SOIL STRUCTURE AND CARBON SEQUESTRATION AS ECOSYTEM SERVICES UNDER DIFFERENT LAND USES IN THE ECUADORIAN AMAZON REGION
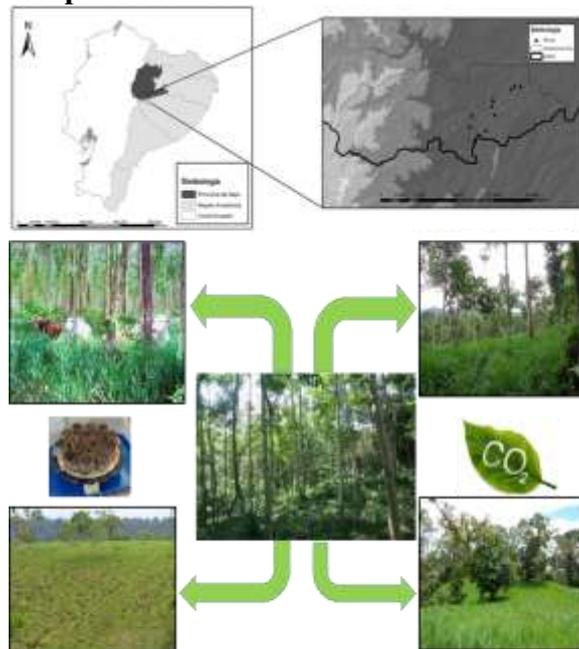
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Graphical Abstract

Structural indexes/Carbon Stock	Depth 10-30 cm				
	AFSs GGWT	GGWTHT	AFSs DGWT	DGWTHT	Secondary Forest
Bulk density (BD)	0.57b	0.82a	0.81a	0.84a	0.44b
saturated hydraulic conductivity (Ksat) cm h⁻¹	6.27b	10.34b	0.78c	10.69b	25.51a
Total porosity (TP)	81.89a	72.63b	73.15b	69.79c	83.14a
Aeration porosity (AP)	9.51a	9.18 a	9.19 a	9.50 a	12.31a
Retention porosity (RP)	72.47a	63.45a	63.97a	60.29a	70.83a
Soil C stocks (Mg C ha⁻¹)					
0-30 cm	49.44b	41.03c	46.91b	36.75c	51.49u
Reduced soil C stock	-2.05	-10.46	-4.58	-14.74	---
(Mg C ha⁻¹)	(4 %)	(20 %)	(9 %)	(29 %)	

Abstract

The identification of the factors that cause changes in agroecosystems and the services they provide is essential to design management that minimizes negative impacts on the environment. In this sense, the objective of this research was to characterize some structural indices and the carbon sequestration potential under different land uses in the Ecuadorian Amazon region. In each selected land use, we collected disturbed an undisturbed soil samples within depths from 0-10 and 10-30 cm. From these samples were evaluated some structural indexes such as the bulk density (BD), saturated hydraulic conductivity (K_{sat}), total porosity. (Tp), aeration porosity (Ap), retention porosity (Rp) and total organic carbon (TOC). The results showed significant differences by treatment and depth, obtaining the best physical condition in the Forest and in some uses of grass with trees. Regardless of land use, the structural conditions evaluated through the structural indexes exhibited better results in the surface horizon, which is strongly associated with the content of organic matter. It is shown that the reduction of greenhouse gas emissions (CO_2) is associated with the increase and protection of organic matter with agroforestry systems.

Key words: *Multivariate analysis, fertility, impact, Amazon Region, land use*

Introduction

The soil resource represents a fundamental subcomponent of natural ecosystems and agroecosystems due to the multiple functions attributed to it and the relationships it maintains with the rest of the components. The soils of the tropics are relevant for the global C cycle due to the magnitude of their area and the production of biomass (Gardi et al., 2014). In tropical regions, extensive conversion of forests to pastures and agricultural intensification are typically identified as the most important promoters of land use change, with consequent loss of fertility, quality and biodiversity (Bravo et al., 2017; Valera et al., 2016; Vallejo-Quintero, 2013). Moreover, the intensification of agricultural production and the management systems with a focus on monoculture have profound effects on the ecosystem services provided by the soil and its biodiversity (Altieri and Nicholls, 2013). Soils and their biodiversity are the engine of all production systems and most of the environmental services of terrestrial ecosystems are provided by this resource. For example, primary production, nutrient recycling, water and carbon storage, detoxification, pest and plant disease control, and flood control are highly dependent on the quality of the soil and the integrity of its functioning biological (Lavelle, 2009). In this context, it has been pointed out that of the 24 largest environmental services registered in the Millennium Ecosystem Assessment, 12 are produced by the soil to a large extent and 5 depend very much on it (Lavelle, 2009, MEA, 2005). Therefore, the identification of the factors that cause changes in agroecosystems and the services they provide is essential to design management that minimizes negative impacts on the environment.

Ecosystem services can be defined "the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly" and the Millennium Ecosystem Assessment (MEA, 2005) describing four categories being: supporting, provisioning, regulating and cultural service. In this perspective, agroecosystems can be suppliers and consumers of ecosystem services and humans value these systems chiefly for their provisioning services, and these highly managed ecosystems are designed to provide food, forage, fibre, bioenergy and pharmaceuticals. However, the functioning of agroecosystems depends strongly on a set of ecosystem services provided by the natural resources of untouched ecosystems (Zhang et al., 2007).

Soil structure along with genetic biodiversity for use in crop and livestock breeding, soil fertility, nutrient recycling and water supply are considered as support services (Zhang et al., 2007). While carbon sequestration is classified as a regulatory service due to the effect it has on climate regulation through greenhouse gas emissions (Power, 2010).

Soil structure and aggregate stability are important to improving soil fertility, increasing productivity, enhancing porosity and decreasing erodibility (Bronick and Lal, 2005). The structure of soils is composed by primary and secondary particles. Primary particles are individual units of sand, silt and clay, while the secondary particles result from the arrangement and binding of primary particles into aggregates by the effect of organic compounds and inorganic cementing agent's suelo (Alvarez y Taboada, 2008).

Soil structure and fertility play a large role in determining where different kinds of farming take place and the quantity and quality of agricultural output (Zhang et al., 2007). Earthworms and macro and micro invertebrates increase soil structure via burrows or casts and enhance soil fertility through partial digestion and communion of soil organic matter (Edwards, 2004). Moreover, well-aerated soils with abundant organic matter are fundamental to nutrient acquisition by crops, as well as water retention (Zhang et al., 2007). Also, soil pore structure, soil aggregation and decomposition of organic matter are influenced by the activities of bacteria, fungi and macrofauna, such as earthworms, termites and other

invertebrates (Power, 2010; Martinez et al., 2008). Management practices in agroecosystems can degrade, maintain or improve soil structure (Bravo et al., 2017; Pla, 2010), as well as affect soil microbial communities as bioindicators sensitive to changes in land use (Vargas-Machuca, 2010). For example, agricultural management practices as mechanical ploughing, disking, cultivating and harvesting can degraded soil structure (Power, 2010), but other management practices as cover crops, incorporation of crop residues and agroforestry system reduce erosion and runoff and can maintain soil organic matter, fertility by minimizing the loss of nutrients and keeping them available to crops (Bravo et al., 2016; Espinoza-Dominguez, 2012) Together these practices conserve a suite of ecosystem services to agriculture from the soil (Power, 2010).

Soil organic carbon (SOC) is related to the sustainability of agricultural systems affecting soil properties related to the sustained yield of crops. However, the amount of COS does not only depend on local environmental conditions, but it is strongly affected by soil management (Martinez et al., 2008). Soil carbon sequestration thus provides additional ecosystem services to agriculture itself, by conserving soil structure and fertility, improving soil quality increasing the use efficiency of agronomic inputs, and improving water quality by filtration and denaturing of pollutants (Lal 2008). Therefore, the identification of management systems or land uses for carbon capture and the improvement of soil structural conditions can restore the functionality and productivity of the soil resource. Appropriate management practices can reverse degradation, reducing CO_2 emissions to the atmosphere and providing a series of benefits not only in the mitigation of climate change, but also in desertification and erosion control, water quality, food security and Soil fertility increasing the absorption of water in the soil as corrective measures for global warming (Bravo et al., 2016; Lal, 2008). Numerous works both globally and nationally show the capacity of agroforestry systems to store organic carbon in the soil, which reflects its potential to mitigate climate change, ranging from 24 to 70 Mg ha^{-1} (Bravo et al., 2016; Deng et al., 2016; Somarriba et al., 2012; Jadan et al., 2012). Despite hundreds of field studies and at least a dozen literature reviews, there is still considerable disagreement about the direction and magnitude of changes in C stocks in the soil with the change in land use (Deng et al. al., 2016).

With this perspective, the objective of this work was to characterize the structure and carbon stored in the soil as ecosystem services under different land uses in the Ecuadorian Amazon region.
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Materials and Methods

The work was carried out in municipality of Carlos Julio Arosemena Tola, Napo province, Ecuador (Figure 1). The climate is characteristic of a humid tropical forest, with an altitude of between 500 and 600 masl. The average annual rainfall is 3000mm, an evapotranspiration of 150mm, temperatures between 23.4 to 25°C and a relative humidity of 86% (Uvidia et al., 2015). The soils belong to the inceptisol order and are recent, shallow and generally acidic soils without well-defined horizons but with high organic matter content, low natural fertility (low potassium, calcium and phosphorus content) and high iron contents (Bravo et al. 2017, Nieto and Caicedo, 2012). Land uses related to livestock systems were selected, which were compared with the primary forest as reference system, describe as: GGWFT: Gramalote grass with trees; GGWTHT: Gramalote grass without trees; DGWT: Dali Grass with trees; DGWTHT: Dali Grass without trees and SF: Secondary Forest.
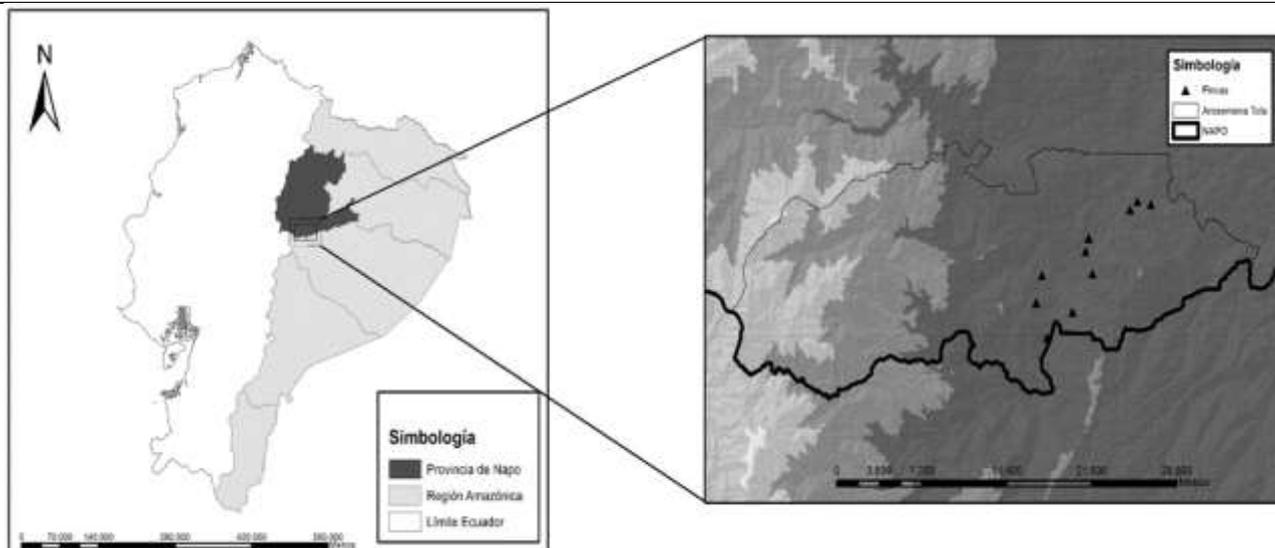
Figure 1. Relative location of selected land uses in municipality of Arosemena Tola, Napo province, Ecuador.

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Soil sampling, determination of structural indices and total organic carbon.

The impact of land-use change on structural indices and total organic carbon was assessed using a systematic sampling scheme, establishing a transect of five sampling points for each selected land use. We collected disturbed an undisturbed soil samples at 0-10 and 10-30 cm depth. From these samples undisturbed were determined, Bulk Density (BD) using the cylinder method (Blake and Hartge, 1986); the saturated hydraulic conductivity (K_{sat}) by the variable loading method (Pla, 2010); and the pore size distribution (Tp: total porosity), aeration porosity (Ap: pores of radius> 15µm) and retention porosity (Rp) using the table of saturation tension and to a matric potential of -10kPa (Gee and Bauder, 1986). Total organic carbon (TOC) was analyzed by Walkey-Black method (Nelson and Sommer, 1982).

Results and Discussion

Table 1 shows the results of the average values of structural indices and carbon sequestration in the different land uses and the two soil depths considered. As can be seen, the structural indexes showed significant differences ($P < 0.05$), resulting in better physical conditions the surface horizon indistinctly of land use. When comparing the different land uses and the two depths considered, a good physical behavior is observed, which is reflected in the evaluated structural indexes (BD, K_{sat}, Tp, Ap, Rp) with better values in the superficial horizon, especially the use with secondary forest. Bulk density (Da) varied significantly ($P < 0.05$), obtaining the lowest value in the Secondary Forest (SF,) (0.34 Mg m^{-3}) and GGWT (0.43 Mg m^{-3}), while the rest of the selected land uses reached the highest densities. Regardless of the land use, the value of the bulk density increased with depth (10-30 cm), reaching values between 0.81 to 084 Mg m^{-3}. Bulk density represents a very important variable of great agricultural significance whose values must be interpreted according to the textural class. In general, the textural classes determined in the field for the selected land uses varied between clayey and clay loam, categorized as fine textures. Therefore, when comparing the values obtained from BD with any depth and land use with the value indicated as critical of 1.3 Mg m^{-3} for this type of texture, it can be noted that there is no soil compaction (Pla, 2010) and therefore a good functioning that favors a greater possibility of exploration of the volume of soil by the roots of the plants. In addition, bulk density has a strong influence on the development of roots, the resistance to penetration, the movement of water, air, the content of nutrients and their availability (Alvarez and Taboada, 2008). Sometimes the most important effects of land use

change are associated with the change in pore geometry, which even without large variations in density, determine strong changes in the soil hydrological behavior (Bravo, et al., 2015). When we analyzed the value of saturated hydraulic conductivity (Ksat), associated with soil permeability, high values were recorded in all uses, well above the critical limit of 0.5 cm.h^{-1}, (Pla (2010), in special, in the Forest and GGWT (Table1).

This behavior is related to the textural and structural condition that favors the penetration and movement of water in the soil profile. In general, the hydraulic behavior of the soil, presented the highest values of Ksat in the surface horizon (0-10 cm), which decreases with depth (layer of 10 to 30 cm) to reach values close to 0.78 cm h-1 in some land uses (DGWT). The values of the total porosity (Tp) were much related to bulk density, suggesting that the higher the density, the lower the porosity. Total porosity (Tp) was high in all the land uses studied (greater than 60%), with a large fraction of the total volume represented by the retention pores (Rp), which gives these soils a high moisture retention capacity, indistinctly of the land use. On the other hand, the volume of aeration pores (macropores (Ap)> 15 μm) that actively contribute to the water flow (Bravo et al., 2008; Alvarez and Taboada, 2008), they are in smaller proportions.

Table 1. Structural indexes and carbon sequestration under different land uses systems.

| | Depth 0-10 cm | | | | |
| | AFSs | | AFSs | | Secondary |
Structural indexes	GGWT	GGWTHT	DGWT	DGWTHT	Forest
Bulk density (BD) Mg m^{-3}	0.43**b**	0.56**a**	0.53**a**	0.56**a**	0.34**b**
saturated hydraulic conductivity (K$_{sat}$) cm h^{-1}	33.48**b**	39.80**b**	17.42**c**	13.10**c**	49.74**a**
Total porosity (TP) %	85.01**a**	82.01**a**	80.47**a**	84.12**a**	86.77**a**
Aeration porosity (AP) %	13.66**b**	14.92**b**	13.87**b**	15.74**b**	18.77**a**
Retention porosity (RP) %	71.41**a**	67.09**a**	66.60**a**	68.38**a**	68.00**a**
	Depth 10-30 cm				
Structural indexes/Carbon Stock	AFSs GGWT	GGWTHT	AFSs DGWT	DGWTHT	Secondary Forest
Bulk density (BD)	0.57**b**	0.82**a**	0.81**a**	0.84**a**	0.44**b**
saturated hydraulic conductivity (Ksat) cm h^{-1}	6.27**b**	10.34**b**	0.78**c**	10.69**b**	25.51**a**
Total porosity (TP)	81.89**a**	72.63**b**	73.15**b**	69.79**c**	83.14**a**
Aeration porosity (AP)	9.51**a**	9.18 **a**	9.19 **a**	9.50 **a**	12.31**a**
Retention porosity (RP)	72.47**a**	63.45**a**	63.97**a**	60.29**a**	70.83**a**
Soil C stocks (Mg C ha^{-1}) 0-30 cm	49.44**b**	41.03**c**	46.91**b**	36.75**c**	51.49**a**
Reduced soil C stock (Mg C ha^{-1})	-2.05 (4 %)	-10.46 (20 %)	-4.58 (9 %)	-14.74 (29 %)	---

Agroforestry systems (AFSs); GGWT: Gramalote grass with trees; GGWTHT: Gramalote grass withoth trees; DGWT: Dali Grass with trees; DGWTHT: Dali Grass without trees. Significant differences of the means according to Tukey's adjustment (P< 0.05) in the same row are indicated with different letters.

In general, all land use showed adequate physical condition, reflected by the average values obtained in the structural indexes with low values of bulk density (BD), high values of total porosity (Tp), aeration porosity (Ap), retention porosity (Rp) and saturated hydraulic conductivity (Ksat) (Table 1). Moreover, due to the peculiarities of the Ecuadorian Amazon region (EAR), characterised by soils with high organic matter content, a type of granular structure is generated that allows one to obtain higher values of Ksat and Ap, which improves the soil's rate of infiltration and its capacity (Bravo et al., 2017). However, this situation changes with the depth where the values are decreasing, showing limiting values from 10 cm around 9% for most land uses with the exception of the soil under secondary forest (Table 1). A reduction of the infiltration rate, as a consequence of the decrease of macroporosity in high precipitation conditions (>3000 mm), landscapes with high slopes common in the Ecuadorian Amazon region, represent one of the main causes of the activation processes of water erosion commonly observed in the area (Bravo et al; 2017). Our results suggest that the studied structural indices such as bulk density (BD), total porosity (Tp), aeration porosity (Ap), retention porosity (Rp), saturated hydraulic conductivity (K_{sat}), help to characterize different processes in the soil (compaction, aeration, infiltration), which may be affected by the change of land use. In addition, the role of the soil resource as a regulator of the ecosystem and its contribution to the mitigation of global climate change is reinforced (Bravo et al., 2016, Lal, 2008).

Effect of land use change on soil carbon stocks

Some authors point out that the soil C sequestration due to land change use is likely to be affected by multiple factors such as climatic conditions, soil texture, site preparation and management, vegetation type, land use history, etc. (Deng et al., 2016). In our case, the land history use in the ecuadorian amazon region is with forest which has allowed to store large amounts of soil carbon stocks (Bravo et al., 2017). Land use change, can cause a changes in soil C stock (Table 1), showing significantly higher values in the use with secondary forest and GGWT 51.49 and 49.44 Mg C ha^{-1} respective in compared to the rest of the land uses. Despite the history of use, in all cases there is a decrease in the carbon reserves in the soil when converting forest to livestock systems, with a higher proportion in those systems without trees, with values that fluctuated from 2.05 (4%) in GGWT to -14.74 (29%) in DGWHT, as shown in Table 1. Similar results have been reported by other researchers who report a decrease in the carbon stock in the soil between 8 to 42% when there is conversion of forest to livestock systems and cultivation (Powers et al., 2011)
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Conclusions

The structural indexes studied such as bulk density (BD), total porosity (Tp), aeration porosity (Ap), retention porosity (Rp), saturated hydraulic conductivity (K_{sat}), help to characterize different processes in the soil (compaction, aeration, infiltration), which may be affected by land use change. All this, together with the potential for carbon sequestration, reinforces the role of the soil resource as a regulator of the ecosystem and its contribution to the mitigation of global climate change.

Conflicts of Interest

The authors declare no conflict of interest".

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