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Original article

Effects of peasant and indigenous soil management practices on the biogeochemical properties and carbon storage services of Andean soils of Colombia

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A B S T R A C T

Indigenous and peasant management systems that produce food, fibre and fuel have long been used in many Andean cultures, but their effects on soil biogeochemical properties and storage of soil organic carbon have been poorly analysed. The aim of this study was to evaluate the physical, chemical and biological properties and carbon storage in Andean soils under three peasant and indigenous management practices in Popayan, Colombia: Natural Pasture (NP) (*Holcus lanatus*), Forage Crops (FC) (*Pennisetum purpureum*), and Natural Forest (NF) (dominated by *Quercus humboldtii*). In all, 216 samples were analysed over a 12-month period. The soils under the three soil managements had optimum texture (loamy and sandy loam), bulk density (<0.71 gr cm^3) and hygroscopic moisture content (11.45%) derived from the local Andosols. These soils were highly acid, particularly the forest soil (pH 4.68), but the high content of organic matter in the pasture and addition of calcium compounds to the cultivation soil had improved the pH (5.38 and 5.21 for NP and FC, respectively). Soil cultivation had produced a high metabolic quotient (qCO_2 2.46) in relation NP (0.85) and NF (0.75), perhaps owing to an imbalance of the microbial community caused by disturbances and by excess external organic carbon. However, the soils under all three management systems stored high contents of total organic carbon (TOC): 127, 111 and 110 t ha^{-1}, for NP, NF and FC, respectively. The presence of allophones in these soils leads to the formation of highly stable organo-mineral complexes, impeding mineralisation of the organic matter and allowing a high potential for soil carbon storage. A lack of temporal variability of the soil physical properties is due to the characteristics dominated by soil genesis and by the high resilience of Andosols. We conclude that the food production management practices of these indigenous communities and farmers are compatible with maintenance of the carbon storage service in these soils at the local scale.

1. Introduction

The current demand for food, fodder, fibre and fuel has led to the increased use of fertilisers, pesticides, and farming technology. These practices have had deleterious effects on soil properties and processes that determine soil fertility. For example, they increase water and wind erosion, reduce water storage capacity and water quality, alter metal and xenobiotic mobilisation and reduce productivity and sustainability [1]. Most studies have shown that significant amounts of total organic carbon (TOC) in the form of carbon dioxide have been lost because of the release of physically protected soil or because of the alteration of the microclimate when forests were transformed for the introduction of agriculture. Moreover, the increase in food production at the expense of soil ecological processes may undermine the sustainability of agro-ecosystems, including crop production.

Therefore, alternatives for managing agricultural systems must reduce soil perturbation, maximise coverage and stimulate the soil biological activity in order to counteract the adverse effects of intensive farming practices [2]. Traditional practices of integrated

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soil management (e.g., managed grazing, rotation of crops and introduction of earthworms and native species) favour the soil carbon content and prevent CO_2 emissions into the atmosphere. It is essential to recover beneficial soil attributes and improve soil biological properties that allow the subsequent establishment of animal species, food production and the flow of ecosystem services [3].

In the past decade, an attempt has been made to understand the multiple ecosystem services [4] that agriculture, pastures and forests provide: supply of food, timber and firewood; biomass production; provision of raw materials; carbon cycling and storage; climate regulation; and maintenance of biodiversity [5]. Traditional agropastoral methods are particularly illustrative of successful farm management because these methods follow some of the fundamental principles of sustainability of these systems. Food provision is a major concern, but consideration must also be given to ecosystem services that involve the properties, processes and functions of the soil and its microbial communities [6]. However, studies regarding ecosystem services that include the soil biological activity in Andean soils are scarce.

Tropical America (Mexico, Central America and South America) covers 11% of the land on which 8% of the world population lives, and 23% of this population relies on rural activities. Agropastoral and silvopastoral grasslands cover 77% of tropical America (548 million ha) and 11% of the land devoted to agriculture in the world [7]. Savannahs (250 million ha) and tropical forest (44 million ha) are the most important ecosystems in tropical America for grazing and for silvopastoral production. Mountain ecosystems predominate, with the Andes covering 960 000 km^2 of Peru, Ecuador, Colombia and Venezuela. In Colombia, the Andean region occupies 300 000 km^2 and is the most populated area of the country, with 74% of the indigenous and rural population inhabiting this area. Agricultural practices are conducted in this area: management practices are intensive (modernised) in the lowlands with the production of various crop plants, whereas systems in the highlands are more extensive and subsistence-based (a higher proportion of the land is used for food production and use of the area's natural resources) [7]. However, the effects of these practices on the ecosystem services of the soil are not monitored or evaluated. To assess the changes made by agricultural practices in these Andean ecosystems will require an understanding of carbon storage and CO_2 emissions via biogeochemical cycle management under different management practices [8]. Therefore, the aim of this study was to evaluate the effects of three practices of indigenous and peasant management on physical, chemical and biological soil properties and soil carbon storage. This information is crucial for adaptive management to correct or improve soils and their contribution to the ecosystem service of carbon storage and nutrient cycling in these ecosystems that are so widely distributed in the Colombian Andes.

2. Materials and methods

2.1. Study area

The study was conducted in the basin of the Las Piedras River, which is representative of the South American tropical Andes owing to its physiographic features. This basin (2°21′35″ N, 76°33′10″ W) has an area of 66.26 km^2 and a perimeter of 39 km (Fig. 1). The terrain is mountainous, with slopes between 16% and 50%. The soils have Andosol properties; they are derived from volcanic ash, with a medium clay-loam texture that is loosely structured and well drained. They show strong acidity (pH between 4.6 and 5.0), high aluminium saturation and low amounts of calcium, magnesium and phosphorus [9]. This region has a typical equatorial mountain climate with climatic zones (temperate, cold and páramo climates and sub-Andean and Andean bioclimatic zones) that are affected by the trade winds. The average temperature varies between 10.4 °C and 18.4 °C [10]. This region has orographic precipitation, with a mean monthly rainfall of 136 mm: 183 mm $month^{-1}$ between October and May, and 42 mm $month^{-1}$ during the dry season from June to September.

This area corresponds to the Andean forest formations [11]; according to the Holdridge classification, these formations belong to lower montane wet forest. The vegetation is characterised by Oak (*Quercus humboldtii*), Laurel (*Nectandra* sp.), Alder (*Alnus acuminata*), Motilon (*Brunellia* sp.), Myrtle (*Myrcianthes* sp.), Encenillo (*Weinmannia* sp.), Mano de oso (*Oreopanax* sp.), Huesillo (*Critoniopsis* sp.), Siete cueros (*Tibouchina mellis*), Wax laurel (*Myrica pubescens*), Guarango (*Mimosa* sp.), *Palicourea angustifolia*, grasses and ferns; also present are root crops, vegetables and forage grasses.

The basin is populated by indigenous families belonging to the Nasa of the Páez de Quintana reserve and to the Kokonucos and by peasant families included in the Association of Peasants of Popayán and Reserve Network and in the Peasant Association of Quintana Asoproquintana [10]. The peasants work as individuals, whereas the indigenous people organise themselves into community crop production based on subsistence agriculture and the presence of family productive units. Tropical Andean areas have heterogeneous climatic zones and vegetation types, and the various mixed crops raised by small farmers are primarily potatoes, grains, legumes and fodder. Already, 90% of the land with human intervention has problems of overuse. The practice of soil management in these areas is also diverse and depends primarily on the social customs, economy, geographic location and access to technology. The importance of water conservation is recognised, and many of the practices are directed towards forest maintenance and water conservation.

Management practices are based primarily on the establishment of the following three systems. 1) Natural pasture (NP) (*Holcus lanatus*) is managed by rotating livestock between fields, allowing the land to rest to retrieve and store organic carbon and moisture, and then using it to feed the cattle once more every 3 months. Normally, nitrogenous compounds such as urea and faeces remain on the pasture after cattle grazing. 2) Forage Crops (FC) (*Pennisetum purpureum*) are managed by manual tillage and weeding as well as by added compost, composted manure product and lime to improve the pH and to control pests, and these crops are very productive for 5 years. 3) Natural Forest (NF) management by communities (silvopastoral areas and timber extraction) tends towards conservation through the establishment of barriers (field fencing) to encourage natural regeneration. The forest is characterised by *Quercus humboldtii*, *Guarea kunthiana* A. Juss., *Myrcianthes* sp., *Nectandra reticulata* Mez, *Chrysochlamys* sp. and *Croton* sp. The forest is about 100 years old.

2.2. Selection of sampling sites

A 594.08 ha portion of the Andean basin strip in the municipality of Quintana was chosen on the basis of the heterogeneity of its microclimate, soil type and use, its coverage and the anthropogenic interventions; its average height was 2495 m a.s.l. The experimental units (plots) were selected according to soil managements, NF, FC and NP, and the total area for each [12]. Approximately 50% of this land supports livestock (natural pasture), 35% comprises protected areas (natural forest), and 15% is used for agriculture (forage crop).

Establishment of two experimental plots of 200 m^2 for each of the three soil managements led to a total of six plots, and each of

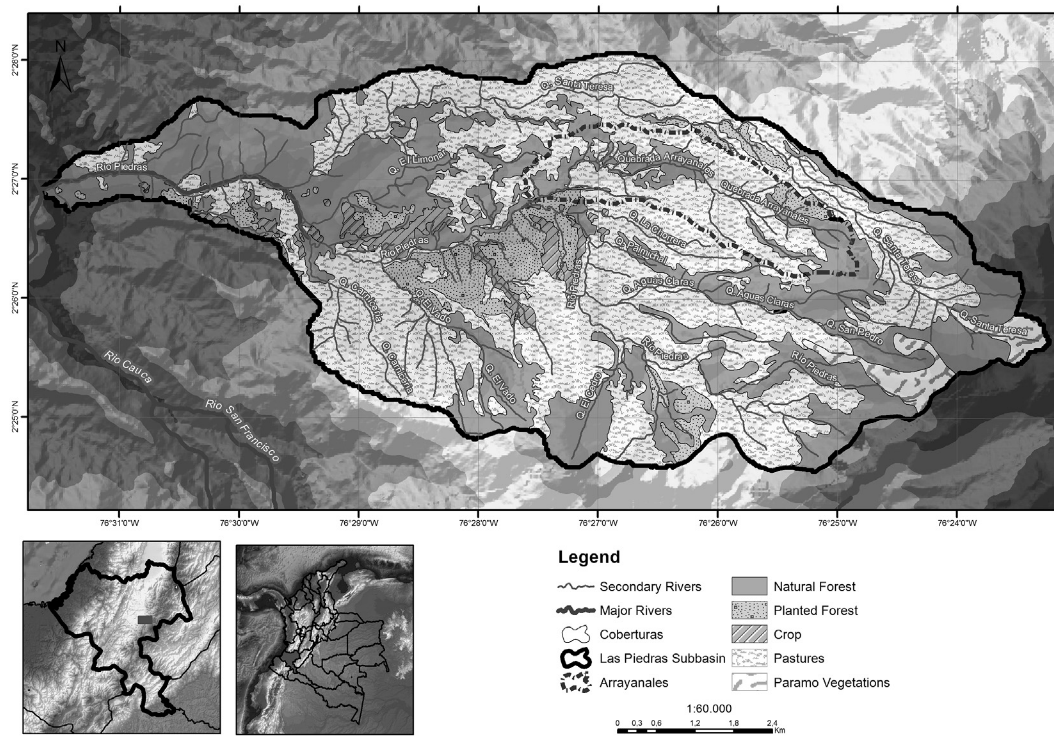

Fig. 1. Study area in the basin of the Las Piedras river, Cauca, Colombia.
Source: GIS team, Environmental Studies Group, Cauca University

these was subdivided into a grid with 25 sub-plots (8 m^2 each). In each subplot three composite samples of eight soil subsamples were taken in 2012, yielding a total of 18 monthly composite samples for the 12-month period ($n = 216$). The samples represented the horizon 'A', defined for each soil management regime and corresponding to a depth of 0.20 m for NP and FC, and 0.30 m for NF. The air-dried samples were sieved (mesh No. 10, <2 mm) and stored at 4 °C until laboratory analysis determined their physical, chemical and biological properties.

2.3. Methods

2.3.1. Physical analysis

The texture of the samples was determined by the Bouyoucos method using an American Society for Testing and Materials (ASTM) HYDR Fisher Brand D2487-06. The soil hygroscopic moisture content (HMC) was determined gravimetrically, linking water mass and soil solids mass D2216-05 [13]. The bulk density (BD) was determined by the cylinder method [14]. Soil moisture (SM) content was determined thermogravimetrically by measuring water retained after the soil had been saturated and subjected to $P = 0.3$ atm NTC ISO/IEC 17025:2005 [15].

2.3.2. Chemical analysis

The pH (H_2O) was determined potentiometrically in a soil-saturated pulp and in a 1:1 soil: water suspension with a Metrohm E-744® model pH meter (Herisau, Switzerland) following the US Environmental Protection Agency (EPA) combined glass electrode method 9045D [16]. TOC was measured by the Walkey and Black method of oxidising the organic carbon in the soil with 1 N potassium dichromate ($K_2Cr_2O_7$) in an acidic medium. After each sample had stood for 12 h, it was measured colorimetrically in a Spectronic Gensys 20® spectrometer (Madison, WI, USA) set at 585 nm [17]. The carbon content in the soil (t C ha^{-1}) was calculated from the percentage values of carbon, bulk density and volume of each sample (cross-sectional area of the sample by the sampling depth). Soil Total Nitrogen (STN) in the soil samples was determined by the Kjeldahl method [18] by quantitative determination of N from different materials. This protocol consists of three stages: oxidation of the sample, acid decomposition of ammonium sulfate, and titration with ammonium borate. All physical, chemical and biological analyses were made in the Agrochemical Laboratory of the University of Cauca, Popayán, Colombia.

2.3.3. Biological analysis

Microbial biomass-C (MB-C) was estimated by fumigation–extraction: samples were fumigated with ethanol-free chloroform, whereas control samples were left unsprayed; after three days, the microbial carbon was extracted [19].

To determine the soil microbial activity (SMA), the CO_2 output was measured by the respirometry method ($C–CO_2$) recommended by the Agrobiology Centre of Brazil [20]: the sample was incubated for five days in a closed system, then 1 N sodium hydroxide (NaOH) was added and precipitated with barium chloride, followed by the addition of two drops of phenolphthalein. Finally, the sample was titrated with 0.5 N hydrochloric acid to quantify the amount of hydroxide that had not reacted with CO_2, and a control or blank sample was always included. The metabolic quotient (qCO_2) allows evaluation of the efficiency of the use of substrates by microorganisms.

2.4. Statistical analysis

Soil chemical, physical and microbial variables were analysed by a repeated-measures analysis of variance (RMANOVA) for each sampling date. The three soil managements were considered as the major effect, and months were considered as a within-plot effect. For each RMANOVA the sphericity was adjusted with Greenhouse

Geisser tests, to have a more robust and conservative *F*. Additionally, a Pearson correlation analysis was conducted to examine relationships between TOC, HMC, pH (H_2O), BD, SOC, STN, C:N ratio, SMA, MB-C, and precipitation. The analyses were performed with the IBM-SPSS Statistics V19 program (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Physical characteristics of the three soil management practices

The physical characteristics of soils were modified by the management practices (Table 1). The soil bulk density (BD) of NP was lower than that of the NF and FC soils ($F = 9.83$, $p < 0.001$). It differed significantly between months ($F = 10.38$; $p < 0.001$), but interaction with the management practices also had an effect ($F = 6.75$; $p < 0.001$). The BD of the NF soil was lower than those of the NP and FC soils in April 2012 and June 2012, but higher than them during September 2012 to December 2012, and March and April 2013 (Fig. 2A).

Soil hygroscopic moisture content (HMC) was modified by soil management: the NP soil had higher hygroscopic moisture content than FC and NF soils ($F = 976.84$, $p < 0.001$) (Table 1). The HMC varied significantly over time ($F = 24.53$, $p < 0.001$) and with time × soil management interaction ($F = 26.95$, $p < 0.001$). The NP soil had the highest HMC during all months except April and June 2012. Sand and lime varied with soil management practice (sand, $F = 165.67$, $p < 0.001$; and lime $F = 153.908$, $p < 0.001$), but clay did not differ significantly between management practices. The NF soil was loamy, whereas the NP and FC were sandy loam. Soil moisture (SM) content was modified by soil management ($F = 37.88$, $p < 0.001$) (Table 1). SM varied significantly over time ($F = 899.48$, $p < 0.001$) (Fig. 2B) and with time × soil management interaction ($F = 171.58$, $p < 0.001$), and temporal variation was high; SM was highest in 2013 and lowest in September 2012.

3.2. Chemical characteristics of the three soil management practices

The percentage of soil organic carbon (SOC) in NP soil was 1.3 times higher than in FC soil and 1.8 times higher than in NF soil ($F = 498.90$, $p < 0.001$) (Table 1). However, SOC varied significantly over time (36.18, $p < 0.001$) and with time × soil management interaction ($F = 14.38$, $p < 0.001$). It was higher in NP soil than in FC and NF each month, except April and June 2012. NP soil was higher in FC soil than in NF soil in all months.

The soils of the three management practices are very acidic; however, the soil of the NF was significantly more acidic than the NP and FC soils ($F = 243.22$; $p < 0.001$) (Table 1); however, soil pH (H_2O) varied significantly over time (14.85, $p < 0.001$) and with the time × soil management interaction ($F = 16.68$, $p < 0.001$). The NP soil pH (H_2O) was higher than that of FC soil during September, October, November 2012 and June 2013, but lower in April 2012.

The soil total nitrogen (STN) concentration was significantly higher in NP soil than in FC and NF soils ($F = 715.58$, $p < 0.001$) (Table 1). It varied significantly with time (41.12, $p < 0.001$) and with the time × soil management interaction ($F = 28.99$, $p < 0.001$). NP had higher STN than FC and NF soil in each month, but FC had higher STN than NF in April, June, September, October 2012, March, April and June 2013. No significant differences were observed in relation to the dry or rainy season or to ambient temperature.

The C:N ratio varied with soil management ($F = 34.44$, $p < 0.001$): it was highest for FC soil, followed by the NP and NF. The C:N ratio differed between months ($F = 19.63$, $p < 0.001$) and with the time × soil management interaction ($F = 10.85$, $p < 0.001$). FC had a higher soil C:N ratio than NP and NF in October and November 2012, February and April 2013; however, the soil C:N ratios of the three soil managements were statistically similar in January and June 2013.

The NP soil had higher total organic carbon (TOC) than did the FC and NF soils ($F = 12.59$, $p < 0.001$) (Table 1). TOC varied significantly with season ($F = 39.186$, $p < 0.001$) and with the time × soil management interaction ($F = 9.58$, $p < 0.001$) (Fig. 3). The TOC values were higher in NP soil than in FC and NF in April, September and November 2012, and January to June 2013; in FC soil they were higher than NF only in February 2013, and were lower than NF soil in October and December 2012.

3.3. Biological characteristics of soils from the three management practices

The FC soil had the highest soil microbial activity (SMA), followed by the NP soil and NF soil ($F = 3964.23$, $p < 0.001$) (Table 1). SMA varied with time, being higher in November 2012 than March to June 2013 in the three management practices (737.92, $p < 0.001$). It also SMA varied with the time × soil management interaction ($F = 194.049$, $p < 0.001$) (Fig. 4A). It was higher in FC than in NP and NF soils in March to June 2013. The SMAs of NP soils were statistically similar to those of FC soils in September 2012, October 2012, and January 2013. NF soil had the lowest SMA in almost all months.

The microbial biomass-C (MB-C) varied with soil management practice ($F = 2698.63$, $p < 0.001$), being higher in NP and NF soils than in FC soil. It varied significantly with time ($F = 195.78$,

Table 1
The physical, chemical and biological characteristics of soil under three soils management: natural pasture (NP), forage crops (FC) and natural forest (NF) (Means and standard errors). Different letter indicate a statistically significant difference between land use management ($p < 0.05$).

Soil characteristics		NP	FC	NF
Physical	Bulk density (g cm^3)	0.66 (0.005)b	0.70 (0.004)a	0.71 (0.008)a
	Hygroscopic moisture content (%)	13.90 (0.17)b	10.83 (0.29)c	9.57 (0.10)a
	Sand (%)	56.92 (0.16)b	64.80 (0.25)c	51.29 (0.32)a
	Silt (%)	32.69 (0.14)b	24.39 (0.29)c	38.36 (0.32)a
	Clay (%)	10.39 (0.04)ab	10.80 (0.14)b	10.34 (0.03)a
	Soil moisture (%)	66.20 (1.31)b	64.25 (0.83)a	64.80 (1.44)a
Chemical	Soil Organic carbon (%)	9.65 (0.12)b	7.63 (0.10)c	5.20 (0.10)a
	pH (H_2O)	5.38 (0.02)b	5.21 (0.03)c	4.68 (0.02)a
	Soil Total Nitrogen (%)	0.99 (0.01)b	0.77 (0.02)c	0.59 (0.01)a
	C:N ratio	9.86 (0.19)b	10.24 (0.21)c	8.95 (0.16)a
	Total Organic Carbon (t ha^{-1})	126.67 (1.50)b	110.03 (1.53)a	111.12 (2.53)a
Biological	Soil microbial activity (μg C-CO_2 g^{-1} d^{-1})	144.83 (3.74)b	173.44 (4.30)c	119.08 (2.68)a
	Microbial biomass carbon(μg C g^{-1})	195.80 (7.94)b	100.38 (9.39)c	199.95 (9.73)a
	Metabolic quotient	0.85 (0.04)b	2.46 (0.14)c	0.75 (0.06)a

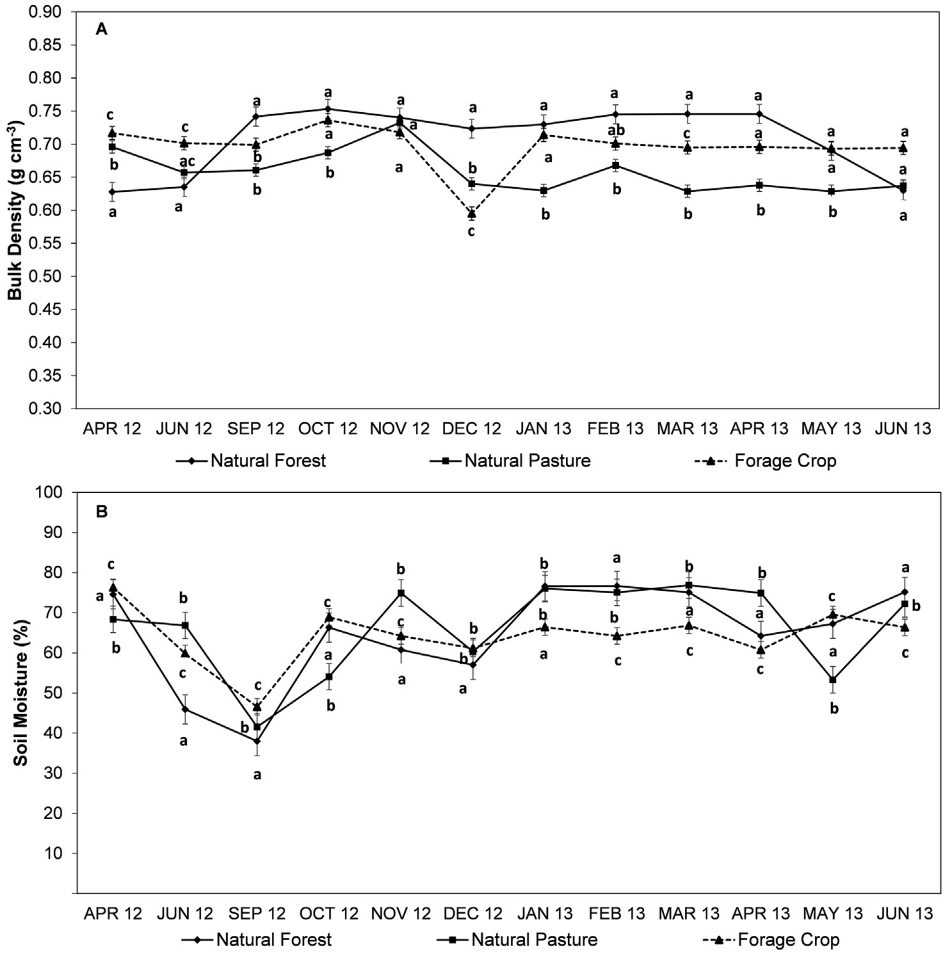

Fig. 2. Temporal variation in A) Bulk density and B) Soil Moisture under three soil management systems (mean ± standard error). Different letters among the soil management systems indicate difference at $P = 0.05$ (Bonferroni multiple comparison).

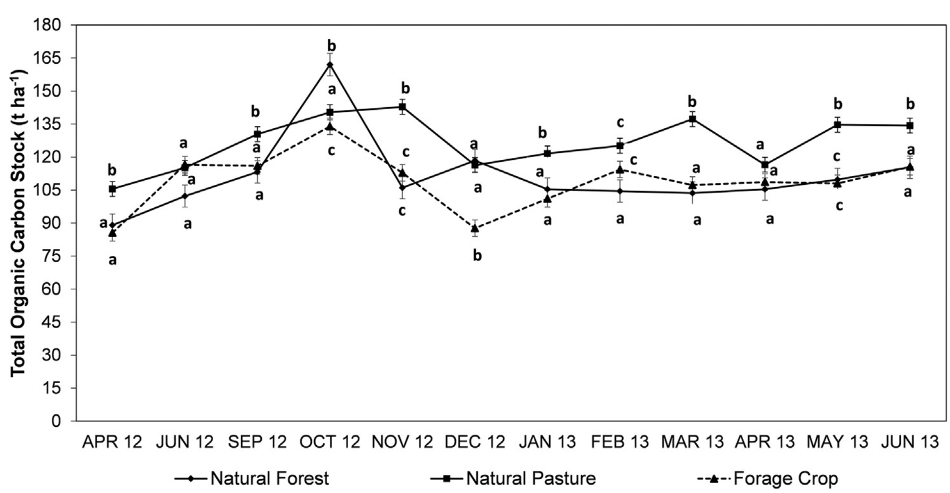

Fig. 3. Temporal variation in total organic carbon of soils under three soil management systems (mean ± standard error). Different letters among the soil management systems indicate difference at $P = 0.05$ (Bonferroni multiple comparison).

$p < 0.001$) and with time × soil management interaction ($F = 392.25$, $p < 0.001$) (Fig. 4A). Soil MB-C of NF was higher than NP and FC in September and November 2012. Soil MB-C of NP and NF were statistically similar. Soil MB-C of FC was higher than NP and NF soils in April 2012.

The metabolic quotient (qCO_2) varied with soil management practice ($F = 15148.62$, $p < 0.001$); the average qCO_2 of FC soil was higher than those of NP and NF soils. The qCO_2 varied significantly with time ($F = 435.02$, $p < 0.001$) and with time × soil management practice interaction ($F = 784.45$, $p < 0.001$). FC soil had the highest

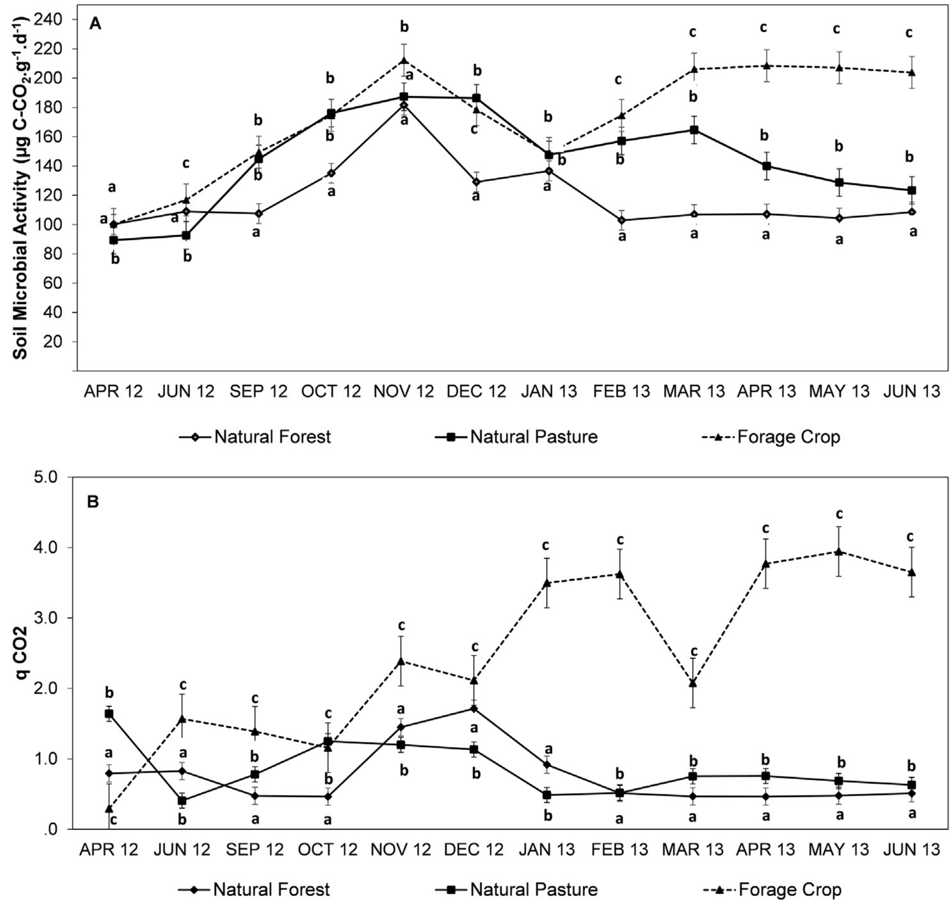

Fig. 4. Temporal variation in A) soil microbial activity and B) Metabolic quotient under three soil management systems (mean ± standard error). Different letters among the soil management systems indicate differ at $P = 0.05$ (Bonferroni multiple comparison).

qCO_2 during all months, except April and October 2012, with higher values during 2013 (Fig. 4B).

3.4. Relations among variables

In general, TOC was positively correlated with the SMA, STN and C:N ratio. BD was negatively correlated with SOC and pH (H_2O). The C:N ratio was positively correlated with TOC, SMA and pH (H_2O). Monthly precipitation was positively correlated with SMA and SM (Table 2).

4. Discussion

4.1. Effects of management practices on soil physical properties

The three management practices have similar effects on soil physical properties. The forest, pasture and fodder crops soil management systems have optimum texture, bulk density and hygroscopic moisture content, these being characteristic of such Andosols. For example, the soil bulk density values did not exceed 0.94 g cm^{-3}, which is considered a critical threshold for establishing crops on Andean soils. Low soil bulk density is associated with the presence of allophane and with high soil organic carbon, as shown by a highly significant negative correlation with the SOC ($Cp = -0.538^{**}$). This correlation also explains the temporal changes in the soil bulk density resulting from changes in the soil organic carbon. These results are consistent with Maturana and Acevedo [21], who suggested an inverse relation between the soil bulk density and the soil organic carbon. Also, tillage can influence the temporal changes in the bulk density and texture by rearranging the soil particles [22]. In the present study there were significant changes in BD, but the three soils all remained a sandy loam with low BD.

The soils of this area are characterised by strong acidity, which is typical of volcanic soils. The forest soil showed the highest acidity because this soil has higher organic acid production and lower cation recycling [23]. The lower acidity of the forage crop soil is attributable to its management with a supply of calcium compounds in the form of carbonates and oxides with high acid neutralising power. These results are similar to those reported by Tonneijck et al. [24] and by Dahlgren et al. [25], they observed that the addition of calcium compounds in the form of carbonates and oxides with high acid neutralising power is the most common management practice for acidity correction and elimination of toxicity in soils of volcanic origin. The significant increase in soil pH (H_2O) over time in the pasture soil was probably due to the continuous supply of organic carbon by cattle, which gradually generates highly condensed molecules (humic substances) that produce strong aluminium retention, consistent with that reported by Haynes and Williams [26].

4.2. Effects of management practices on soil organic carbon storage

The average total organic carbon stock values in the present study are twice the values recorded in Andean soils of the Valle del Cauca and in the rain forests of Costa Rica [27] and three times the

Table 2
Pearson correlation of the physical, chemical and biological characteristics of soil under three soils managements: natural pasture (NP), forage crops (FC) and natural forest (NF).

	SOC (%)	BD (gr cm^{-3})	TOC (ton ha^{-1})	HMC (%)	pH	SMA (μg C-CO_2 g^{-1} d^{-1})	MB-C	SM (%)
Precipitation (mm)								
Correlation coefficient						.288[a]		.310[a]
Sig. (2-tailed)						.000		.000
SOC (%)								
Correlation coefficient		−.408[a]	.622[a]	.683[a]	.634[a]	.358[a]		
Sig. (2-tailed)		.000	.000	.000	.000	.000		
TOC (ton ha^{-1})								
Correlation coefficient	.666[a]			.296[a]		.149[b]	176[a]	
Sig. (2-tailed)	.000			.000		.003	0.10	
pH								
Correlation coefficient	.634[a]	−.330[a]	.188[a]	.490[a]		.454[a]		
Sig. (2-tailed)	.000	.000	.005	.000		.000		
STN (%)								
Correlation coefficient	.823[a]	−.318[b]	.489[a]	.715[a]	.544[a]	.175[a]	.166[a]	
Sig. (2-tailed)	.001	.000	.000	.000	.001	.010	.015	
C:N ratio								
Correlation coefficient	.337[a]	−.168[b]	.225[a]	.683[a]	.228[a]	.321[a]		
Sig. (2-tailed)	.001	.000	.000	.000	.001	.000		
SMA (μg C-CO_2 g^{-1} d^{-1})								
Correlation coefficient	.355[a]		.200[a]		.468[a]			
Sig. (2-tailed)	.000		.003		.000			
Sand (%)								
Correlation coefficient	.316[a]			.243[a]	.544[a]	.534[a]	−.484[a]	
Sig. (2-tailed)	.000			.000	.000	.000	.000	

[a] Correlation is significant at 0.01 level (2-tailed).
[b] Correlation is significant 0.05 level (2 tailed).

values reported for oxisol soils of Brazil and in the Colombian eastern plains [28]. In our study, the soil type and soil management practices are responsible for the high carbon storage potential. Allophane present in these soils form highly stable organo-mineral complexes with organic matter, preventing its easy mineralisation and allowing high carbon storage potential. The higher total organic carbon values for pasture soils were probably due to ranching with prolonged periods of abandonment, which can increase the organic carbon input to the soil. Fisher et al. [29] reported that the productivity of pastures in Colombia was 15–18 t ha^{-1} annually and that the amount of mulch was relatively lower (0.8–1.5 t ha^{-1}), indicating that the mulch decomposes rapidly (mulch half-life of 22–33 days). The present study does not report productivity data; however, the soil total nitrogen concentration values and soil C:N ratio suggest an external supply of STN by the application of urea or most likely by symbiotic fixation; nutrient and organic matter are transferred through the faeces of animals, and this product increases the accumulation of organic carbon in the soil, stimulating the growth of grasses and thus increasing the organic matter above and below the soil [26]. These results differ from those reported by Ibrahim et al. [27], who demonstrated that the improvement of pastures (organic matter inputs) did not favour an increase in SOC, which was statistically similar between improved pastures (81.3 t ha^{-1}), degraded pastures (68.5 t ha^{-1}) and pastures with intensive uses (63.25 t ha^{-1}). However, degraded pastures and intensively used pasture do not significantly contribute to carbon sequestration, because of the high degree of soil degradation and poor return of organic matter to the soil [27].

Despite the high carbon sequestration potential of soils in this region, the three management practices differed from each other in their carbon storage potential. The forest soil stored less TOC than the pasture soil because its processes of nutrient cycling are slower, but it had fluctuating changes over the time when inputs are increased; however its own microclimate causes the organic matter to stay for a long period without transformation in the A_{00} horizon (mulch) of the soil, and the ratio between organic carbon in litter and soil is 7:1 (36%–5.2%). Echeverry [30] reported that the percentage of organic carbon in leaf litter is significantly higher, indicating a lack of mineralisation and soil organic carbon accumulation in this same region. Ibrahim et al. [27] indicated that it is common to find a lower pattern of organic carbon deposits in aged secondary forest soils than in soils under pasture, and this has also been recorded in the present study site [31]. The introduction of agriculture leads to losses of soil organic carbon ranging between 30% and 50% [32] due to the low input of organic matter under conventional cultivation conditions and because the loss of humic material from cultivated soils is higher than the rate of formation of humus in undisturbed soils. Management practices that alter crop yields and soil productivity can affect the soil surface, with a decrease in TOC storage and an increase in greenhouse gas emissions. In the present study, the TOC stored in the forage crop soil is higher than that reported for other cultivated areas in this region [27]; hence, proper management can mitigate many of the potential negative effects of agriculture on soil.

4.3. Effects of management practices on soil metabolic activity

The three management practices examined in this study differ in the soil organic carbon processes that are biologically mediated (soil microbial activity, microbial biomass-C and metabolic quotient) and that determine the soil organic carbon (%). The qCO_2 is one of the indicators of soil quality that quickly responds to induced changes. For the fodder crop soil, the qCO_2 exceeds 1 μg C g^{-1}, suggesting a possible imbalance of the microbial community caused by the type of management. Additionally, the lowest microbial biomass-C and highest soil microbial activity values were found in this soil, reflecting decreased efficiency in the use of organic substances of the soil by the microbial community, and the higher energy consumption by the microorganisms in processing the added mature organic matter (compost) [33]. A previous study of these fodder crop soils in the Las Piedras region reported qCO_2 values below 1 μg C g^{-1} soil, further indicating that the practice of progressive and ongoing management is causing stress to the soil

[30]. In the present study, the pasture and forest soils had qCO_2 values significantly lower than that of the fodder crop soil, reflecting their lower mechanical and chemical intervention. The forest soil is a undisturbed terrain where the quantity and quality of leaf litter affects the state of substances and moisture for microbial growth [34], resulting in a lower value of qCO_2; this quotient should decrease progressively when the ecosystem is not disturbed and tends to equilibrium. This forest ecosystem presents higher microbial biomass-C and lower soil microbial activity possibly as a result of the influence of the strongly acidic pH of this soil [35]. The pasture soil is protected by vegetation cover, by the absence of tillage and by grazing every 2–3 months. The temporal fluctuation in the metabolic activity in the pasture system over the course of a few months is probably due to the use of fertilisers, such as urea and animal manure for farmers.

4.4. Temporal variation of the soil properties

The temporal fluctuations in chemical and physical properties of the three systems were associated more with soil management practices than with the rainfall seasonality. However, soil microbial activity, microbial biomass-C and qCO_2 values had pronounced seasonal changes due to soil moisture. Therefore, forest soils had a significant increase in TOC in October, when the rainy season began after a dry period. Also in October, a significant increase occurred in soil organic carbon from litter and SMA, which led to significant increases in C:N ratios of both soil and litter; this probably stimulated the microorganism activity in the litter to increase the contribution of CO_2 to the soil in October. The increase in TOC represents a major source of energy and nutrients for the development and activity of microorganisms; similar results were found in other tropical ecosystems such as that of the Rio Maracay region of Venezuela [36]. The stimulation of SMA in the rainy season enhances the continuous mineralisation of organic matter, reflected in the sharp decrease of TOC in November in the present study and the decrease in C:N ratio of both soil and litter. In the following months, no changes occurred in the TOC of three these soils; this is probably because decreased rainfall activity prevented populations of microorganisms because a decrease of soil nutrients occurs during the rainy season due to nutrient uptake by plants and soil leaching [37]. A similar trend seen in fodder crop soils but the changes were less pronounced because characteristics such as humidity and pH are controlled in these soils.

The physical properties of these soils showed low temporal variability because 1) these characteristics are dominated by the genesis of soils, and 2) Andosols are highly resilient because of the stability of their organic matter, as mentioned above. However, soil microbial activity fluctuations are positively and highly significantly associated with precipitation ($Cp = 0.304^{**}$) and are associated with the soil moisture content. Pabst et al. [38] reported a decrease in the water content of a mountain soil during the dry season; this is responsible for the reduction of soil CO_2 fluxes and the biomass productivity in systems of higher altitude. After the rewetting of the soil at the beginning of the wet season, high CO_2 emissions are often observed, primarily owing to increased soil microbial activity.

5. Conclusions

In this study, natural pasture promoted the increase of total organic carbon and sustained this ecosystem service in these Andean soils. Management practices promote positive changes in the chemical properties, soil microbial activity and soil nutrient availability of soils under these natural pastures and fodder crops; nevertheless, they adversely affect soil microbial metabolism (qCO_2). Also, the management of the pasture and the fodder crop favours the ability to build stable soil organic carbon, and mechanisms for conservation and protection of soil carbon. The carbon stored depends on the management practices, species composition and soil type, and is enhanced by organic fertiliser application on crops, as well as cattle rotation on grazing soils, extensive ranching, manure spreading, and the rational application of urea on the soils. However, these soil properties must be continuously monitored because the dynamics of organic carbon storage are affected by changes in the rainfall pattern and by interaction with the soil management. These results suggest that the traditional management strategies of this Andean region are successful in achieving food production using low levels of technology and limited resources, without degrading the soils.

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