SOIL NATURAL CAPITAL MODIFICATION THROUGH LANDUSE AND COVER CHANGE IN A TROPICAL FOREST LANDSCAPE: IMPLICATIONS FOR MANAGEMENT

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CRAM S, SOMMER I, FERNÁNDEZ P, GALICIA L, RÍOS C & BAROIS I. 2015. Soil natural capital modification through landuse and cover change in a tropical forest landscape: implications for management. The aim of this study was to describe the effects of landuse change on soil properties using a space-for-time sampling strategy based on a mosaic of landuses (tropical forest, cropland maize, pastures and natural fallow plots) in three localities that differ in parent material, slope and climate. A multivariate discriminant function analysis was used to describe the results. Some soil properties did not change with landuse while others are use-sensitive. Landuse change from forest to maize has clear negative effects on β-glucosidase, dehydrogenase, total organic carbon concentration, nitrogen, bulk density and electrical conductivity with differences in magnitude between localities. With a change in landuse to pasture and secondary vegetation, soil properties responded positively, showing differential recovery. This study provides information that can be used to promote sustainable agricultural procedures that can change cultivation patterns and promote biological activity.

Keywords: Soil degradation, soil recovery, soil ecosystem services, discriminant analysis, Los Tuxtlas Biosphere Reserve, space-for-time sampling strategy

INTRODUCTION

Soil is an important determinant of the economic status of nations. The concept of soil security has been introduced to emphasise the crucial influence of soil on sustainability and to bridge the gap between science and policy (McBratney et al. 2014). Soil ecosystem services fulfils human needs (Robinson et al. 2012), assigning economic value to things that contribute to human well-being. The value of ecosystem service of soil formation calculated by Costanza et al. (1997) is approximately 0.3% of global gross domestic product. Soil natural capital is a complex system characterised by a diversity of quantifiable properties that can be used to assess adverse changes in the soil indicating degradation processes (Dominati et al. 2010). Although degradation is a natural, slow process, anthropogenic activities speed it up and can modify soil characteristics in the short, medium or long term with adverse effects on soil functions (Lal et al. 1998).

Several human activities are preceded by deforestation and consequently a change in landuse in response to economic opportunities mediated by institutional factors (Lambin et al. 2001). The removal of vegetation causes changes in some soil properties with negative consequences on the soil ecosystem processes. Deforestation causes less amount of litter to fall on the soil, and hence there is decrease in the diversity and quantity of food for soil organisms, decrease in soil humidity and increase in temperature by direct soil exposure to sunlight. The amount of organic matter decreases as do nutrient fluxes and decomposition rate, thereby causing reduction in soil fertility (de Souza Braz et al. 2013). Other adverse effects are increase in bulk density and decrease in porosity and,

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consequently, decrease in the infiltration rate, promoting runoff and soil erosion (Zimmermann et al. 2010). Vegetation removal also affects soil enzyme activity, a variable that has been suggested as a good indicator of soil quality because it shows rapid response to changes in soil management (da Silva et al. 2012). It adversely affects carbon (C) dynamics (Sotomayor-Ramírez et al. 2009), specifically the ability of soil to store C as stable organic matter and off-setting greenhouse gas emissions (Lal 2004). Edaphon (all soil organisms) responsible for a myriad of soil functions intervening in all biogeochemical cycles and decomposition of xenobiotics (Sylvain & Wall 2011) also suffers with landuse and cover change (LUCC).

However, it is difficult to establish unique quality criteria to measure the magnitude and direction of both the negative effects of LUCC and the positive evidence of recovery of soil properties after landuse abandonment because they are influenced by many factors such as intensity of landuse, management practices and landscape (topography, parent material and soil type) (Barois et al. 2011). Severe changes in use and coverage have occurred in Mexico especially in tropical forests which are disappearing at a rate of 263,500 ha $year^{-1}$ (Palacio-Prieto et al. 2000). Forests have been subjected to intense deforestation and subsequent establishment of agricultural activities particularly in the region of Los Tuxtlas, Veracruz, Mexico. Currently, about 38% of the area is used for crop production and 46–65% for livestock grazing (Fuentes et al. 2009) but there are also abandoned plots left fallow, where secondary vegetation develops (García-Romero et al. 2010). Thus, mosaics of vegetation types and landuse are very common in various landscapes, differing in intensity and duration of use. This situation provides an opportunity to describe trends of soil degradation and recovery using space-for-time sampling strategies (Tugel et al. 2005) and, thereby, allowing the comparison of localities where past conditions can be inferred by reference to the soil that has not undergone anthropogenic transformation.

The aim of this study was to describe the effects of landuse change on soil properties using a space-for-time sampling strategy based on a mosaic of landuses (tropical forest, cropland maize, pastures and agroforestry/natural fallow plots) in three pedological contexts (three localities that differ in parent material, slope and climate). A multivariate discriminant function analysis was used to reduce the number of physical, chemical and biological variables and identify soil characteristics that are most sensitive to soil use changes. This information will aid land managers and policy-makers in developing monitoring programmes followed by management strategies that protect soil functions and hence support ecosystem services.

MATERIALS AND METHODS

Study area

The Los Tuxtlas Biosphere Reserve is in the state of Veracruz and the coastal plains of the Gulf of Mexico (Figure 1). It is a volcanic massif dating back to the Tertiary period and lava flows, volcanic ash and other pyroclastic materials cover almost the entire area. The altitude ranges from sea level to 1780 m, with the San Martín Tuxtla volcano as the highest elevation. The climate of the region is hot and subhumid in the coastal plains and temperate and humid in the highlands (García et al. 2009). The Los Tuxtlas Reserve is one of the most threatened protected areas in Mexico and is subject to anthropogenic pressure. This has led to continuous and rapid disappearance of habitat and natural vegetation. The principal causes are the expansion of agricultural activities (maize culture and livestock production) and population growth (Negrete-Yankelevich et al. 2013).

The study was carried out in the buffer zone of the reserve on terrain representing the natural vegetation (tropical forest) and three landuses (cropland maize, cattle pasture and agroforestry/natural fallow). Three localities were studied, namely, (1) Adolfo López Mateos, municipality of Catemaco, (2) San Fernando, municipality of Soteapan and (3) Venustiano Carranza, municipality of Tatahuicapan. These localities differ in proportion of forest cover, altitude, landform, precipitation, geology and hence soil type (Table 1, Figure 1). This mosaic is considered representative of the land cover and use of the area. The landuse trajectories in Los Tuxtlas follow the pattern described by Guevara et al. (1997), with initial clearing of the forest for maize polycultures or, nowadays, monocultures, followed by grazing or conversion

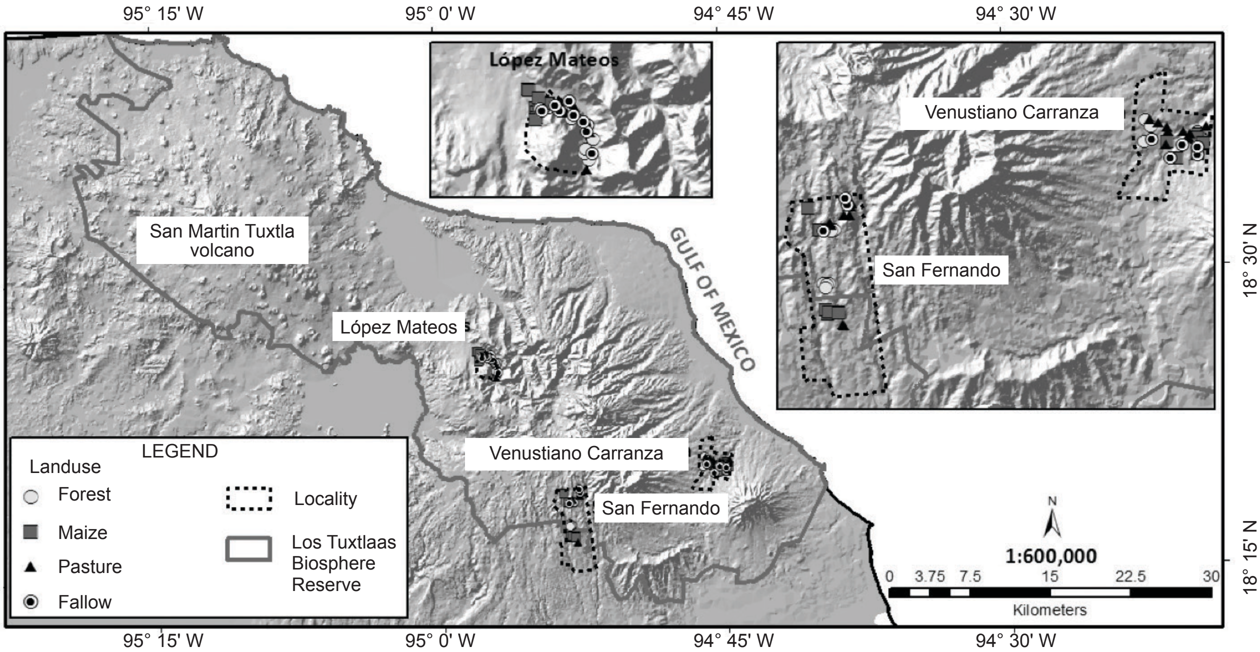

Figure 1 Sampling localities in the Los Tuxtlas Biosphere Reserve, Mexico

Table 1 Geographical features of the studied localities in Los Tuxtlas, Veracruz

Feature	Adolfo López Mateos	San Fernando	Venustiano Carranza
Locality	18° 24'–18° 26' N, 94° 56'–94° 58' W	18° 15'–18° 19' N, 94° 52'–94° 54' W	18° 19'–18° 21' N, 94° 44'–to 94° 46' W
Altitude (m asl)	238.3	994.8	225.7
Rainfall (mm)	2000–2500	1182	2900
Soil type	Humic Andisol	Chromic Acrisol and Mollic Acrisol	Chromic Luvisol and Ochric Luvisol
Geomorphology	Mountain with convex hillsides, 25–40° slope, undulated relief	Hilly in middle part of the mountains and plateau, fluvial valleys	Fluvial valleys and gentle dissected plains
Geology	Highly modified volcanic rock and ashes	Rhyolite slabs and weathered volcanic molasse	Basalt and tuff breccia
Principal landuse	Forest conservation	Shaded coffee plantations	Grassland for cattle raising
Forest cover (%)	76.8	49.5	27.2
Dominant species	*Trichilia breviflora, Trichospermum galeottii, Trophis mexicana, Cynometra retusa*	*Quercus insignis, Talauma mexicana, Dendropanax arboreus, Alfaroa mexicana*	*Protium copal, Tapirira mexicana, Brosimum alicastrum*
Size (ha)	571.99	2192.3	970.7

Source: García et al. (2009), Barois et al. (2011)

to other cropping systems such as coffee (López-Cano & Castillo-Campos 2009), sometimes using slash and burn of the forest and also annual burning of crop residues (Negrete-Yankelevich et al. 2013). Another option is to allow the growth of secondary vegetation or to use the land for agroforestry with citrus or coffee crops (Fuentes et al. 2009). Natural fallow plots constitute the most heterogeneous group because the abandonment may have been recent or several years ago and the plots were already in transition to tropical forest.

Soil sampling strategy

A space-for-time sampling strategy (Tugel et al. 2005) was used to compare tropical forest with landuses (maize, pasture, natural fallow). In addition, soil-forming factors, i.e. relief, parent material (Table 1), were also considered. In each landcover/landuse of the three localities, soil composite samples (12 cores of 0–20 cm) were taken in 8–12 plots of 20 m × 20 m (n = 106, Table 2). A total of 50 g of each sample was stored in the dark at 4 °C for enzyme activity assays and the 600 g was used for soil analysis (particle size distribution, total organic C (C_{org}), nitrogen (N), pH and electrical conductivity (EC)). For bulk density and total porosity, 10 undisturbed samples were taken in each plot using stainless steel cylinders.

Soil analysis

Physical and chemical analyses used duplicate air-dried soil samples (n = 96) sieved through 2-mm mesh. Biochemical tests used triplicate samples in field-moist soils, sieved to < 2 mm and stored in the dark at 4 °C until analysis. Particle size was determined using hydrometer method (ISO 1998b). Bulk density and particle density were calculated from the mass and volume of unaltered samples collected using core sample holder (volume = 100 mL) according to ISO 11272 and 11508 methods (ISO 1998a, c respectively). Total porosity was determined through direct relationship between particle density and bulk density.

Soil pH was measured in soil suspension (1:2.5 w/v soil:$CaCl_2$ solution) using pH meter (ISO 1994b). EC was measured in 1:5 w/v soil: distilled water suspension using conductivity meter (ISO 1994a). C_{org} and total N were determined using CNHS autoanalyser.

Dehydrogenase activity was estimated using the INT (2-(p-iodophenyl)-3-(p-nitrophenyl)-5-phenyltetrazolium chloride) reduction method (Friedel et al. 1994). Tris buffer (0.1 M) used was adjusted to pH 7.7 to produce the INT–Tris solution. Soil samples (2.5 g) were treated with 2.5 mL of the INT–Tris solution, incubated in stoppered assay tubes, kept in the dark and heated in water bath (4 hours at 47 °C). The INT–formazan (INTF) produced by this reaction was extracted with 10 mL of tetrahydrofuran by shaking the samples in the dark (2 hours, 250 rpm). The aliquot was then dissolved in acetone. A calibration curve was created using INTF at concentrations ranging from 0 to 24 μg INTF mL^{-1}. The INTF concentration was determined spectrophotometrically with UV–Vis spectrometer at 487 nm. Six blanks were prepared, as well as samples of each soil type (n = 15) treated with formaldehyde (15% v/v) before incubation to detect any abiotic reduction of INT.

β-glucosidase activity was determined according to Tabatabai (1994). Soil samples (1.0 g, oven dry basis) with ρ-nitrophenyl-β-D-glucoside 0.05 M and toluene in pH 6 modified universal buffer were placed in stoppered Erlenmeyer flasks and incubated in water bath (1 hour at 37 °C). The ρ-nitrophenol produced was extracted by filtration (Whatman No. 2) after addition of 0.5 M $CaCl_2$ and 0.1 M THAM (trometamol; tris-hydroxymethyl aminomethane) buffer and the concentration was spectrophotometrically determined using UV–Vis spectrometer at 420 nm. Four blanks and control samples, one for each soil type, were included. Control samples were treated with $CaCl_2$–THAM before incubation to inhibit microbial growth. Four control samples spiked with β-glucosidase standard were also included.

Statistical analysis

Statistical significance for all tests was $p < 0.05$. A factorial ANOVA was used to test significance of mean differences of soil properties analysed for the localities and landuses. In order to assess

Table 2 Number of soil samples taken in each locality and landuse in the study

Landuse/locality	Tropical forest	Cropland maize	Cattle pasture	Natural fallow	Total
Adolfo López Mateos	10	9	8	8	35
San Fernando	10	8	12	8	38
Venustiano Carranza	8	8	9	8	33
Total	28	25	29	24	106

whether there was a group of soil variables that defined landuse and another that related more to locality or pedological context, locality and landuse were assigned as categorical variables while soil characteristics, as dependent variables (Table 2).

To find the discriminant functions for the pedological context or landuses, several multivariate discriminant analyses were conducted. In the first analysis, locality was the grouping variable. Landuse was the other grouping variable to differentiate soil degradation or recovery processes. Variables that did not contribute to differentiation by use in the factor analysis (clay, sand, silt and pH) were omitted from the corresponding discriminant analyses. All analyses were performed with the STATISTICA program, version 10.

Dependent variables in all cases were physical (clay, bulk density and porosity), chemical (N, pH and EC) and biological (C_{org}, dehydrogenase, β-glucosidase) soil characteristics. In the forward stepwise method, tolerance was 0.01, assuming that there was no collinearity. Data missing from the database were replaced by the average of the variable by use/locality.

RESULTS

All soil characteristics were highly variable (Tables 3–5). Differences for locality and use were evident with ANOVA factorial analysis. All interactions were significant, indicating that locality and landuse could be considered as independent variables since there was a combined effect. Enzyme activities (β-glucosidase and dehydrogenase) and EC differed with landuse, with highest values for forest and lowest for maize, although with differences in magnitude among localities. Highest value of β-glucosidase was measured in Adolfo López Mateos and lowest in San Fernando. Highest EC values was observed in Adolfo López Mateos and the lowest in Venustiano Carranza. Change in bulk density by landuse was significant, increasing with the first LUCC from forest to maize in all localities while total porosity decreased. Adolfo López Mateos had the lowest bulk density. In all localities a recovery of bulk density can be seen with successive landuses but without reaching the values measured in forest. C_{org} concentration also presented higher values in forest than in maize, especially in San Fernando. Particle size (clay, lime, sand) and pH values did not show specific pattern with landuse change but lower pH value and higher clay content occurred in cattle pasture. Adolfo López Mateos soil is sandy while Venustiano Carranza soil has higher clay contents.

In summary, enzyme activities, EC, bulk density, N and C_{org} are landuse change-dependent variables that explain differences between landuses. The pH values, clay, lime and sand contents reflected variables determined by the pedological context (Table 1).

Discriminant analysis with locality as the grouping variable

The group definition was highly significant (p = 0.0000, Wilks Lambda = 0.1232). The percentage of correct assignments by locality was good (94% Adolfo López Mateos, 92% San Fernando and 79% Venustiano Carranza) (Figure 2). In the first function, sand and porosity discriminated Adolfo López Mateos and San Fernando. The second function discriminated San Fernando and Venustiano Carranza through β-glucosidase and pH. This analysis explained differences in soil properties between localities. Venustiano Carranza had soils with the highest clay content (55%) and lowest pH (average 4.6) due to its greater development and loss of exchangeable cations. Adolfo López Mateos had sandier soils with the lowest clay contents (20%) and highest pH values (average 5.2). These are younger soils developed from volcanic ash. San Fernando soils had values between these two. The soils are classified as Luvisols, Andosols and Acrisols respectively (Table 1).

Discriminant analysis with landuse as the grouping variable

Adolfo López Mateos

The group definition was significant (p = 0.0063, Wilks Lambda = 0.3969). The analysis included four variables (two enzymes, N and C_{org}) and left out porosity, bulk density, C:N ratio and EC. The eigenvalues indicated that three factors explained 100% of the variance. The first factor

Table 3 Mean values of physical, chemical and biological soil properties in Adolfo López Mateos

Parameter	Forest	Maize	Pasture	Natural fallow
Clay (%)	25.45 (9.43)	18 (9.82)	28.13 (10.33)	15 (7.07)
Silt (%)	19.90 (5.26)	27.56 (6.52)	20.25 (3.54)	20.5 (4.38)
Sand (%)	54.60 (11.13)	54.44 (11.91)	51.63 (11.16)	64.5 (9.96)
Bulk density (g cm^{-3})	0.54 (0.16)	0.72 (0.06)	0.66 (0.08)	0.61 (0.19)
Porosity (%)	77.1 (4.66)	71.4 (3.72)	74.3 (3.37)	76.1 (6.58)
Electrical conductivity (mS cm^{-1})	88.8 (28.56)	67.9 (18.41)	79.9 (11.92)	84.6 (9.93)
pH	5.17 (0.35)	5.25 (0.19)	5.17 (0.16)	5.13 (0.13)
C_{org} (%)	5.67 (2.08)	5.48 (1.85)	5.17 (1.20)	6.26 (1.38)
N (%)	0.54 (0.24)	0.56 (0.22)	0.65 (0.17)	0.65 (0.12)
β-glucosidase (mmol g^{-1} $hour^{-1}$)	12,731 (2556)	8103 (1407)	11,012 (1650)	11,499 (1910)
Dehydrogenase(mg g^{-1} $hour^{-1}$)	102 (19.14)	70.4 (9.13)	88.8 (13.66)	98.2 (18.99)

Values in brackets are standard deviations; C_{org} = total organic carbon, N = nitrogen

Table 4 Mean values of physical, chemical and biological soil properties in San Fernando

Parameter	Forest	Maize	Pasture	Natural fallow
Clay (%)	44.95 (18.8)	44.47 (19.9)	54.81 (10.9)	43.79 (20.3)
Silt (%)	23.65 (12.9)	28.65 (18.0)	15.21 (5.7)	23.79 (9.3)
Sand (%)	31.40 (12.1)	26.88 (5.2)	29.88 (7.5)	32.43 (14.5)
Bulk density (g cm^{-3})	0.45 (0.1)	0.82 (0.11)	0.80 (0.1)	0.72 (0.1)
Porosity (%)	77.9 (5.2)	66.81 (1.91)	62.99 (12.6)	71.07 (4.3)
Electrical conductivity (mS cm^{-1})	101.58 (20.5)	48.0 (14.4)	52.35 (19.1)	87.09 (23.4)
pH	4.81 (0.6)	5.34 (0.3)	5.00 (0.4)	5.17 (0.48)
C_{org} (%)	9.70 (2.1)	4.23 (0.6)	6.9 (1.8)	5.96 (1.1)
N (%)	0.87 (0.2)	0.39 (0.1)	0.5 (0.1)	0.59 (0.09)
β-glucosidase (mmol g^{-1} $hour^{-1}$)	3663 (3354)	1458 (1052)	4318 (2071)	4187 (2536)
Dehydrogenase(mg g^{-1} $hour^{-1}$)	114 (26.6)	81.6 (24.4)	117.1 (33.7)	123.6 (40.6)

Values in brackets are standard deviations; C_{org} = total organic carbon, N = nitrogen

Table 5 Mean values of physical, chemical and biological soil properties in Venustiano Carranza

Parameter	Forest	Maize	Pasture	Natural fallow
Clay (%)	54.75 (12.37)	53.88 (9.13)	60.44 (7.28)	51.63 (9.38)
Silt (%)	20.88 (7.66)	21.19 (6.91)	14.33 (7.30)	23.06 (10.69)
Sand (%)	24.38 (5.35)	25.44 (6.08)	25.22 (6.90)	25.31 (3.81)
Bulk density (g cm^{-3})	0.61 (0.07)	0.83 (0.08)	0.86 (0.11)	0.75 (0.09)
Porosity (%)	71.8 (2.12)	63.93 (5.15)	61.88 (5.22)	66.64 (4.15)
Electrical conductivity (mS cm^{-1})	79.56 (11.63)	56.26 (14.39)	45.95 (11.08)	53.03 (13.23)
pH	4.54 (0.45)	4.94 (0.28)	4.53 (0.25)	4.53 (0.33)
C_{org} (%)	5.27 (0.58)	4.70 (1.78)	5.08 (1.01)	4.54 (1.13)
N (%)	0.48 (0.15)	0.47 (0.12)	0.50 (0.16)	0.47 (0.10)
β-glucosidase (mmol g^{-1} $hour^{-1}$)	15,634 (9784)	5487 (1425)	9097 (5463)	8598 (3320)
Dehydrogenase(mg g^{-1} $hour^{-1}$)	108.3 (64.2)	55.6 (21.71)	69.2 (40.25)	104.2 (47.3)

Values in brackets are standard deviations; C_{org} = total organic carbon, N = nitrogen

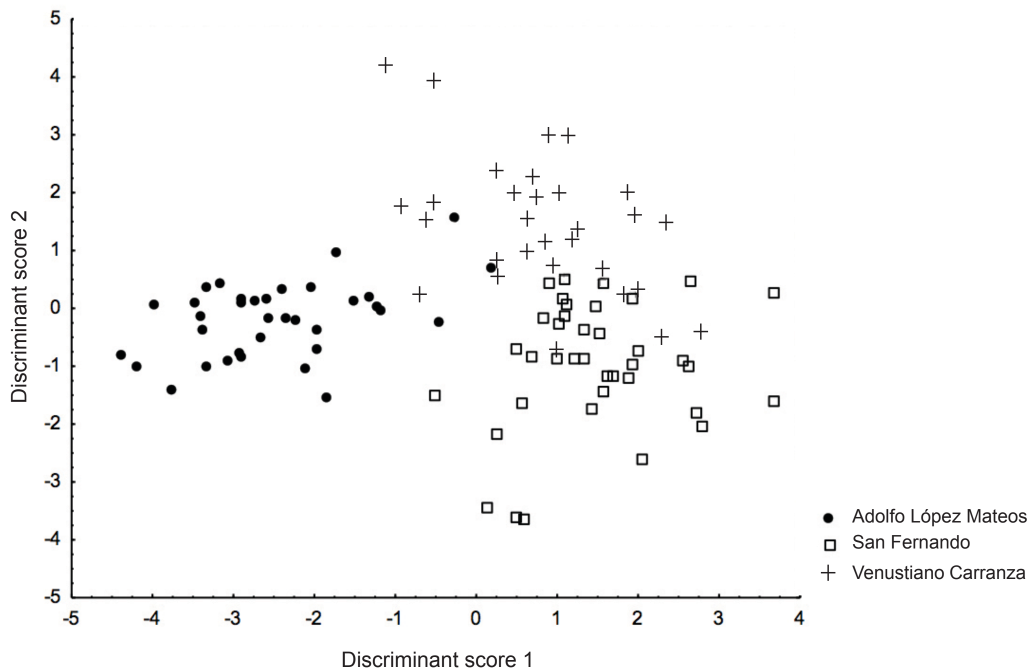

Figure 2 Group definition according to locality using discriminant analysis

accounted for 83.6% of the variance, with all four variables as contributing variables (r for C_{org} = 0.92, β-glucosidase = 0.81, dehydrogenase = 0.54 and N = 0.53). The second factor accounted for a further 11.2%, with N (r = 1.14) and C_{org} (1.11) as the major contributing variables. The third factor accounted for another 5% with β-glucosidase (0.74) and dehydrogenase (0.73) as explanatory variables. The percentages of correct assignments by landuse were 60% for forest, 77% for maize, 37% for pasture and 25% for natural fallow. The groups forest and maize did not mix at all, suggesting that there was determinate effect of landuse change on biological parameters (enzymes, N and C_{org}) (Figure 3). The group comprising pasture and natural forest was mixed mostly with the forest group, which could be interpreted as a sign that soil characteristics were recovering.

San Fernando

The group definition was significant (p = 0.0000, Wilks Lambda = 0.05493). The analysis included seven variables and left out C_{org}. The first factor accounted for 75.6% of the variance, with bulk density (r = 0.86) and N (0.69) as major contributing variables. The second factor accounted for a further 15%, with C:N ratio (0.79) as the major contributing variable. The third factor accounted for another 9.2% with β-glucosidase (0.7) as explanatory variable. The percentages of correct assignments were good (forest 100%, maize 87.5%, pasture 91.6% and natural fallow 75%). Again, forest and maize did not mix at all, showing a clear effect of LUCC. The first function discriminates forest with lower bulk densities and higher N contents than for other landuses.

Venustiano Carranza

The group definition was significant (p = 0.0001, Wilks Lambda = 0.1869). The analysis included five variables and left out porosity, N and C:N. Three factors explained 100% of the variance. The first factor accounted for 84.4% of the variance, with bulk density (r = 0.73) and EC (0.68) as contributing variables. The second factor accounted for a further 8.58%, with β-glucosidase (0.86) and EC (0.76) as major contributing variables. The third factor accounted for another 6.9% with dehydrogenase (0.59), β-glucosidase (0.57) and C_{org} (0.56) as explanatory variables. The percentages of correct assignments were forest 87.5%, maize 50%, pasture 77.7% and natural fallow 62.5%. Forest and maize did not mix.

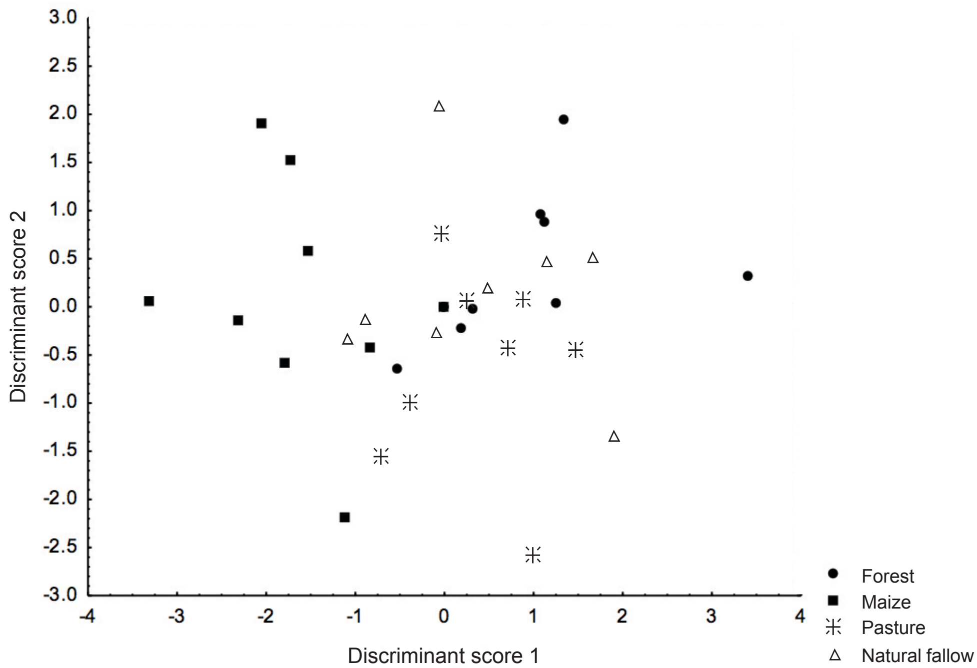

Figure 3 Group definition according to landuse in Adolfo López Mateos using discriminant analysis

Discriminants including all localities

The group definition was also significant ($p = 0.0000$, Wilks Lambda = 0.3755). The analysis left out C_{org} since this variable did not help to discriminate between landuses because it was also strongly influenced by the pedological context. Three factors explained 100% of the variance. The first factor accounted for 77.9% of the variance, with bulk density ($r = 0.97$), EC (0.44) and porosity (0.41) as contributing variables. The second factor accounted for a further 14.1%, with N (0.83), β-glucosidase (0.50) and dehydrogenase (0.50) as major contributing variables. The third factor accounted for another 7.8% with dehydrogenase (0.72) and C:N ratio (0.63) as explanatory variables. The percentages of correct assignments were forest 89.2%, maize 68%, pasture 55.1% and natural fallow 29.1%. The elements of forest and maize did not mix, confirming a clear effect of LUCC on bulk density, EC and porosity (Figure 4). In the second function, N, β-glucosidase and dehydrogenase accounted for the difference between maize and pasture. Table 6 shows a summary of gains and losses in soil properties by LUCC that are discussed below.

DISCUSSION

Discrimination between localities in a pedological context

LUCC in the three localities of Los Tuxtlas had not modified particle size and pH of soils substantially. Both properties are determined by pedogenetic processes. Particle size is an inherent or use-independent property (Kuykendall 2008). The surface horizons of the analysed soils under use might differ from the same type of soil under natural vegetation but this is due to loss of topsoil exposing more clayey subsurface horizons. Soil pH, although a use-dependent variable (Grossman et al. 2001), is shielded against rapid change by the soil buffering capacity (Scheffer & Schachtschabel 1989).

All variables contributed to separation of the three localities (Figure 2), since there were differences in magnitude for all variables between localities, reflecting the effect of soil forming factors and pedogenetic processes. For instance, altitude, temperature, rainfall and vegetation type influenced the concentration of C_{org}. San Fernando, at higher altitudes with less precipitation (Table 1), had the

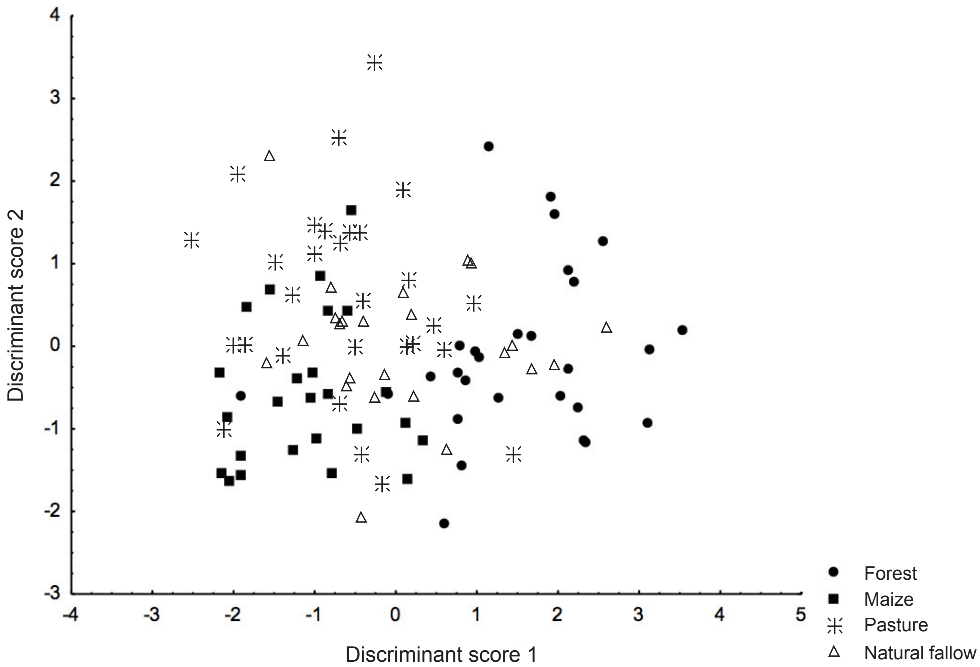

Figure 4 Group definition according to landuse in the three studied localities (Adolfo López Mateos, San Fernando, Venustiano Carranza) using discriminant analysis

highest concentration of C_{org} in forest soil. Mineralisation of organic matter is more rapid in humid and warmer regions than in regions with lower rainfall at higher altitudes and, therefore, lower temperatures such as Adolfo López Mateos and Venustiano Carranza. C_{org} contents of Adolfo López Mateos and Venustiano Carranza were also lower than in San Fernando.

Discrimination between landuses

The discriminant analysis showed that landuse clearly affected soil quality. Human-induced ecosystem and landscape processes always involve soil change (Yaalon 2007). Nevertheless, the abandonment of agricultural activities had allowed the recovery of some soil properties in this complex landscape.

Removal of natural vegetation exposes the soil to the elements of climate and modifies the dynamic soil properties, affecting the soil natural capital which provides ecosystem services (Lorencová et al. 2013). For example, the first LUCC (forest to maize) affected chemical (electrical conductivity), physical (bulk density and porosity) and biological soil properties (C_{org}, N and enzymes).

The increased bulk density in maize compared with forest, with a consequent reduction in porosity probably caused by a collapse of macropores, will also affect the infiltration rate of water (Martínez & Zinck 2004, Zimmermann et al. 2010). This will in turn lead to increased surface runoff and erosion (Korkanc et al. 2008). Both processes were observed in this study but were not quantified.

Lower contents of C_{org} under maize culture may be explained through the breakdown of soil aggregates, which will accelerate the decomposition of C_{org} and hence subject nutrients to runoff and/or leaching (Six et al. 2006). The reduction of EC could be related to this nutrient depletion in cultivated soil, a common form of soil degradation related to anthropogenic changes (Yaalon 2007). Apparent soil EC is a quick, reliable, simple soil measurement that often relates to crop yield (Corwin & Lesch 2005).

Our results indicated that LUCC generally led to a reduction in C and enzymes. C_{org}, N and enzyme activity were correlated and had major effects on nutrient cycling and soil fertility. Systems with low levels of organic matter input due to LUCC show decrease in enzymatic activity and reduction in available nutrients (Landgraf & Klose 2002). Likewise,

Table 6 Percentage change in soil properties (gains and losses) compared with value for tropical forest in each locality

Locality	Landuse	Bulk density	EC	C_{org}	N	β-glucosidase	Dehydrogenase
Adolfo López Mateos	M	+33	-23.5	-3-3	+3.7	-36	-30.9
	P	+22	-10.0	-8.8	+20.3	-13.5	-12.9
	NF	+12.9	-4.7	+10.4	+20.3	-9.6	-3.7
San Fernando	M	+82	-52	-56	-55	-60.1	-28.4
	P	+77	-48	-28	-42	+17.8	+2.7
	NF	+60	-14.1	-38	-32	+14	+8.4
Venustiano Carranza	M	+36	-29	-10.8	-2	-64.9	-48.6
	P	+40	-42.2	-3.6	+4.1	-41.8	-36
	NF	22.9	-33.3	-13.8	-2	-45	-3.7

M = cropland maize, P = cattle pasture, NF = natural fallow; EC = electrical conductivity, C_{org} = total organic carbon, N = nitrogen; + = gains, - = losses of the values relative to forest

the reduction in enzyme activity associated with conversion of natural areas to agricultural use has been connected to decreasing viable microbial biomass (Nsabimana et al. 2004). Soils with active soil biology exhibit good fertility and lower abundance of herbivorous insects (Altieri & Nicholls 2003).

Recovery status

The LUCC in the region, caused by the abandonment of agricultural activities and conversion to pasture or growth of secondary vegetation, had positive effect on soil characteristics. Pasture and natural fallow showed some recovery in bulk density, enzyme activity and EC but not in C_{org} or N (Table 6). Poor recovery of C_{org} and nutrients is consistent with Tobón et al. (2011) who found no differences in C and N in tropical forest, crops and pasture. C_{org} generally responds very slowly to changes in factors that control its accumulation (Freibauer et al. 2004). It takes at least 20 years to see an effect of regeneration on C concentration (Hughes et al. 1999). The history of prior use is decisive for the recovery of soil organic C (Lugo & Brown 1993). It takes more time to restore C_{org} levels than it does to lose them from the soil. This is caused by decrease in quantity and quality of C_{org} entering the system after LUCC, and there is also a shift in soil microbial community composition and activity affecting the humification process (Yin et al. 2014). The greater concentration of β-glucosidase in San Fernando could be related to the more readily decomposable C in pasture and natural fallow promoting mineralisation rather than accumulation of C_{org}. Enzymes have been used as early indicators of LUCC, which makes them useful for evaluating different types of management (da Silva et al. 2012). The enzymes showed better response to LUCC from maize to grass and forest than C_{org} did, which required more time to recover.

This study showed that soils of the three localities had low ability to withstand disturbances because there was clear effect of LUCC from forest to maize on use-dependent soil variables. For example, C_{org} content decreased by 56% in San Fernando and dehydrogenase activity by 28% in San Fernando and 49% in Venustiano Carranza (Table 6). However, these characteristics showed resilience or the ability to recover functionally (Seybold et al. 1999) since there was a tendency towards the recovery of values found for forest, particularly in natural fallow. Adolfo López Mateos had the most favourable conditions for recovery. In this regard, an increment in biomass as well as in enzyme activities has been reported (Speir & Ross 2002), possibly attributable partially to plant growth and increased litter input such as in pasture or growth of secondary vegetation. The reestablishment of edaphic microbiota is very important since soil bacteria and fungi produce a variety of compounds resulting in the aggregate formation and stabilisation that have been lost during agricultural landuse (Six et al. 2006).

Tropical mountain environment is highly variable in terms of soil characteristics and resilience and there will be differential response to LUCC. Results of this study provide information to land managers and policy-makers who need to design and implement management and soil conservation programmes to maintain soil natural capital. The cost of recovering soil properties will always be higher than that of protection through sustainable management with agroecological techniques. In 2010, the total cost by depletion and environmental degradation in Mexico represented 7% of gross national product and the protection spending by the Mexican government amounted to only 1% (INEGI 2012). With better practices to recover and maintain soil quality and, therefore, soil functions we could cut depletion costs and maintain our natural capital to ensure sustainable human development for the present and future generations.

CONCLUSIONS

The use of a mosaic of landuses in a region is a good strategy in assessing the impact of LUCC on dynamic soil properties over time if no long-term data are available. Discriminant analysis is a powerful tool to handle large data sets and reduce dimensionality to a manageable size, while keeping as much of the information as possible. It allowed us to identify the most useful soil variables that were influenced under diverse pedological contexts (particle size and pH) and landuses (bulk density, enzymes, N, C_{org}). Conversion from tropical forest to maize changes soil quality. This will affect the natural capital of soil, but there is a recovery process that must be monitored to identify the resilience in the studied localities. This study provides information that can be used to promote sustainable agricultural procedures that change cultivation patterns and promote biological activity.

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