original level after disturbance. In contrast, O horizon thickness, soil pH, plant-available P, and exchangeable Al^{3+} showed a slow rate of change during the fallow period. SQI did not always change linearly nor improve with the age of the forest. The highest exchangeable Al^{3+} concentration was detected in 45-year-old forests, suggesting that at this forest age, soil become an important filter against Al^{3+} sensitive species, potentially affecting vegetation composition. Considering the slow recovery rate of some SQI, we estimate that fallow periods of at least 100 years are required in order to reach good soil quality in TMCF ecosystems. Management practices should therefore consider the maintenance of forest of different ages spanning at least 100 years in the landscape. Doing so would achieve more sustainable management practices by allowing a relatively continuous recovery of the ecosystem without prolonged interruptions of land utilization.

1. Introduction

The deforestation and degradation of natural ecosystems have accelerated as a result of increasing population pressure. However, isolated efforts have been made to regenerate the degraded land. In general, the criteria for judging the regeneration success of disturbed ecosystems have been based on inspection of visual aboveground indicators (Mummey et al., 2002); soil components, in most cases, have received little attention. Ignoring soil components is a grave mistake, considering the importance of soil in ecosystem recovery: soil (i) sustains biological activity, diversity and productivity; (ii) regulates and partitions water and solute flow; (iii) filters, buffers, degrades, immobilizes, and detoxifies organic and inorganic contaminants; and (iv) is involved in nutrient storing and cycling (Karlen et al., 1997).

Abbreviations: D_B, soil bulk density; MDS, minimum data set; PC, principal component; PCA, principal component analysis; SMBC, soil microbial biomass carbon; SOC, soil organic carbon; SQI, soil quality indicators; TMCF, tropical montane cloud forest; TN, total nitrogen.

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The assessment of soil quality, and the identification of key soil properties that serve as indicators of soil function, is complicated by the many issues defining quality and the multiplicity of physical, chemical and biological factors that control soil processes (Doran and Parkin, 1994). According to the Soil Science Society of America's Ad Hoc Committee, soil quality is "the capacity of soil to function" (Karlen et al., 1997). Other authors have defined soil quality as a combined expression of soil attributes within fixed levels of site factors, such as slope and aspect (Burger and Kelting, 1999).

Land use has changed rapidly in many tropical areas of the world (Geissen et al., 2009). Primary tropical forests are disappearing across the planet and secondary forest is becoming the predominant type of forest vegetation. Moreover, common agricultural practices in the tropics, such as slash-and-burn, are closely linked to forest dynamics, particularly the vegetation that develops during the fallow period (del Castillo and Blanco-Macías, 2007). The assessment and rehabilitation of degraded land can be done effectively if soil quality indicators (SQI) are defined and properly quantified. According to Doran and Parkin (1994) SQI should: (a) reflect ecosystem processes; (b) integrate physical, chemical, and biological soil properties and processes; (c) be accessible to many users; (d) be applicable to field conditions; and (e) be sensitive to variations in management and climate. In forestry, the monitoring of SQI has been acknowledged as fundamental for sustainable management practices (Burger and Kelting, 1999). Nevertheless, SQI have not yet been defined for many tropical forest ecosystems in the world.

Tropical montane cloud forests (TMCFs) are characterized by a persistent, frequent or seasonal, cloud cover at vegetation level. This kind of ecosystem usually occurs at higher elevations than lowland tropical rain forests, and the tree height is lower (Bruijnzeel and Hamilton, 2000). TMCFs are one of the ecosystems most affected by land use change (Churchill et al., 1995; Aldrich and Hostettler, 2000; Bruijnzeel and Hamilton, 2000). Vast areas of TMCFs have been cleared for agricultural purposes (Ortega and Castillo, 1996; Aldrich and Hostettler, 2000). A number of estimates indicate that more than 50% of the original Mexican TMCF area has been replaced by other forms of land use (Toledo-Aceves et al., 2010). Second-growth forests are usually established on degraded agricultural lands that become unproductive due to loss of soil fertility or human emigration (del Castillo and Blanco-Macías, 2007). Despite the importance of this ecosystem, no attempts have been made to select SQI for assessing the changes resulting from crop fields being replaced by second-growth forests in TMCFs areas. Such indicators are essential when evaluating plans of forest restoration or management (Oldeman, 1994). Employing multivariate statistical approaches such as principal component analysis (PCA) to identify the indicators with the largest impact on soil quality could be an appropriate first step toward soil quality assessment (Pajares-Moreno et al., 2010). This approach provides a non-subjective mean to extract and weight information in complex univariate data sets (Wander and Bollero, 1999).

In the present work, soil quality is considered to be an inherent feature of the soil, given by its forming factors as proposed by Zornoza et al. (2008). Doran and Parkin (1994) proposed two methods for establishing reference conditions against which to compare observed levels of SQI: the first uses the soil characteristics of undisturbed soil to establish reference conditions; the second compares observed characteristics with a range of conditions that have previously been established to maximize productivity and environmental performance. The latter approach presupposes an understanding of the optimum functioning of the soil; unfortunately, such information is lacking for many tropical forest ecosystems. The present study applied the first method proposed by Doran and Parkin (1994) to a TMCF area in southern Mexico managed under a slash-and-burn system of cultivation, in order to: (a) select soil properties that can be used as SQI during forest regeneration for abandoned crop fields in a TMCF area associated with this practice of land management; and (b) examine the ecological significance of stand age for function-based interpretations of SQI. Three chronosequences were studied, including well-preserved old-growth forests, whose soil properties were taken as reference conditions.

2. Materials and methods

2.1. Study site

The study site (17°15′N to 17°30′N and 95°15′W to 96°25′W, 1850 ± 150 m a. s. l.) is located at El Rincón, in the Sierra Norte Mountain Range of the State of Oaxaca, Mexico, which encompasses the largest surface of cloud forests in this country, covering approximately 125,000 ha (World Wildlife Fund, 2003). The main steep slope ranges from 15% to 64%. The bedrock is Mesozoic schist (Castillo and Castro, 1996). The climate is temperate-humid to sub humid, with 1719 mm yr^{-1} of mean annual precipitation, and a mean annual temperature of 20–22 °C (Anonymous, 1999; Comisión Nacional de Biodiversidad, 2004). The soils of the forest stands were classified as *Humic Dystrudepts* (stands 15 to 45 yrs old) and *Typic Dystrudept*s (stands 75 to 100 yrs old); crop field soil was classified as *Typic Udorthents* (Bautista-Cruz et al., 2005). Soil erosion was evident in both crop fields and early successional stages, revealing a rejuvenating process. In the crop fields, soil was very shallow (15 cm depth), with an A, C horizon sequence. In the 15 yrs stands, soil was constituted by colluvial materials which buried a clayed material, in such a way the soil horizon sequence was: O, A, C, ABb. In the 45 and 75 yrs stands, soils, at surface layer, were rich in clay and clay coatings, typical of truncated soil profiles. Soils from old-growth forest (⩾100 yrs) showed the lowest effect of erosion, as revealed by its increasing clay content with soil depth (Bautista-Cruz et al., 2005).

According to its floristic composition (Cordova and del Castillo, 2001; del Castillo and Blanco-Macías, 2007), the original vegetation was an upper TMCF (*sensu* Webster, 1995). Part of the original forest has been cleared for cropping maize. Many maize fields were abandoned at different periods due to human emigration, slash-and-burn practices, and the introduction of coffee plantations at lower elevations. Therefore, the landscape is a mosaic of crop fields and forests of different ages. Incipient forests appear approximately from 10 to 15 yrs after abandonment, and are dominated by a single or few cohorts of the white tropical pine *Pinus chiapensis*. Shading at the forest floor level precludes further establishment of this shade-intolerant species, but many shade-tolerant hardwoods, typical of TMCFs become established under the canopy of this pine and other shade-intolerant-species. At 45 yrs, *P. chiapensis* remains to be the tallest tree species, but its density drastically declines owing to a self-thinning process. If the stands are not severely disturbed, many hardwoods and shade-tolerant species such as oaks, *Quercus* spp., *Clethra kenoyeri, Bejaria mexicana,* and *Vaccinum leucanthum*, replace the pine trees. At 75 yrs, only a few, large, and old individuals of *P. chiapensis* remain. Hardwoods are the dominant species in old-growth forests (>75 yrs), and the vegetation resembles that of a typical upper TMCF, characterized by the abundance of species in the Actinidiaceae, Chloranthaceae, Clethraceae, Hamamelidaceae, Fabaceae (oaks), Symplocaceae, Theaceae, and Winteraceae families (del Castillo and Blanco-Macías, 2007).

We used the chronosequence, or space-for-time substitution method to study successional changes associated with soil properties. In this method, stands of different ages within the same site are compared. The differences observed are assumed to be the result of successional processes. This method assumes that the conditions of all stands at the beginning of succession are the same. This is not necessarily the case (see Chazdon et al., 2007 and references in Glenn-Lewin and van der Maarel, 1992). However, this method is still the most viable for studying long-term successional processes. Misinterpretation of successional trends using chronosequences can be minimized to some extent by including replicate plots of similar age (Chazdon et al., 2007).

Three chronosequences were selected for the present study: Tanetze, Juquila and Yotao. Each chronosequence consisted of ordered series of five stands of different age after abandonment (seral stages): cornfield (stage I), and adjacent forests of ~15 (incipient forest, stage II), ~45 (young forest, stage III), ~75 (mature forest, stage IV), and ⩾100 (old-growth forest, stage V) years after abandonment. In each chronosequence, the age of the stands was estimated. Three sources of information helped in this task. (i) The estimated age of *P. chiapensis* trees calculated from growth ring counts taken from wood core samples. Wood rings are formed in this tree since growth activity is slow or arrested during winter time owing to low temperatures and rainfall, which is, on average, ⩽5% that of summer time. (ii) The composition and structure of the vegetation of the stands with particular reference to the age, density, and size of shade-tolerant and shade-intolerant species. For instance, the presence of many reproductive individuals of species typical of TMCFs, which are shade-tolerant, with few and large individuals of shade-intolerant species, reveals a secondary old-growth forest. Finally (iii), local people were consulted about the land use history of the stand. These three sources of information gave the same age rank to the stands in each chronosequence, but an exact age determination could not be accomplished (Cordova and del Castillo, 2001; Bautista-Cruz and del Castillo, 2005; del Castillo and Pérez-Ríos, 2008). All the stands share the same climate, parent material, and similar topography (see Cordova and del Castillo, 2001 and Bautista-Cruz and del Castillo, 2005, for vegetation and plot age estimation details). The approximate distance (km) between chronosequences is as follows: Tanetze-Juquila (3.46), Juquila-Yotao (7.54) and Tanetze-Yotao (8.69). The mean distance (m) among plots within each chronosequences was 641 (min = 77, max = 846). The mean slope and standard error of our study sites was 52.0 ± 4.8%.

2.2. Soil sampling, processing and analysis

The methods of soil sampling and analyses used in the present study are described in detail in Bautista-Cruz and del Castillo (2005); what follows is a brief description. Soil sampling followed the procedures described by Dick et al. (1996), Petersen and Calvin (1996), and Boone et al. (1999). A 0.4 ha plot was delineated in each seral stage. Within each stand, a central sampling point was randomly chosen; the other four sampling points were set 20 m from the central point in each cardinal direction. O horizon thickness was measured with a tape measure; the O horizon was subsequently discarded. A pit was dug using a shovel and soil samples were taken at 0 to 20 cm and 20 to 40 cm soil depth (Bautista-Cruz and del Castillo, 2005). At the present study, we selected the SQI only for the 0 to 20 cm soil depth, as the topsoil is the most affected by disturbance, and has the greatest impact on plant growth, water infiltration, and nutrient conservation (Franzluebbers, 2002). Only core soil samples used to test bulk density (D_B) were taken with a soil auger. Fresh soil subsamples for soil microbial biomass carbon (SMBC) determination were stored at 4 °C until analysis as suggested by Lee et al. (2007). SMBC and D_B were determined from three replicates in each soil plot. The remaining physical and chemical soil properties analyzed in this study were determined from five replicates from each soil plot. Soil samples were air-dried and passed through a 2-mm screen prior to chemical and physical analysis. Soil organic carbon (SOC) was analyzed by dry combustion in a carbon autoanalyzer TOC-5050 (Shimadzu). Plant-available P was determined using the Bray and Kurtz 2 method; total nitrogen (TN) was quantified using Kjeldahl digestion. Exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+ were extracted with *1N* ammonium acetate (pH 7.0) and quantified by atomic absorption spectrophotometry. Exchangeable Al^{3+} was extracted with *1N* KCl and determined by NaOH titration. Soil pH was measured using a 1:2 soil to water mixture and a digital pH meter. Soil D_B was determined using the core method (Klute, 1986). SMBC was measured by the fumigation-extraction method. Organic C that had previously been rendered extractable through fumigation was extracted with 0.5 M K_2SO_4 and subsequently quantified using a TOC-5050 (Shimadzu) carbon autoanalyzer (Vance et al., 1987; Voroney et al., 1993; Horwath and Paul, 1994). During laboratory soil analysis, at least 10% of the samples were randomly replicated to reduce analytical error; an average of two replicates per sample was used. The difference between replicates was usually <5% (in >90% of samples) and never exceeded 10%. An internal soil reference sample was run along with each set of determinations.

2.3. Selecting soil properties as soil quality indicators during forest regeneration

Following the procedure reported by Brejda et al. (2000), Sparling and Schipper (2002), and Mandal et al. (2008), appropriate properties suitable to be used as SQI were selected using PCA with the PRINCOMP procedure of SAS (SAS Institute Inc., 1990, v. 6.0). The following soil variables, previously standardized or normalized ($\bar{X} = 0$ and $\sigma = 1$), were included in the analysis: O horizon thickness, pH, SOC, D_B, exchangeable cations (Na^+, K^+, Ca^{2+}, Mg^{2+} and Al^{3+}), plant-available P, SMBC, TN.

Data resulting from PCA of a given data set are referred to as principal components (PCs) (Dunteman, 1989). Only PCs with eigenvalues ⩾1 were selected as they best represent system attributes (Brejda et al., 2000). The assessment of loading significance in the PCA was based on scaling the eigenvectors to Pearson product moment correlations between the PC scores and the original variables. Said scaling was calculated by multiplying the eigenvectors by the square root of their associated eigenvalues. Following Jackson (1991), correlation values ⩾70% were judged to be significant. The variables with high factor loading were retained for the minimum data set (MDS), as they explain the greatest proportion of the total variability given by the age of the stand.

2.4. Examining the ecological significance of stand age for function-based interpretations of soil quality indicators

The observed levels of SQI after disturbance were compared with existing conditions in an analogous old-growth TMCF in the study site. This old-growth TMCF had not been subjected to human intervention for at least 100 years. Two major assumptions underlie the application of the undisturbed/disturbed comparison approach: first, that all of the ecosystems under study were identical before disturbance, and second, that the climate has not changed, and is similar for all sites used in the comparison. Such assumptions are considered to be justified in our study, given the proximity of the stands and their similar ecological conditions, as described above.

The recovery rate of the SQI selected via PCA was determined according to the control charts proposed by Larson and Pierce (1994). The mean values of the indicators found in the old-growth forest sites were compared with those found in cornfields and mature, young, and incipient forests in the three chronosequences studied. The similarities and differences between the range of natural variability of the SQI found in the old-growth forest soils and SQI values obtained in cornfields and secondary forests provided a measure of the severity of the changes for a given SQI during each of analyzed stages.

3. Results and discussion

3.1. Soil properties as soil quality indicators

The first three PCs in the PCA provided a good synthesis of the original set of variables, as they showed eigenvalues $\geqslant 1$, explaining approximately 76% of the total variance of the observations (Table 1). The highest loadings of PC1 (39.36% of total variance) included SOC, pH, plant-available P, O horizon thickness, and exchangeable Al^{3+} in decreasing order of importance. The only significant factors in PC2 (24.64% of total variance) and PC3 (11.79% of total variance) were TN and SMBC, respectively.

PC1 best separated the soil properties from the different successional stages (Fig. 1a). Four groups were discernible regarding the age of the stand: (a) cornfield soils, (b) incipient forest soils, (c) young and mature forest soils, and (d) old-growth forest soils (Fig. 1a). The PC1 indicators with the highest loadings are well known for their close relationship with soil acidity. The low soil pH value found in the old-growth forest soils probably is the result of low quality organic matter accumulation, which may contribute to explain the O horizon thickness. The high accumulation of leaf litter in the old-growth forest soils suggests high quantities of substrate available for soil microbes, as well as the presence of recalcitrant materials such as lignin. Micromorphological analyses of these soils showed them to possess the highest fungal activity of those analyzed (Bautista-Cruz et al., 2005). Fungi are generally much more efficient at assimilating and storing nutrients than bacteria; in fact, bacterial lignin degradation appears to be negligible in terrestrial environments when compared to the activity of white-rot fungi (Tuomela et al., 2000).

Exchangeable Al^{3+} had a high loading value in the first PC, suggesting that this cation significantly affects soil quality in TMCF ecosystems (Table 1). Al^{3+}can inhibit Ca^{2+} and Mg^{3+} uptake (de Wit et al., 2010), reduce fine root growth, alter photosynthetic activity, and lead to nutrient imbalances in forest tree species (Wright et al., 1989). Soil pH values lower than 5.5, such as those detected at the study sites, are associated with Al^{3+} toxicity problems in plants (Sanchez et al., 2003). High levels of Al^{3+} may play an important role in vegetation composition by excluding species sensitive to this cation. By reducing competition levels, this exclusion may favor Al^{3+} tolerant plants in soils with high concentrations of soluble Al^{3+}. Indeed, some species of Theaceae, Melastomataceae and Rubiaceae, which are well represented in the study site (del Castillo and Blanco-Macías, 2007) are Al^{3+} tolerant (Watanabe et al., 1998; Jansen et al., 2000). In this context, exchangeable Al^{3+} can be considered an important soil quality factor in TMCF ecosystems; the same has been recognized for some other tropical ecosystems (Sanchez et al., 2003).

PC2 was mostly explained by TN (Table 1). However, the 100-year-old forest displayed the greatest variation of all the successional stages studied (Figs. 1a and 2). The SMBC content was the only significant variable of PC3 (Table 1). However, it did not contribute to discriminate areas in the PCA plot (Fig. 1b). As in the case of TN, this soil property showed a great variability (Fig. 2). As a result, both TN and SMBC are not recommended as a SQI. These results illustrate that PCA should only be considered one of several tools for selecting SQI in agro-forest systems. Other statistical criteria, such as dispersion measures, particularly in the reference soil, should also be taken into account. Therefore, only SOC, pH, plant-available P, O horizon thickness and exchangeable Al^{3+} are suggested as the appropriate SQI of TMCF in the study site. These SQI are similar as those found by Pennock and Van Kessel (1997) in a mixed-wood forest.

Table 1
Results from the principal component analysis of the statistically significant soil quality indicators. Only principal components with eigenvalues >1 and correlation values $\geqslant$70% were retained.

Principal component	1	2	3
Eigenvalue	4.72	2.95	1.41
Proportion	39.36	24.64	11.79
Cumulative proportion	39.36	64.00	75.79
Eigenvectors			
O horizon thickness	<u>0.325 (0.707)</u>	0.060	−0.146
pH	<u>−0.398 (−0.866***)</u>	−0.006	0.079
Soil organic carbon	<u>0.400 (0.871***)</u>	0.108	−0.071
Bulk density	−0.235	0.035	0.319
Exchangeable Na^+	0.298	0.217	0.312
Exchangeable K^+	−0.086	0.145	0.079
Exchangeable Ca^{2+}	−0.300	0.184	−0.231
Exchangeable Mg^{2+}	−0.234	0.042	−0.221
Exchangeable Al^{3+}	<u>0.324 (0.704**)</u>	−0.111	−0.415
Plant-available P	<u>0.356 (0.774***)</u>	0.264	0.112
Soil microbial biomass carbon	0.140	0.112	<u>0.670 (0.796***)</u>
Total nitrogen	0.157	<u>0.445 (0.766***)</u>	−0.156

Underlined original variables and their eigenvectors correspond to the soil properties that were included in the minimum data set.
** $P \leqslant 0.001$.
*** $P \leqslant 0.0001$.

3.2. Ecological significance of stand age for function-based interpretations of soil quality indicators

This study shows that the selected SQI displayed different rates of change in TMCF areas previously cleared for maize cultivation. SOC had a fast recovery rate, as only the crop field values of this SQI were outside the upper and lower limits defined by the old-growth forest soil (Fig. 2). This result may be explained by a rapid recovery of forest biomass coupled with lower rates of SOM mineralization, thus, the low rate of SOM mineralization can induce SOM accumulation and decrease in pH (Sojka and Upchurch, 1999; Seybold et al., 1999). These results indicate that SOC is a SQI with relatively high resilience in TMCF landscapes under slash-and-burn agriculture in spite of the erosion processes during the soil genesis detected in the soil profiles (Bautista-Cruz et al., 2005). SOC is fundamental during soil genesis, as it provides a substrate for SMBC, the responsible of biological weathering (Brady and Weil, 1999).

In contrast, other soil properties, namely O horizon thickness, pH, plant-available P and exchangeable Al^{3+}, showed a slow rate of change along forest recovery (Fig. 2). The mean values of these SQI over the course of succession were outside the natural range of variability found in the old-growth forest soil. In the case of O horizon thickness and available-P, the mean values were below the natural range of variability in the reference soil (Fig. 2). For soil pH, the mean values were above the natural range of variability in the old-growth forest soil (Fig. 2). Overall, these results show different patterns and rates of change after disturbance for each of the SQI selected. An important point here is that in some properties, such Al^{3+}, soil quality of the TMCF ecosystem is first reduced along the forest regeneration. This is somewhat against the common perception that soil quality (or soil functions) always improve after an agricultural field is left on fallow.

A noticeable decrease in tree density (self-thinning) was detected in 45-year-old forests; pines are the dominant group of trees at this seral stage (del Castillo and Blanco-Macías, 2007).

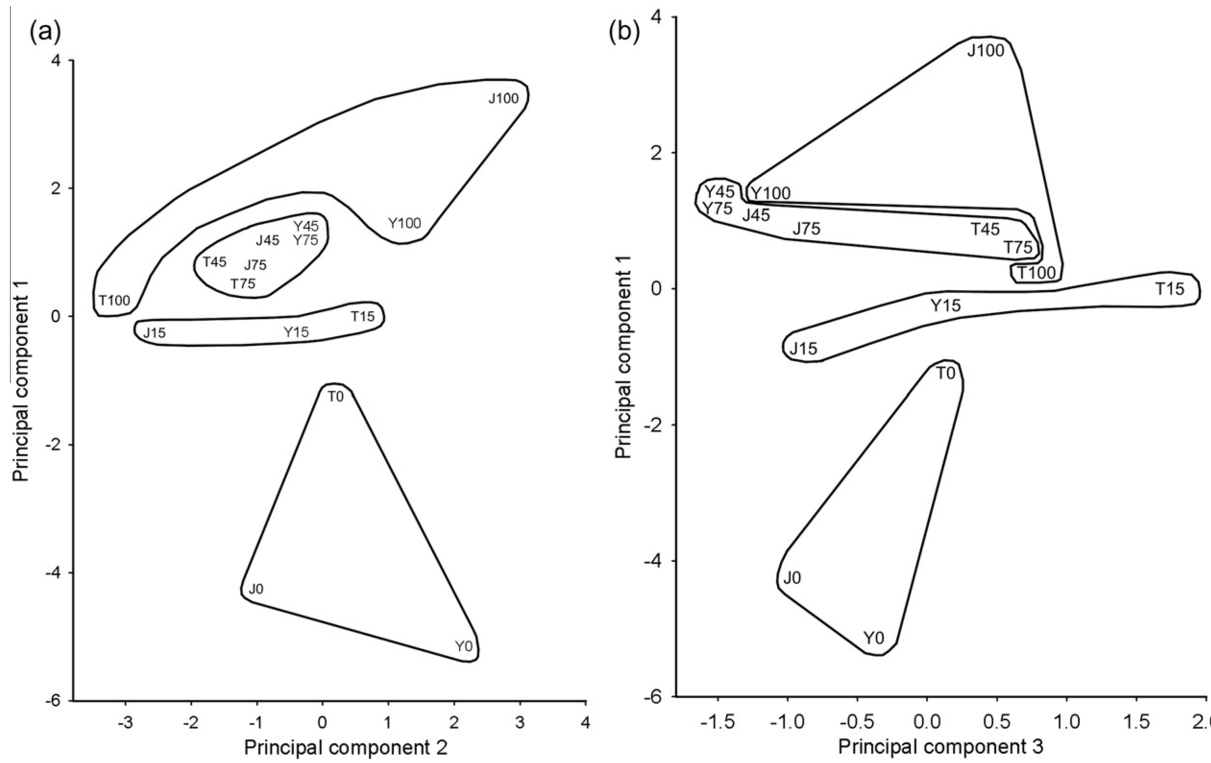

Fig. 1. Factor scores of the plots and their assignment to (a) the 1st and 2nd principal components, and (b) the 1st and 3rd principal components at 0 to 20 cm soil depth in a tropical montane cloud forest in El Rincón, Oaxaca, Mexico. T, Tanetze; J, Juquila; Y, Yotao. 0, 15, 45, 75 and 100 indicate the approximate forest age.

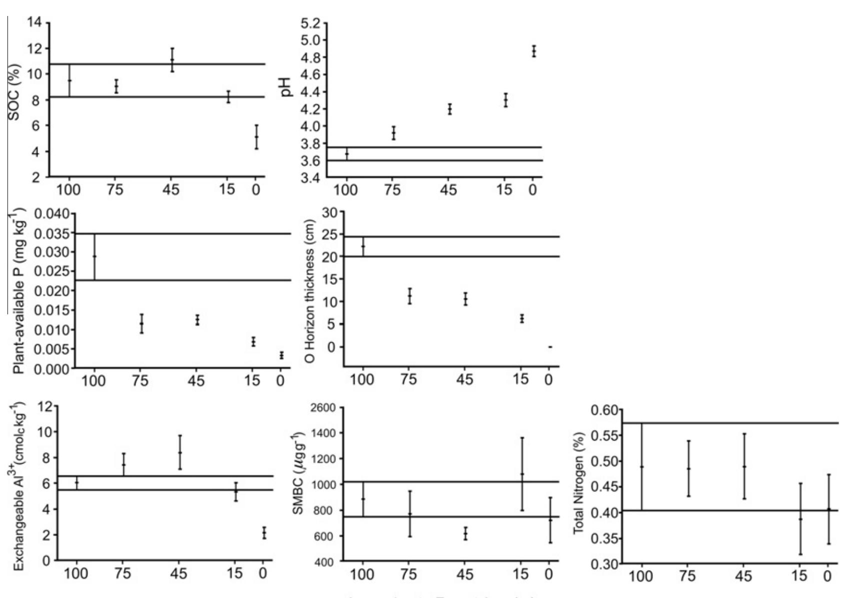

Fig. 2. Soil quality indicator control charts for tropical montane cloud forest regeneration. The two horizontal lines delineate the upper and lower limits of each soil quality indicator in the old-growth forest sites. Mean value ± one standard error ($n = 3$) of each soil quality indicator are indicated. SMBC, soil microbial biomass carbon; SOC, soil organic carbon.

The consequent apportion of dead wood to the soil caused by this process may explain the high increase in SOC content observed for this time interval (Fig. 2). Pine litter decomposition is expected to generate high Al^{3+} and H^+ concentrations in the soil solution (Augusto et al., 2002). This may help to explain the peak in the soil exchangeable Al^{3+} concentration in 45-year-old forest. After 45 years, exchangeable Al^{3+} decreases, despite a steady increase in soil acidity. This apparently contradictory result could be explained by the progressive release of humic and fulvic acids, as soil becomes progressively older. At 45 years old most of SOM has not been humified as evidenced by the lack of the Bh horizon (Bautista-Cruz et al., 2005). As soil mature, the release of organic acids, mostly fulvic and humic acids increases, as evidenced by the presence of a Bh horizon in old-growth forest soils (Bautista-Cruz et al., 2005). The negative charges of these acids bond with Al^{3+} cations to form organometallic complexes, helping to reduce exchangeable Al^{3+}. This process is very important in tropical areas as it stabilizes the SOM (Egli et al., 2008). Furthermore, old-growth forests are abundant in plant species in the Aquifoliaceae, Cornaceae, Cunoniaceae, Ericaceae, and Symplocaceae families (Blanco-Macías, 2001; del Castillo and Blanco-Macías, 2007), which are known as Al hyperaccumulators (Jansen et al., 2002). The great biomass of old-growth forest and the abundance of Al hyperaccumulators may have also contributed to reduce soil Al levels. Further research is needed to explain these results.

Soil phosphorous levels are expected to decline during succession as a result of the increasing demand for this nutrient by the large-sized plants common to old-growth forests. However, the results of the present study show a very different pattern. Old-growth forests displayed the highest soil phosphorous levels of all the forests included in this study. Phosphorous input from bed rock weathering is expected to be minimal in this area as no minerals containing this element have been identified in the schist that predominate the bed rock (Bautista-Cruz et al., 2003). The atmosphere, then, is the most likely source of phosphorous in this ecosystem. A great proportion of fog covers this area throughout the year. Fog droplets, as a result of their small size, contain high concentrations of dissolved nutrients (Schlesinger, 1997). Old-growth forest is expected to have a greater capacity for trapping water from fog, due to its larger canopy surface and higher proportion of epiphytes. The surface covered by epiphytic bryophytes (mostly mosses and liverworts) was found to increase nearly 800% from 15-year-old forest to mature forest (100 years or more), where more than 89% of the trunk surface is covered by epiphytes in this region (Cordova and del Castillo, 2001). Epiphytic bryophytes can collect enormous amounts of water from fog. Shih-Chieh et al. (2002), for instance, estimated that more than 50% of the ecosystem nutrient input in a montane forest in Taiwan was through fog deposition.

Some studies have proposed insect communities (Palladini et al., 2007; Yu et al., 2006) or bryophyte species diversity (Frego, 2007) as indicators of forest recovery or forest integrity. The present results demonstrate that soil properties can also be useful in monitoring forest recovery after disturbance in TMCF areas, and may be easier to evaluate in field conditions. Although soil properties like SOM or SMBC depend mostly on the vegetation cover, it is more difficult to interpret the effect of topography on other soil variables such as pH or exchangeable Al^{3+}, which partially depend on the quality of the mineral phases. Future research is needed to investigate the interactions between topographical variables and vegetation development on soil properties.

4. Conclusions

This study demonstrates that the following soil properties can be used as soil quality indicators in tropical montane cloud forest areas managed under the slash-and-burn system of cultivation: soil organic carbon, soil pH, plant-available P, O horizon thickness, and exchangeable Al^{3+}. These soil properties meet the criteria established by Doran and Parkin (1994) for such indicators. The selected soil quality indicators displayed different rates of change during forest recovery in tropical montane cloud forest areas previously cleared for maize cultivation, with relatively high rates for soil organic carbon, and low rates for O horizon thickness, soil pH, plant-available P and exchangeable Al^{3+}. Soil quality indicators did not always change linearly nor improve with the age of the forest. The highest exchangeable Al^{3+} concentration detected in 45-year-old forests, suggests that at this forest age, soil become an important filter against Al^{3+} sensitive species, potentially affecting vegetation composition.

Principal component analysis should be considered as one of several tools for selecting soil quality indicators in agro-forest systems; other statistical criteria, such as dispersion measures, particularly in the reference soil, should also be taken into account.

Considering the slow recovery rate of key soil quality indicators, it is estimated that fallow periods of at least 100 years are required to reach good soil quality in tropical montane cloud forest ecosystems. Management practices should therefore consider the maintenance of forest of different ages, spanning at least 100 years, in the landscape. This would allow for more sustainable management practices, by permitting a relatively continuous recovery of the ecosystem without prolonged interruptions of land utilization.

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