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RESEARCH ARTICLE

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Evaluation of physical and chemical soil properties under different management types in the south-western Colombian Andes

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Abstract

Aim of study: Evaluating the variability of physical and chemical soil properties under different soil uses in an experimental farmland of the southwestern Colombian Andes.

Area of study: This research was conducted at the Botana Experimental Farm in the mountainous area of Nariño, at the south-western Colombia.

Materials and methods: Nine soil variables were measured under six soil uses which included traditional agriculture, agroforestry systems, and a 67-year-old secondary forest that was used as a reference for comparisons with other soil uses. Data was analyzed through Principal Component Analysis and Dunnet's test.

Main results: Organic carbon, cation exchange capacity, clay contents and base saturation were the variables with higher variability among soil uses. The secondary forest and an agroforestry system with alley-cropped wax laurel showed the best soil conditions, whilst pastures and monoculture potato crop plots showed the least desirable conditions for all variables.

Research highlights: We found that soils under alley-crop with wax laurel presented the characteristics most similar to the secondary forest. Conversely, soils under alley-crop with alder resembled the soils under intensive management (pasture and potato monocrop); which is related to the inadequate management of this agroforestry systems, provoking that the woody component does not accomplish its goal when implemented.

Keywords: soil; agroforestry systems; Andes; forest.

Abbreviations used: ACAL, Alley cropping of Alder Trees, ACWL; Alley cropping of Wax Laurel; AFS, agroforestry systems; AWC, available water capacity; BD, Bulk Density; BS, Base saturation; CEC, Cation Exchange Capacity; CLA, Clay; CI, Confidence Intervals, INF, Infiltration; ANOVA, Analysis of Variance; OC, Soil Organic Carbon; PAST, Pasture; PCA, Principal Component Analysis; PC, Principal Component; POCR, Potato Crop; POR, Soil Porosity; SCAL, Scattered Alder Trees; SEFO, Secondary Forest; SU, soil uses; AU, Animal unit.

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Introduction

Soil degradation is characterized by a variety of negative changes in soil structure and functioning, which cause a reduction of ecosystem services (Palm *et al.*, 2007). The major consequence of this degradation is the deterioration of the physical, chemical and biological properties of soils in the short, medium and long term (Islam & Weil, 2000). These negative effects are caused by harmful technologies such as farming on slopes, over-tillage, acidic fertilizers, excess of pesticides, etc. (Cartes, 2013). Damages in physical soil properties include increased bulk density, changes in the ratios of macroaggregates, and decreased macroaggregate stability (Celik, 2005), whilst the chemical damages include increased soil acidity, nutrient deficit, and a reduction in the amount of soil organic matter (Cartes, 2013).

During the last decade, the implementation of agroforestry systems (AFS) has been an effective and interesting way to mitigate soil deterioration in productive areas, with a special focus on maintaining ecosystem services (Miccolis *et al.*, 2016). Nair (2011) point out that the main benefits of AFS for soils are the fixation of atmospheric nitrogen by species from the Fabaceae and Betulaceae families, the increase of nutrient availability due to biomass production and their mineralization, and the increase of soil organic matter content. Farfán (2014) highlights that AFS provide improvements in soil fertility due to an increased capacity of nutrient re-cycling and water infiltration rates, and a decreased erosion and N volatilization (due to a lower soil temperature under canopies).

According to Moreno (1993), AFS have been in use for over 20 years in Colombia and have proved their benefits to improve physical and chemical properties of the soils. Some of the most noticeable effects of AFS to soils in this country, as reported by several studies, are the decrease of bulk density, increase in soil porosity, increase in soil permeability, increase in the average size of macro-aggregates, and mostly important, the increase in organic matter contents. Furthermore, AFS also generate positive effects for productive systems such as the improvement of pastures and crops (Ramos *et al.*, 2002; Navia *et al.*, 2003; Murray *et al.*, 2014; Murgueitio *et al.*, 2015; Arteaga *et al.*, 2016).

In Colombia, 9.1% of soils are destined for traditional agriculture, 19% for AFS, and 62.5% for forestry, conservation, and restoration (IGAC, 2004). However, 80% of the Andean soils in Colombia are affected by soil erosion (Corponariño, 2012). This degradation is mainly caused by agriculture with harmful technologies that do not consider the suitability of soils for adequate uses. This results in 2,000 ha of degraded soil every year (Corponariño, 2007; 2012).

The Nariño region in south-western Colombia is one of the most important agricultural sources of the country (and abroad), contributing with 3.5% to the national agricultural Gross Domestic Product (DANE, 2019). Only 9% of the Nariño soils are suitable for agriculture, however 22% are used for this activity (Salas & Valenzuela, 2011; IGAC, 2020). This is a warning of a high level of soil degradation in this region, which is related to productivity losses and possible trade-offs between soil use, soil capacity, and soil conservation (Nachtergaele *et al.*, 2012).

Then, a large percentage of the productive lands in Nariño is subject to soil degradation. This degradation has been evidenced by negative impacts on the effective depth, structural stability, bulk density, soil porosity, soil organic matter, Ca and Mg contents, soil water retention, and biological activity (Ordóñez, 2007). However, the information about these processes is still poor in the region, which restricts the possibilities for decision making around sustainable use, restoration, AFS management, and soil conservation.

Hence, this research aimed at analyzing and evaluating the variation of some important physical and chemical properties of the soils under six different soil uses in an Andean landscape of south-western Colombia, where AFS have been applied during the last two decades.

Materials and methods

Study area

This research was conducted at the Botana Experimental Farm (BEF), which belongs to University of Nariño (Colombia; Fig. 1). The farm is located at 77º18'58" W and 1º10'11.4" N and 2820 m above sea level.

The average annual total rainfall is 796 mm, with a first rainy season from October, to December, and a second from March to May. The dry season goes from June to August. The average temperature is 12.8 ºC, with a maximum temperature up to 20°C and a minimum temperature around 9.5 ºC. The relative humidity ranges from 74 to 80%, being higher in the rainy season from October to December. (IDEAM, 2014).

The life zone of BEF belongs to a lower montane humid forest (Cabrera & Muñoz, 2013). The geological record shows undifferentiated volcanic deposits from intercalations of lavas, pyroclastic, fluvio-glacial deposits and lahars in different proportions, with a high degree of fracturing (Colombian Geological Service, 2015). BEF is surrounded by landscapes such as plateaus, hills and mountains (IGAC, 2004).

According to IGAC (2004) there are two andosol types in BEF (Fig. 1B), Vitric Haplustands, and Acrudoxic Hapludands (Table S1 [suppl.]), both very close in physical-chemical configuration. Vitric Haplustands are characterized by deep horizons, good drainage, moderately thick textures, strong acidity, low fertility, high aluminum saturation, and high organic matter contents, whilst Acrudoxic Hapludands are characterized by deep horizons, moderately thick textures, well drained, very strongly acidic, low fertility, high aluminum saturation and high organic matter contents.

Study design and sampling

The study area is divided in six soil uses (SU; Fig. 1) because of the historical farm managements during the last 20 years. These SU's are:

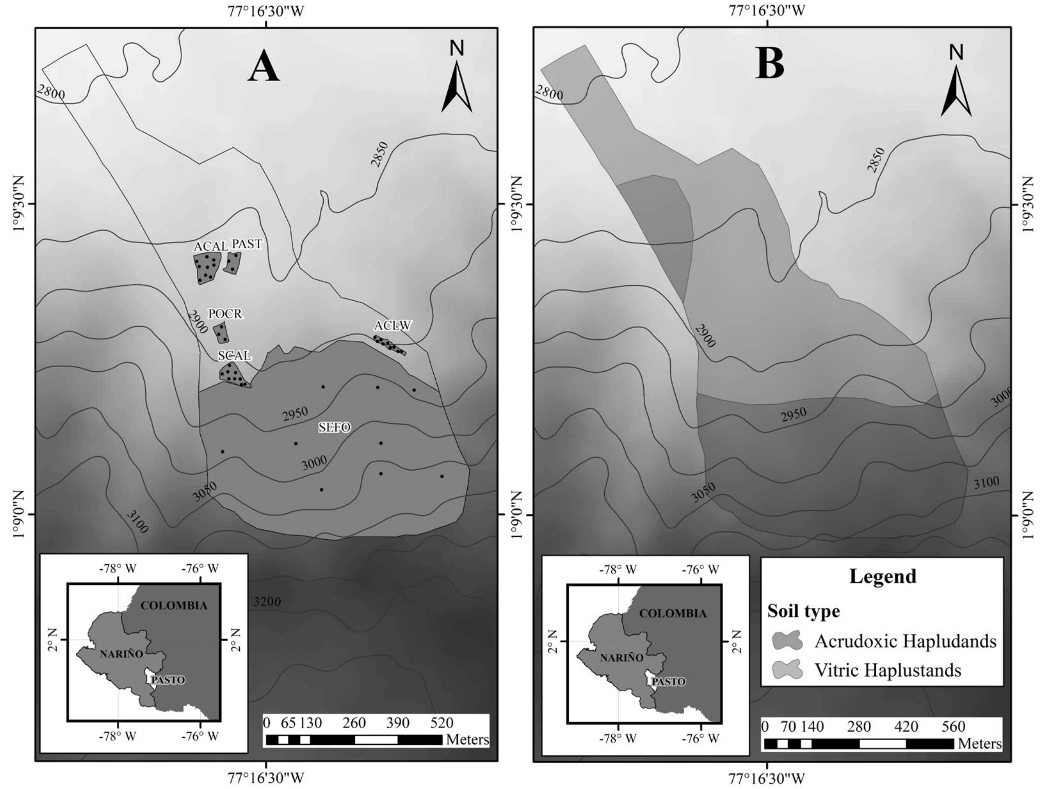

Figure 1. A) Map of the Botana Experimental Farm showing the studied Soil Uses. Black dots represent the sampling sites within each SU. Alley cropping of Wax Laurel (ACWL), Scattered Alder Trees (SCAL), Alley cropping of Alder Trees (ACAL), Potato crop (POCR), Pasture (PAST), Secondary Forest (SEFO). **B)** Map of soil types in the study area.

1. Potato crop (POCR) (*Solanum tuberosum* L.), with a total area of 0.23 ha and a slope ranging from 12 to 25% in S-N direction. Soil under POCR has been subject to chemical fertilizers and pesticides since year 2005.
2. Pasture (PAST) *Pennisetum clandestinum* Hochst. ex Chiov., with a total area of 1.0 ha, a loading capacity of 3.0 AU ha^{-1} (Holstein cattle) and a slope higher than 50% in E-W direction. This system has been kept invariant during the last 10 years
3. Alley cropping of Alder Trees (ACAL), stablished since year 2002. This AFS has a total area of 0.46 ha and 172 trees arranged in rows of six trees in NW-SE orientation (equivalent tree density: 374 trees ha^{-1}). Distance between rows is 5 m and between trees 3 m. The slope ranges from 25 to 50% in S-N direction.
4. Scattered Alder Trees (SCAL) (*Alnus acuminata Kunth*) stablished since year 2000. This AFS has a total area of 0.72 ha and 57 trees (equivalent tree density: 79 trees ha^{-1}) associated with *P. clandestinum*. This system has a loading capacity of 4.5 AU ha^{-1} (Holstein cattle) and a slope ranging from 12-25% in SE-NW direction.
5. Alley cropping of Wax Laurel (ACWL) (*Morella pubescens* (Humb. & Bonpl.) Wilbur), stablished since year 2000 (Ramírez *et al.*, 2002). This AFS has a total area of 0.3 ha, 83 trees (equivalent tree density: 277 trees ha^{-1}) with a planting distance of 6.0 m, and a slope ranging from 12-25% in SE-NW direction.
6. Secondary Forest (SEFO), under conservation since year 1953, composed by 34 plant species but dominated by *M. pubescens*, *Myrisine coriaceae* (Sw.) Roem and Schult, *Viburnum triphyllum* Benth. and *Vallea stipularis* Mutis ex. L.F. (Argotty & Collazos, 2001). SEFO has a total area of 40 ha and a slope ranging from 25-50% in S-N direction. SEFO was considered in this study as a reference to compare with the rest of SU's. This was because the soil under this SU has experimented nearly 60 yr of natural soil restoration and currently is under strict protection from any kind of anthropogenic perturbation. Thus, we assumed that SEFO would reflect the best physical and chemical soil conditions.

SU's were divided in three plots (high, mid, and low, according to the slope; Fig. 1). Ten soil samples were randomly taken from each plot, following a zig-zag-pattern that covered the whole SU (IGAC, 2014; FAO, 2018). Soil samples from each plot were mixed and homogenized to obtain two representative samples. Only five random samples were taken from POCR and PAST plots, following the same zig-zag pattern as mentioned above. These were mixed and homogenized to obtain one representative soil sample from each plot.

Only the low part of SEFO was sampled because the mid and high parts belong to a different soil type from the rest of SU's (Fig. 1). This resulted in only one plot stablished at SEFO and hence, only one value for each soil variable was available at this SU for further data analyzes.

Measurement of physical and chemical soil variables

After extraction, soil samples were labeled and transported to University of Nariño (Colombia) to be immediately analyzed. A total of 12 physical and chemical soil variables were measured in each soil sample directly in the laboratory, and 3 variables were computed later using equations and previously measured variables. Six of the variables measured at the laboratory were not directly included in subsequent statistical analysis, but indirectly as parameters in equations for computed variables. Therefore, nine final variables were used for further statistical analysis. Table S2 [suppl.] lists these variables and the methods followed for their measurements. Previous soil data from SEFO (Enríquez & Goyes 2018) was used as reference values to allow for additional comparisons against the rest of SU's.

Statistical analysis of data

A Principal Component Analysis (PCA) with a correlation matrix was performed in order to first explore the variability of physical-chemical soil variables among SU's. Later, simple Analyzes of Variance (ANOVA) were performed taking every soil variable as response, and SU as a fixed factor. Since only one mean value was available for SEFO, the statistical significance of the differences between SEFO and each SU was tested using the Dunnet's test for multiple comparisons against a single reference value, followed by Bonferroni adjustments of p-values to control for family-wise error rate (FWER) (R-package 'multcomp') (Hothorn *et al.* 2021). The difference among SU's excluding SEFO, was assessed by visually inspecting their 95% confidence intervals (CI) (Cumming *et al.* 2007). All the analyzes were performed in R-studio version 3.4.1 (R-studio Team, 2019), and $\alpha = 0.05$ was used as the significance threshold.

Results

The two first Principal Components (PC1 and PC2) explained 64.5% of the original variance in the physical and chemical soil variables (PC1 = 47.3%, PC2 = 16.7%) (Fig. 2). This percentage of variance was considered satisfactory as the result of the reduction in data dimensionality, and hence, these two components were kept and used

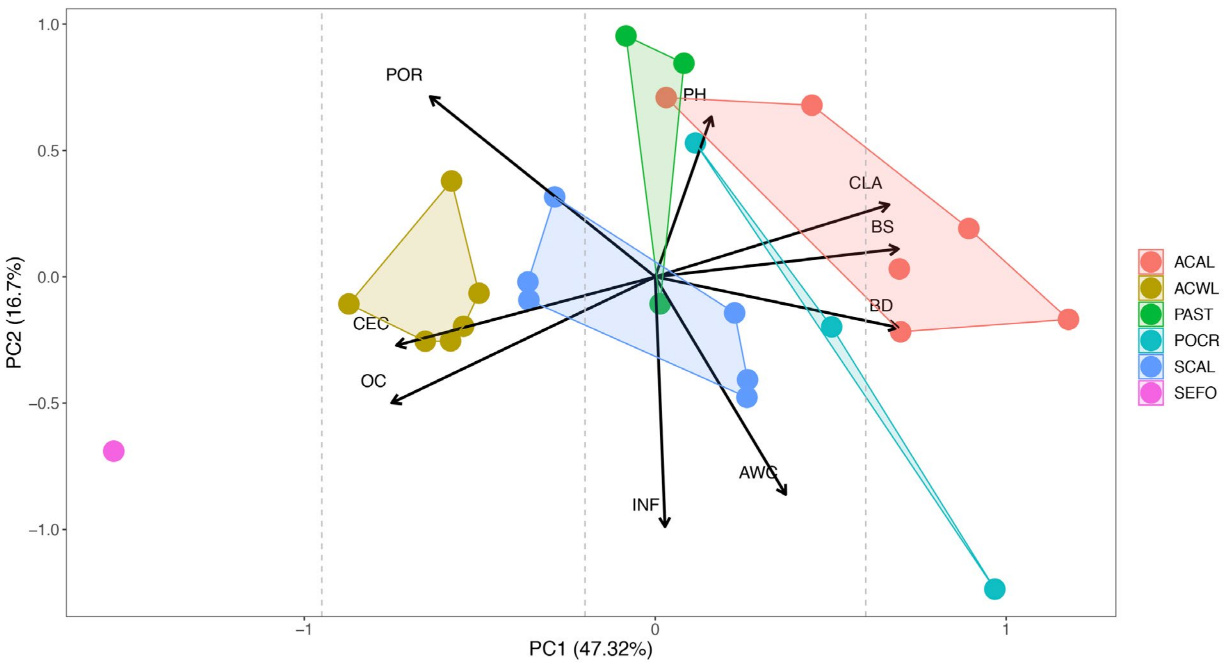

Figure 2. Scatterplot of scores from Principal Component Analysis performed to soil variables in plots under different soil uses in the study area. Dotted vertical gray lines represents the limits of quartiles for PC1. Alley cropping of Wax Laurel (ACWL), Scattered Alder Trees (SCAL), Alley cropping of Alder Trees (ACAL), Potato crop (POCR), Pasture (PAST), Secondary Forest (SEFO).

to interpret the variability among SU's. By inspecting the correlation coefficients (r) between PC's and the original soil variables, it was observed that PC1 was mainly correlated with OC (-0.42), CEC (-0.41), CLA (0.37), BD (0.39) and BS (0.39), whilst PC2 was with pH (0.36), POR (0.40), INF (-0.56), and AWC (-0.49) (Table 1). The scatter plot of Fig. 2 show that SEFO is located far to the left of graph in the first quartile of PC1. By examining PCA loadings (arrows), this position is characterized by the highest levels of OC and CEC, and the lowest levels of CLA, BS and BD. Next to SEFO to the right, ACWL plots are grouped within the second quartile of PC1, showing the second highest levels of OC and CEC, and the second lowest levels of CLA, BS and BD. Next to the right between the second and third quartile, most of the SCAL, PAST, POCR and ACAL plots are mixed, and finally, a few samples from POCR and ACAL are found within the fourth quartile, showing the lowest levels of CEC and OC, and the higher levels of CLA, BS and BD.

Table 1. Loadings of every physical and chemical soil variable on PC1 and PC2. Only variables with the higher loadings are shown

Component	Variable	Loadings
1	OC	-0.42
	CEC	-0.41
	CLA	0.37
	BD	0.39
	BS	0.39
2	pH	0.36
	POR	0.40
	INF	-0.56
	AWC	-0.49

OC: Soil Organic Carbon; CEC: Cation Exchange Capacity; CLA: Clay; BD: Bulk Density; BS: Base saturation; pH; POR: Soil Porosity; INF: Infiltration; AWC: Available water capacity.

The variability of SU's throughout PC2 was not so clear as for PC1, however two interesting observations are the highest pH for two plots from PAST and the lowest INF for a plot from POCR. For the rest of soil variables, no further among-SU differentiation was observed in PC2.

Fig. 3 show the statistical comparison of mean values among SU's for each soil variable, and for SEFO against the each of the other SU's. Mean OC in SEFO (10%) was the highest, and was significantly different from all SU's. Mean OC in ACWL (5.66%) was the most similar to SEFO, and also, the most similar to the mean OC value from Enriquez & Goyes (2018) (6.7%). CI of mean OC in AWCL did not overlap with the CI's from the rest of SU's, indicating significant differences. CI's from SCAL, POCR, PAST and ACAL did overlap, pointing to significantly lower mean OC values compared to SEFO and ACAL. Results for CEC similar. SEFO showed the highest mean CEC for both our data (45.2 $cmol_+ \cdot kg^{-1}$) and the data from Enriquez & Goyes (2018) (36.3 $cmol_+ \cdot kg^{-1}$), and AWCL showed the second highest mean value (29.8 $cmol_+ \cdot kg^{-1}$). Means of SCAL, POCR, PAST and ACAL were significantly lower, with values below 25 $cmol_+ \cdot kg^{-1}$.

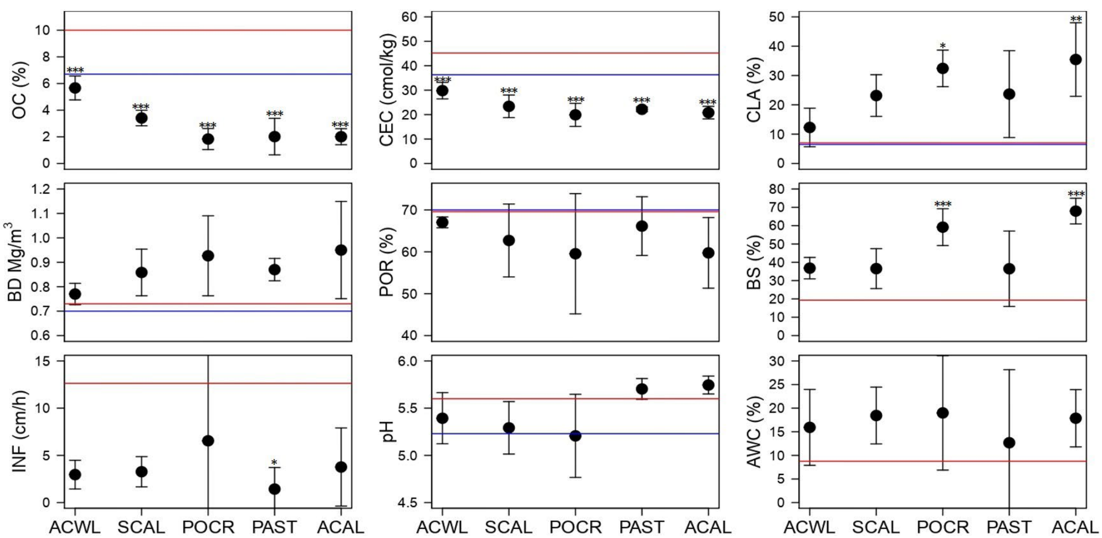

Figure 3. Comparison of mean values of soil variables among soil uses in the study area. Horizontal red line represent the mean value from SEFO and horizontal blue line the mean value from Enríquez & Goyes (2018). Vertical black bars represent 95% confidence intervals, and asterisks the significance of the difference between SEFO and each of the SU's according to Dunnet's test with bonferroni adjustments. * p<0.05; ** p<0.01; *** p<0.001. Dunnet's test were performed only for the red line. Alley cropping of Wax Laurel (ACWL), Scattered Alder Trees (SCAL), Alley cropping of Alder Trees (ACAL), Potato crop (POCR), Pasture (PAST), Secondary Forest (SEFO).

For CLA, SEFO showed the lowest mean value (7%) both in our data and in the data from Enriquez & Goyes (2018) (7.1%), but significant differences were detected only for POCR and ACAL (28.5 and 36.4 % of CLA percentage respectively). Again, for this variable, ACWL showed the most similar mean value to SEFO.

BD did not differ significantly among SU's, however, ACWL and SEFO showed the lowest values both in our data and in the data from Enriquez & Goyes (2018) (0.73, 0.77 and 0.70 Mg/m^3 respectively). POR did not show significant differences among SU's, although SEFO had the highest mean values both in our data (69.6%) and in the data from Enriquez & Goyes (2018) (70%). For BS, only POCR and ACAL showed significantly higher means compared to SEFO, which had the lowest value (19%). For INF, only PAST were significantly lower than SEFO, and for pH and AWC, there were no significant differences among SU's. No data was available for BS, INF and AWC from Enríquez & Goyes (2018).

Discussion

OC values found in SEFO (10±4.0 %) exceeded the 5.8% threshold considered high for OC contents in the Andisols around the study area (Arias *et al.*, 2007; Jaramillo, 2002). CEC levels in SEFO are related to the high OC content, whilst CEC levels in POCR and ACAL are associated to the clay contents (35.4% and 32.4%, respectively). In a study conducted by Arteaga *et al.* (2016) at a site near the study area, the behavior of OC under different soil uses was found to be correlated to CEC. This variable is crucial for plant nutrition and, furthermore, the movement of ions is strongly dependent on the OC and clay contents in the soil (Hemmat *et al.*, 2010; Gruba & Mulder 2015). Shinya *et al.* (2017) evaluated the effect of the application of organic matter to different Andosols in Japan, and found that CEC was correlated to OC, highlighting a positive linear relationship between them. They also found a positive relationship between the temporal change of both variables. This clarifies that a large fraction of CEC is determined by OC, and that changes in CEC are closely related to changes in OC (Hemmat *et al.*, 2010). According to Kapland & Estes (1985) and Fageria *et al.* (2010) there is a direct and proportional relationship between OC and CEC in the soil, where 1.0% increase of OC in dry weight produces an average increase of 2.93 $cmol_+ kg^{-1}$ in CEC. This resembles the data from BEF, because when comparing SEFO to the rest of SU, CEC had an average increase of 2.59 $cmol_+ kg^{-1}$ for each 1.0% increment in OC.

In the study area, the lowest OC values were found in PAST, ACAL and POCR, ranging from 1.8 and 2.0%. There was a difference of 8% OC between PAST and SEFO, which could be explained by the mechanism of organic residuals (OR) incorporation to the soil. In pastures, most of the OR are produced by roots and hence, are directly incorporated into the soil profile, while in forests and AFS's dominated by woody species, the OR produced by canopies comes through soil surface (Céspedes, 2007; Apráez *et al.*, 2014; Zambrano *et al.*, 2014).

In the case of ACAL, the low OC and high BD mean values are probably the result of low tree density along with an inadequate management without periodic pruning, which prevents the contribution of OR to the soil. Pruning provides biomass inputs to the soil and influence long term OC contents (Navia *et al.*, 2003 y Arteaga *et al.*, 2016).

On the other hand, the low contents of OC in POCR are probably associated to the intensive tillage of soil for potato cropping, and to the null incorporation of OR. Extended monoculture practices accelerate OC decomposition in the soil and cause a reduction of C from 20 to 67% (Davidson & Ackerman, 1993; Wei *et al.*, 2015; Lal, 2001; Yang *et al.*, 2019). Soil tillage can negatively affect the processes related with soil respiration, temperature regulation, water content, pH, redox capacity and the community of microorganisms (Kladivko, 2001, Liu, *et al.*, 2006). Beare *et al.* (1994) reported that tillage accelerates the oxidation from OC to CO2 by the increased aeration and the contact between soil and the OR from crops, exposing OC to the microbial action. Tillage also exposes OC from the intra and inter soil aggregate zones to be immobilized inside microbial cells for further oxidation (Roscoe & Burman, 2003). Finally, low incorporation of OR to the soil may lead a progressive decrease in OC (Jhonstom, 1991; Arteaga *et al.*, 2016).

Sanderman *et al.* (2017) recently suggested that the land use change from native vegetation to agriculture cause a rapid decrease of 100 Pg of OC globally. In this regard, Don *et al.* (2010) emphasized the importance of land use change and soil management. They found 12% loss of OC when turning soil use from forest to pastures, and 12% gain from pasture to forest. These values are similar to what was found in BEF, where SEFO showed a mean OC of 10%, whilst POCR and PAST showed means of 2.0% and 1.8% respectively.

According to Salamanca & Sadeghian (2005), BD is affected by solid particles and pore space, which in turn, are determined mainly by OC. Therefore, as pore space increase, BD decrease (Stine & Weil, 2002). This behavior was evidenced in the study area where SEFO showed a mean BD of 0.61 Mg m^{-3} and a mean POR of 74.1%, whilst the opposite was observed in ACAL and POCR with mean BD of 0.95 and 0.93 Mg m^{-3} respectively, and mean POR of 59.7% and 59.5% respectively. Soils under forest canopies have a thicker organic layer (Noguera & Vélez, 2011), which favors porosity, infiltration rates, and permeability, preventing soil and water losses (Apráez *et al.*, 2014; Arteaga *et al.*, 2016). Noguera & Vélez (2011) mentioned that a rich community of forest species cause an increase of macropores involved in drainage and aeration, due to their contribution of OC to the soil, which was the case of SEFO and ACWL in BEF. Furthermore, Noguera & Vélez (2011) stated that land use changes from native forest land cover to crops or pastures, bring a 30% decrease of POR due to a reduction of the organic-residue inputs to soil.

The clay contents in ACAL (35.5%) and POCR (32.4%) were the highest among all SU's. This was probably due to soil mechanization processes carried out before the establishment of the crops. Considering that the study was carried out in the first 0.20 m of the soil, the disc plow (0.40 to 0.50 m deep) used in ACAL and POCR favored the haploidization processes and the ascent of the illuviated clays.

Regarding the available water capacity (AWC), SU's with clay loam textures (finer textures) had the highest percentages of AWC, such as POCR (18.99%) and SCAL (18.44%), whilst SEFO showed the lowest AWC values (8.75%) and a sandy loam texture. According to Eden *et al.*, (2017) and Verberg *et al.*, (2018) finer textures tend to retain more water between field capacity and permanent wilting point.

High BS values in ACAL (67.95%) and POCR (59.19%) are probably related to the application of fertilizers and amendments, which occupy the exchange sites in the colloidal complex of the soil. In the opposite way, SEFO with the lowest BS value (19.31%), is influenced by high OC contents, leaching and mineralization processes of the organic matter, where produced anions such as NO3, SO4 form ionic pairs and drag the basic cations (Espinosa & Molina, 1999).

Finally, INF was higher in SEFO. This result was expected because of the effect of roots, high OC contents, and high sand contents. Higher OC contents improves the conditions for soil structuring, which favors the formation of macro and micro aggregates, increasing infiltration rates (FAO, 2017).

Conclusions

SU's grouped in a descending order according to the physical and chemical soil properties as follows: SEFO>ACWL>SCAL>ACAL>PAST>POCR. ACWL is therefore according with our results, the SU that allows a higher soil preservation.

ACAL showed soil properties similar to POCR and PAST, which is related to the inadequate design, implementation and management of this AFS, implying that the woody component does not accomplish its goal when implemented.

OC contents are associated to other physical and chemical properties and could be therefore an indicator for soil use and management in Andean AFS.

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