A soil quality index for seven productive landscapes in the Andean-Amazonian foothills of Ecuador

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Abstract

Few studies have comprehensively evaluated the effect of changing land use on the soil quality in Ecuadorian amazon region that subject to continued deforestation processes. This study evaluated the influence of different types of land use on soil quality using an integrated soil quality index (SQI) with minimum set of indicators, based on 140 soil samples from 7 land use types, in seven productive distinct landscapes in the Pastaza province, Ecuador. The land use type evaluated were: Chakra_A, Chakra_B, Chakra_C, Cattle_A, Cattle_B, Cattle_C and Forest. Land use type had significant effects on soil properties and thus on soil quality. Soil quality index was developed by using, AP, Zn, TOC, BD and LL; AP and Zn had highest weighting values (0.38), which indicated that these indicators contributed the most to final SQI. In general, the SQI decreased as soil depth increased and for each type of land use, in the surface layer (0-10cm) the uses of Chakra_A (0.46) and forest (0.44) showed the highest SQI, while for the second depth (10-30cm), Chakra_A (0.45) and Chakra_B (0.43) presented significantly higher SQIs than the other land uses. The applied SQI can be used to assess the effect of changes on land use on soil quality in other landscapes of the Ecuadorian Amazon Region.

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Keywords: Land use, soil quality index, indicators, soil properties, Ecuadorian Amazon Region.

INTRODUCTION

Soils are an integral part of natural ecosystem and agroforestry systems, within which their physical and chemical composition shape the quality of ecosystem services (McBratney et al., 2014). Land use change is a global threat to soil quality and related ecosystem services, however, agroforestry systems (AFS) have been introduced as a sustainable alternative for soil reclamation and increasing land productivity (Nair et al., 2009; Shibu & Dollinger, 2019). Agroforestry system is defined as a dynamic and ecologic system of managing natural resources by integrating trees on arable land and pasture; which are diversified and permit the production of little exploitations leading to important social, economic and ecologic advantages (Shibu & Dollinger, 2019). In this context, several soil quality definitions have been proposed (Doran & Parkin, 1997; Karlen et al., 1997). One of the most widely used is defined as the capacity of a soil to function within ecosystem and land use boundaries, to sustain productivity, maintain environmental quality, and promote plant and animal health (Doran & Parkin, 1997; Karlen et al., 2003; Karlen et al., 2006). Soil quality is determined by extrinsic factors such as parent material, climate, topography and hydrology may influence potential values of soil properties to such an extent that it is impossible to establish universal target values, at least not in absolute terms (Bünemann et al., 2018; Carter et al., 1997; Shukla et al., 2006). Soil quality index (SQI) is often used to quantitatively gauge the effect crop management practice on overall soil health (Andrews et al., 2002; Bünemann et al., 2018). Therefore, an important component of soil quality assessment is the identification of a set of sensitive soil attributes that reflect a soil's ability to function and can be used as indicators of soil quality (Cantú et al., 2007; de la Paz Jimenez et al., 2002; Doran & Parkin, 1997; Karlen et al., 1997; Viana et al., 2014).

Soil quality has suffered a remarkable degradation worldwide as a consequence of anthropogenic and natural disturbances (Peng et al., 2013; Pla, 2010; Zhang et al., 2019). The Ecuadorian Amazon Region is particularly susceptible to severe soil degradation due to its special geological conditions and fragile ecosystems (Bravo, Marín, et al., 2017; Custode & Sourdat, 1986; Espinosa et al., 2018; Nieto & Caicedo, 2012). In this region, large areas have been subjected to deforestation process and a change in land use towards agricultural and livestock systems that have greatly deteriorated its resources (soil, water, vegetation and biodiversity), affecting its productive potential and capacity (Bravo et al., 2015; Torres et al., 2019).This situation is magnified by the area's characteristics with unfavourable soil chemical parameters coupled with harsh climatic conditions (abundant, high-intensity rainfall), an irregularly topographical agricultural landscape and high slopes (Espinosa et al., 2018).

Physical and chemical properties have been commonly used to characterise soil quality in areas that are subject to changes in land use (Cantú et al., 2007; Masto et al., 2008; Ngo-Mbogba et al., 2015; Vallejo-Quintero, 2013) and experience various states of restoration (Peng et al., 2013; Viana et al., 2014; Zhang et al., 2019). In the Argentinian Pampas, it was found that the soil quality index obtained by a minimum set of indicators was strongly influenced by soil organic carbon (SOC), which was the property most affected by land use change (Cantú et al., 2007). For soils in the Brazil's central Amazon Region, subjected to several level of restoration, the most sensitive parameters to differentiate restored and degraded areas with respect to the reference soil (in a forest) were bulk density, total nitrogen, exchangeable potassium (K^+) and available phosphorus (P), which were ([?] 0.70) (Viana et al., 2014). In the Ecuadorian Amazon Region, progress has been made in characterising soil quality based on morphological indicators (Bravo, Marin, et al., 2017) and factors associated with fertility, which has allowed for a comprehensive diagnosis of the state of the resource, as well as the influence of land use change (Bravo, Torres, et al., 2017). The results showed that the physical indicators of soil, measured as bulk density (BD), saturated hydraulic conductivity (K_{sat}), total porosity (TP) and aeration porosity (AP) in uses such as forest, agroforestry, livestock and chakra systems were strongly influenced by variation in organic matter content. Although the effect of change use land on soil quality has been studied in different countries (de Lima et al., 2008; Quintero, 2020; Viana et al., 2014; Zhang et al., 2019) few studies were conducted to evaluate the influence of different land use types in Ecuadorian amazon.

The objectives of this study were (1) to examine how land use types affect the physical and chemical properties of soil, (2) to establish a quality index based on a Minimum Data Set (MDS) to evaluate the effect of land use types on soil quality, and (3) to identify the factors that influenced soil quality. In this investigation, the quality of the soil physical and chemical properties was hypothesized to be directly affected by the change in land use.

1. **MATERIALS AND METHODS**
2. **Study Area**

The study was carried out in the Boayacu community, which belongs to the Teniente Hugo Ortiz parish. The parish measures 97 $km^2$and is found in Pastaza canton, Ecuador (Figure 1). This area is characterised by a climate that is typical of an evergreen tropical rainforest (MAE, 2013), with an altitude ranging between 823 and 1086 metres above sea level. The predominant bioclimatic conditions vary between pluvial humid and hyper humid (MAE, 2013), with an average annual rainfall of 3481.7 mm, evapotranspiration of 150 mm, average temperatures of between 23.4 and 25.4degC and a relative humidity of 87%. The lowest precipitation occurs from January to April, whilst the highest occurs from May to July and the temperature varies all year around (Torres et al., 2019). The soils belong to the Andisols order (Soil Survey Staff, 2006), meaning they have a clay loam texture and a granular and blocky structure. They are generally acidic and have low natural fertility (low P, K^+, $Ca^{2+}$and Mg^{2+} contents) and have saturation percentages with bases<35%, high Fe and Al^{3+} contents (Nieto & Caicedo, 2012). With a plant cover of 90%, the biological resources of this region are abundant and the biodiversity quality is high (Estupinan et al., 2007).

Figure 1 .

2.2. Soil Sampling and Laboratory Analysis

For this study, six land uses typically found in the Amazon Region were selected, whose arrangements differ depending on the crops that they comprise of (Table 1).

Table 1.

For each use, a systematic sampling was carried out by establishing a transect covering the entire selected area, over which five sampling points were located equidistantly. At each sampling point, a 10 x 10m subplot was located, in which five soil subsamples were collected at two depths (0-10cm and 10-30cm) and subsequently homogenised in order to obtain a composite sample per point for a total of 10 samples per use for the evaluation of chemical attributes. The soil samples for said evaluation were air-dried and then passed through a 2mm sieve. At the same time, in the central part of the subplot, undisturbed samples were collected with an Uhland-type drill in order to evaluate physical parameters.

2.2.1 Soil Physical Analysis

In order to determine the physical attributes of the soil, undisturbed samples were taken with cylinders that were 5cm tall and 5cm in diameter. Then, the following variables were measured: a) bulk density (BD) using the cylinder method (Klute & Page, 1986); b) saturated hydraulic conductivity (K_{sat}) using the variable load method (Reynolds & Elrick, 2002), following the pore size distribution method (c) total porosity (TP); (d) aeration porosity (AP: pores of >15 µm radius); and (e) retention porosity (RP), using the saturation tension table method with -10 kPa a matric potential (Blake & Hartge, 1986).

2.2.2 Soil Chemistry Analysis

The chemical attributes evaluated included pH determination, which was measured by potentiometry (soil-water ratio 1:2.5), exchangeable acidity (Al^{3+} + H^+) and exchangeable aluminium (Al^{3+}) extracted with KCl 1N and titrated with NaCl, and HCl respectively (McLean, 1965). Total organic carbon (TOC) was measured using the Walkley and Black wet digestion method (Nelson & Sommers, 1983). Available P and extractable cations (K^+, $Ca^{2+}$and Mg^{2+}) were removed using the Olsen extraction solution. P was measured colorimetrically using the molybdenum blue method, while K^+, Ca^{2+} and Mg^{2+} were determined using an atomic absorption spectrophotometer (Okalebo et al., 2002).

Finally, the Leaf litter (LL) was calculated within the subplots of 10 x 10 m with the help of a 0.25 m^2 quadrant; all of the material corresponding to dead plant remains located within was collected. The collected material was weighed and placed in bags for drying at 105 °C for 24 hours, until a constant weight was obtained. Dry matter in terms of kilograms of dry matter (DM) per hectare was calculated (Mg DM ha^{-1}).

Evaluation of the Soil Quality Index, Statistical Analysis and Derivation of the Soil Quality Index

The evaluation of the SQI included three consecutive steps (Masto et al., 2008; Zhang et al., 2019): 1) the selection of a minimum data sets (MDS); 2) scoring the MDS indicators; and 3) calculation of integrated SQI values. To choose the best representative indicator for MDS, principal component analysis (PCA) and Pearson's correlation coefficient were performed (Doran & Parkin, 1997). In order to select the minimum data sets (MDS), only principal components (PCs) that had eigenvalues [?]1 and explained at least 5% of the total variance were chosen (Andrews et al., 2003). Then in each PC, only the factors with absolute loading values within 10 % of the highest factor loading were selected as vital indicators (Sharma et al., 2005; Zhang et al., 2019). When more than one indicator was retained in one PC, Pearson's correlation analysis was used to check whether other indicators should be removed (Bastida et al., 2006). In this context, if the indicators were adequately correlated (correlation coefficient >0.6), with each other, only the highest weighted indicator was selected in the PC (Andrews et al., 2003). After selecting the indicators of MDS, a non-linear scoring function was used to transform the soil indicators into scores that ranged from 0 to 1. The sigmoidal function (Eq. 1) was used as follows (Andrews et al., 2002):

S=a/[1+(x/x$_0$)]^b (1)

where S is the score of the soil indicator, a is the maximum score (a = 1), x is the indicator value, x_0 is the mean value of each soil indicator, and b is the value of the equation´s slope. Slope values (b) of -2.5 and 2.5 were used for a to "more is better" or "less is better" curve, respectively (Bastida et al., 2006). Finally, with the score of indicators and their weighting values, SQI (Eq. (2)) was calculated as follows (Masto et al., 2008):

$$SQI = \sum_{i=1}^{n} Si * Wi \quad (2)$$

where Wi is the weighting value of the soil indicators selected by the PCA, S_i is the indicator score calculated by Eq. (1) and n is the number selected in MDS.

Statistical analysis

A one-way analysis of variance (ANOVA), followed by a Tukey mean comparison test (P [?] 0.05) was used to examine and to compare the differences in soil indicators and SQIs among different land use type at $p < 0.05$ level. The principal component analysis (PCA) and correlation matrices between soil indicators were evaluated using Pearson's correlation analysis. procedure. An additional ANOVA was performed on the overall SQI and MDS-scored soil quality indicators to reveal the effect of different land use type on soil quality. All statistical analyses were performed by SPSS 21.0 (SPSS Inc., Chicago, USA).

RESULTS

3.1. Soil physical Indicators under different land use types

The structural quality of the soil was analysed according to different physical properties under different land-cover uses whose average values are shown in Table 2. It can be seen that bulk density (BD) only showed significant differences in the surface layer (P[?]0.05), ranging from 0.30 to 0.51 Mg m^{-3}, for the uses of forest and Chakra_C respectively. Regardless of use, a slight increase was recorded, ranging from 0.45 to 0.57Mg m^{-3}. At both depths the forest cover presented the lowest value. Saturated hydraulic conductivity (K_{sat}) presented significant differences at both depths (P<0.05), with a higher penetration speed in the surface layer (0-10cm). In said horizon, the order obtained according to type of land use was: Chakra_B > Forest > Chakra_A > Cattle_C > Cattle_B > Chakra_C > Cattle_A, while for the subsurface layer it was: Forest > Chakra_B > Cattle_C > Chakra_C > Cattle_A > Cattle_B > Chakra_A.

Table 2.

As can be seen, although there was a decrease with depth, in most land uses especially in Chakra_A, Cattle_A and Cattle_B - the values obtained are considered adequate and are above the critical limit of 0.5 cm ha^{-1} (Pla, 2010). This behaviour is related to the aeration porosity, the textural and structural condition that favours the penetration and movement of water in the soil profile, especially in the surface horizon (0-10cm). The total porosity (TP) of the soil showed no significant differences, showing high levels regardless of type of coverage or depth, with values close to 90% and above the critical threshold (60%). The TP values obtained were closely related to bulk density (BD), suggesting that a higher density meant a lower TP and vice versa. Independently of the soil cover in the total pore fraction (TP), micropores or retention pores predominate over macropores (AP >15μm) (Table 2), which gives the soil a high moisture retention capacity, related to the predominantly clayey textural class. However, when analysing the fraction of the macropores, values ranging from 12 to 24% were recorded on the surface horizon, while for the second layer (10-30cm) it varied between 9 and 14%, showing a pattern inverse to the bulk density and above the 10% threshold (Pla, 2010). A 10% AP allows for a good transmission of water, air, heat, thereby facilitating root growth, as well as improving soil quality and the soil's productive potential (Bravo, Torres, et al., 2017; Taboada & Álvarez, 2008).

3.2. Soil chemical indicators of soil under different land uses

Figure 2 shows the chemical properties associated with soil quality for the two depths. The acidification process (evaluated through pH, acidity and exchangeable aluminium) showed significant differences ($P<0.05$) according to land use at both depths (Figure 2a, b and c). Most land uses exhibited very acidic pH levels; they were below 5, ranging between 4.47 and 4.72, and the forest land-use type had the lowest pH level (Figure 2a). The acidification process was more accentuated on the surface layer, with higher concentrations of acidity (>1.5 meq 100 s^{-1}) and exchangeable aluminium (>1 meq 100 s^{-1}) levels that are considered toxic but decreased with depth to acceptable levels (Figures 2b and c).

Total organic carbon (TOC) was significantly higher ($p<0.05$) on the surface layer (Figure 2d). The forest land-use type had the highest TOC level, with values between 8 and 13%. However, the rest of the land uses, especially in the surface layer, showed high concentrations of TOC (> 5%), which is related to the historical use of forest cover in the Ecuadorian Amazon Region, leading to higher carbon storage (Nieto & Caicedo, 2012).

Figure 2 .

The availability of some nutrients presented significant differences (p[?]0.05) at both depths (Figure 3). The available P varied significantly with use and depth and Chakra_A (12.3 mg kg^{-1}) and Chakra_C (16.52 mg kg^{-1}) had higher concentrations (Figure 3a). The rest of the uses, particularly the forest land-use type, showed values that were categorised as low, because they are below the critical level of 10 mg kg^{-1}(Bai et al., 2013). Of the exchangeable bases (K^+, Ca^{2+} and Mg^{2+}), only the exchangeable Ca^{2+}content showed significant differences ($p < 0.05$; Figure 3c) for the surface layer. In general, the assessed land uses showed low levels of K^+ (Figure 3b); they were below 0.22meq 100 s^{-1} (INIAP, 2012) and hence are considered low, except for some livestock uses (Cattle_A and _B) that showed medium levels (0.32meq 100 s^{-1}) probably due to the contribution of excreta. The calcium content in most land uses at both depths was low (< 2 meq 100 s^{-1}) and only soils in the Chakra_A, Chakra_C and Cattle_B coverages reached average levels (Figure 3c).

Figure 3.

A similar pattern to Ca^{2+} was obtained with Mg^{2+} content, recording values categorised as low (< 0.5meq 100 s^{-1}) in most uses for both depths. It should be noted that the nutrient content, such as available P and Exchangeable bases, were lowest in the forest land use, reflecting the nature of these soils and illustrating their limited contribution to quality (Bravo, Ramirez, et al., 2017). The available Zn content was significantly higher ($p<0.05$) at 0-10 cm deep (Figure 3e). The chakras (A, B, C) recorded higher values than the rest of the uses, ranging from 2.84 to 0.76 mg kg^{-1}, with a similar pattern for the subsurface layer (10-30cm).

Available Zn concentrations <3mg kg^{-1} have been indicated as critical, therefore, the values obtained ranged from medium to low levels. Finally, leaf litter production (Figure 3f) varied significantly ($p<0.05$) according to land use, defining three groups. The first group of values ranged from 8 to 10Mg ha^{-1} and included the forest and two livestock systems (Cattle_B and _C), the second group had values close to 4Mg ha^{-1} and comprised Chakra_A and Cattle_A, and the third group was Chakra_A and _C with values between 2 and 4Mg ha^{-1}.

3.3. Evaluation of the Soil Quality Index (SQI)

The eigenvalues of the first four components were all [?] 1 and explained 84.87% of the total variance (Table 3). In the first component (PC-1), the indicators with the highest weight were aeration porosity (AP), saturated hydraulic conductivity (K_{sat}), zinc content (Zn) and exchangeable acidity (EA). AP and K_{sat} showed a high correlation ($r>0.80$) (Table 4), therefore, due to the higher load and ease of measurement, AP was selected as an indicator in PC-1. In the second main component (PC-2), TOC and pH had the highest loads and showed a high degree of significant association (P[?]0.01), with $r = -0.79$ (Table 4), thus, TOC was selected in PC-2. In the third main component (PC-3), total porosity (TP) and soil bulk density (BD) had the highest loads and also showed a significant correlation, with $r = -0.63$ ($p<0.05$). However, since total porosity did not show significant differences in Tukey's mean comparison test and considering that bulk density is an integrative variable and influences different important functions that define soil quality, it was selected (Blanco-Canqui & Ruis, 2018). Finally, in PC-4, leaf litter (LL) production was selected because it showed the highest load.

Table 3.

Table 4.

Based on this, the minimum data set selected to calculate SQI were Zn, AP, TOC, BD and Leaf litter. With the value of the weights or loads based on the PCA (Table 5), the SQI was determined using the following equation Eq (3):

$$\mathbf{SQI} = 0.38 \text{ x S (Zn)} + 0.38 \text{ x S (AP)} + 0.27 \text{ x S (TOC)} + 0.22 \text{ x S (BD)} + 0.13 \text{ x S (LL)} \quad \mathbf{(3)}$$

Table 5.

Generally, the SQI decreased significantly with soil depth for each type of land use, showing significant differences between land-use types ($p<0.05$; Figure 4). For surface soil (0-10cm), two groups were established: the first with average SQI values of 0.46, 0.44 and 0.43 for Chakra_A, Forest and Chakra_B, respectively; while the second group registered average SQI values of 0.34, 0.33 and 0.31 for Chakra_C, Cattle_A, Cattle_-B and Cattle_C, respectively. In the second horizon of 10-30cm depth, the SQI in Chakra_A (0.45), Forest (0.43) and Chakra_B (0.39) were significantly higher than the rest of the land uses, whose average values were: 0.32 (Chakra_C, Cattle_A and categorised as having moderate quality, whilst averages between 0.20 and 0.39 are indicated as low quality (Cantú et al., 2007; Vallejo-Quintero, 2013).

Figure 4.

4. DISCUSSION

4.1. Soil properties under different land uses types

In this study, the physical, chemical and biological indicators of soils varied significantly amongst land-use types, indicating that land use change plays an important role in soil properties (Bravo, Marín, et al., 2017; Viana et al., 2014). However, in Amazonian conditions, it is important to consider the effect of soil-forming factors and processes and the historical background of land use (Nieto & Caicedo, 2012; Quesada et al., 2011; Viana et al., 2014). In this sense, the pedogenesis of Amazonian soils shows a very particular character, marked by different factors, including a climate characterised by high and intense rainfall with annual averages of around 4000mm, high temperatures that can range from 24 to 30°C, and habitats ranging from tropical rainforest to very humid rainforest (Nieto & Caicedo, 2012; Torres et al., 2019). In addition to this, traditional forest use generates a stratified profile, with a surface layer of average thickness between 10 and 12cm, with a higher organic matter content than the other horizons (Bravo, Torres, et al., 2017). This in turn generates better conditions in terms of physical and biological properties and nutrient recycling dynamics (Bravo et al., 2015). All of these assumptions should be analysed when assessing the impact of land use change on soil quality. On this basis, physical indicator values are strongly influenced by the normally high content of organic matter in the soil and therefore influence the physical variables associated with its structural quality, such as bulk density (BD), saturated hydraulic conductivity (K_{sat}) and porosity distribution (Blanco-Canqui & Ruis, 2018; Rabot et al., 2018). The soil's BD is one of the variables most sensitive to changes in land use and has a great influence on other attributes, such as porosity distribution, especially macroporosity (AP) and Ksat, which affects aeration capacity, water penetration speed and, with it, the biogeochemical behaviour of the soil (Blanco-Canqui & Ruis, 2018; Pla, 2010). All this means that as the BD increases, the porosity distribution values decrease, especially total porosity and macroporosity. Due to the low density of the soil, these maintain an adequate volume of pores in the soil, improving aeration and drainage in the soil (Torres et al., 2019; Viana et al., 2014). In this study, regardless of land use, the values obtained for physical properties (BD, Ksat, TP and RP), especially the forest and some types of chakras, confirm the strong influence of the content and variation of organic matter in the soil. Soil structure is recognized to control many processes in soils. Although a change in the structural indicators is generated with land use change, the values show an adequate physical functioning that favours an adequate range of aeration, infiltration, root penetration and moisture retention without degradation problems such as compaction, which contributes to soil quality independently of the land-use type (Rabot et al., 2018).

In the case of the chemical indicators selected, they reflect the nature of the soils in the area (Espinosa et al., 2018). In this study, the results for TOC confirm the history of management and potential use of the Amazon Region (forest) and the use of analogous forestry systems such as agroforestry cocoa, silvopastoral systems (Bravo, Torres, et al., 2017; Torres et al., 2019). The components of soil acidity and pH associated with quality reflect the acidic and low fertility nature of these soils, which is confirmed by the values of the primary forest as a reference use. The amounts of available P in Amazon soils are almost always very low and generally phosphorus, becoming the main limiting factor for Amazon region (Müller et al., 2004; Quesada et al., 2011). Some studies report that for the surface of the humid tropical regions, like those in the Ecuadorian Amazon Region, the climate exerts a primordial influence on the pedogenesis that favours the ferralitisation of the soil, generating a dystrophic environment (Custode & Sourdat, 1986). This ferralitisation tends to a total hydrolysis of the modifiable primary materials and the complex clays of the rocks through the leaching of the bases (K^+, Ca^{2+}, Mg^{2+}) and of the silica (Gardi et al., 2014). This causes a predominance of non-modifiable minerals and simple clays, such as quartz, kaolinite, haloisite, gibsite and iron oxides, which confer certain morphological characteristics and decrease the parameters, mainly pH and nutrient availability (Custode & Sourdat, 1986; Gardi et al., 2014). On the other hand, the movement of the cations to lower layers is related to the presence of anions, resulting from the mineralisation of organic matter that, forming ionic pairs, drag the cations in the soil profile with the movement of water (Espinosa et al., 2018). In addition, organic matter in the soil is decomposed with the help of microorganisms producing a constant supply of CO_2 that is easily transformed into bicarbonate (HCO_3), whose reaction releases H^+ions into the soil solution, thereby reducing pH (McGrath et al., 2014). This study also shows that soil nutrients were higher in the surface layer than the second horizon. This is probably associated with the dead wood and leaf litter that accumulates on the surface and subsequently transformed into humus through microbial activity (Zhang et al., 2019). If we only consider the depth factor, AP, TOC, P, K^+, Ca^{2+}, Mg^{2+} and Zn decreased with soil depth, while pH and BD increased. This was probably due to the higher biological activity and root penetration in the soil surface compared to the subsurface layer (Zhang et al., 2019).

Effect of land use types on the soil quality

Land use change can improve soil quality, but the improvement varies according to land-use type. Ngo-Mbogba et al. (2015) indicate that SQI was significantly different amidst different vegetation types, with the forest exhibiting the highest SQI. Mishra et al. (2019) included four physicochemical indicators to the MDS for the calculation of the SQI in deciduous tropical forests in India, being these: the electrical conductivity, the apparent density, the exchangeable Mg and the available P. Other studies have shown that the differentiation between agroecosystems was more evident and significant when only three variables (minimum data set) were used in the soil quality index (Quintero, 2020). Variables that were maintained in the three minimum data sets were: bulk density, stability index, pH, dehydrogenase activity, density of heterotrophs and phosphate-solubilizing bacteria. In this study, land use has changed from primary forest to analogous systems such as agroforestry, including chakra and silvopastoral systems with little soil alteration. Within their arrangements, these systems combine crops and grasses with trees, a condition that improves soil quality. In general, the higher soil quality in the chakra system (A and B) and their respective arrangements together and forest systems was mainly due to the greater availability of Zinc, the greater aeration porosity and the higher content of soil organic matter in both layers. It is important to note that the use of agroforestry systems with cover not only protects the soil from erosion (Bravo et al., 2016; Vallejo-Quintero, 2013), but it also improves soil properties, mainly in organic matter and consequently in soil structure, due to the high amount of leaf litter generated on the surface of the soil (Blanco-Canqui & Ruis, 2018; Bravo, Torres, et al., 2017; Zhang et al., 2019; Zhao et al., 2017). Soil quality can be influenced by many factors, which include its inherent capabilities and environmental elements such as lithology and geography, land-use type, vegetation and human activity (Karlen et al., 2006). In our case, soil-forming factors, vegetation and management with agroforestry systems are essential to protect the soil, reduce erosion and improve the soil attributes associated with its quality (Bravo, Torres, et al., 2017).

The mean values at the two depths indicated that the Chackra C soil quality index and the three livestock systems (Cattle_A, B and C) were lower than the chakra A, Chakra B and forest systems (figure 4), with SQI categorized from moderate to low (Cantú et al., 2007; Quintero, 2020). These results highlights natural fragility of the soils in the amazon ecosystems , in which is common that soils present an acid edaphic environment, high presence of aluminum and low availability of nutrients that do not contribute to soil quality. These characteristics is in agreement with other soils of amazon region which environments are acidic, have low fertility and low cation exchange capacity (CEC), and contain silicate minerals with low activity as kaolinitic and oxidic (Quesada et al., 2011). However, it is normally common to find soils with a high content of organic matter that improves physical indicators (Da, Ksat, Porosity) and that positively influence the final value of the SQI. On the other hand, the results suggest that a change in use towards agricultural or livestock systems, although it may slightly improve soil quality, may also deteriorate it depending on management and the integration of good practices in agroecosystems, which was consistent with what he found in previous studies. (Bravo, Torres, et al., 2017). Soil Organic matter is considered as one of the most important factors among soil quality indexes and have a positive effect on soil properties and beside is the central indicator of soil quality and health, which is strongly affected by agricultural management (Kiakojori & Gorgi, 2014). Bulk density is a structural index that is strongly related to total porosity, aeration porosity and consequently influences hydraulic properties and defines air:water relationships in the soil (Blanco-Canqui & Ruis, 2018; Pla, 2010; Reynolds et al., 2009). The soil under the influence of decomposing wood differed significantly from the control sample in terms of capillary water capacity, which indicates a significant increase in the number of micropores capable of retaining water (Piaszczyk et al., 2020). It is important to discuss, however, that the bulk density values (BD) under the different use land showed ranges from 0.30 to 0.51 Mg m^{-3} in the surface layer and from 0.45 to 57 Mg m^{-3} in the subsurface layer (Table 2), which were below the that threshold values of bulk density deemed to be detrimental to seed germination, root development, and plant growth (Blanco-Canqui & Ruis, 2018). In this context, the interpretation of BD with respect to soil functions depends on soil type, especially soil texture and soil organic matter (SOM) content. The threshold values among soil textural classes can vary due to differences in size and shape of soil particles, the threshold values can be >1.40 Mg m^{-3} for clayey soils, >1.60 Mg m^{-3} for medium-textured soils, and > 1.80 Mg m^{-3} for coarse textured soils (Blanco-Canqui & Ruis, 2018; Pla, 2010).

The examined physical properties correlated with soil carbon content showed (Table 4). In the case of bulk density, it was a negative correlation with total organic carbon (r=-0.80), total porosity, macroporosity (r=-0.63). and saturated hydraulic conductivity(r=-0.35). These results are in agreement with previous studies in which a negative linear relationship was found between BD and macroporosity, and between BD and the saturated hydraulic conductivity (Reichert et al., 2009). According to Chen et al. 2017, organic matter content has a dominant effect on soil bulk density and organic matter concentration is used to predict soil bulk density (Perie & Ouimet, 2008; Prevost, 2004). A positive correlation (Table 4) was observed between TOC and aeration porosity (r=0.71) and between aeration porosity and saturated hydraulic conductivity (r=0.85). Organic remains released from deadwood in the forest and leaf litter in the agroecosystems are delivered to soil and determine soil structure and aggregation (Piaszczyk et al., 2020). Therefore, SOC, AP and BD could play an important role for monitoring soil quality.

Analysing the minimum data set (MDS) is an effective method for assessing soil quality, because it reduces duplication of data, provides good accuracy and is rapid (Cantu et al., 2007; de Paul Obade & Lal, 2014; Yigini & Panagos, 2016; Zhang et al., 2019). In our research, five indicators were selected (Zn, AP, TOC, BD and LL) with a high weighting factor in the evaluation of MDS. All five factors related to one or more soil functions (e.g., water and nutrient retention and transport, soil structure, aeration, etc.) to influence soil pore structure and the capacity of soil to accept, store and release water and nutrients. Previous studies have shown that TOC, BD and TN were potential indicators of soil quality (Karlen et al., 2006; Viana et al., 2014; Zhang et al., 2007; Zhang et al., 2019). We found TOC, BD, LL and AP to be indicators of the physical quality of the soil (structure), reflecting their importance due to their greater contribution to the integrated quality index, despite the lower contribution of available P content and the changeable bases (K^+, Ca^{2+} and Mg^{2+}). This reflects the chemical nature of soils in the Ecuadorian Amazon Region with its dystrophic environments, as pointed out in previous studies (Bravo, Marin, et al., 2017; Custode & Sourdat, 1986; Espinosa et al., 2018; Martin & Perez, 2009; Muller et al., 2004).

Land use changes due to resource exploitation remain a serious threat in Ecuador, a country that is trying to transition towards modern wealthy society. It is clear that such pressures must be considered when discussing and implementing development and conservation plans (Torres et al., 2019). One approach to the prevention of deforestation and soil degradation is to use management and conservation techniques that are appropriate in this region and these methods depend on the knowledge of soil attributes The diversity of the Amazon ecosystem and studies relating to soils in this region should be considered during the application of techniques that can prevent the exploitation of unsustainable natural resources. Information relating to soil attributes can serve as a basis for public policies that target agricultural planning and technologies that increase land use efficiency and conserve biodiversity (de Souza et al., 2018).

CONCLUSIONS

The effect of land use types on the soil quality of a dystrophic landscape was assessed using the soil quality index. Significant differences in physical, chemical and biological soil properties were found between the land uses and the primary forest as a reference system, indicating that the land use change had a significant influence on soil properties. The soil quality index (SQI) varied with depth and was higher in the surface horizon. Regarding land-use type, the chakras and some livestock systems slightly improved soil quality. In general, the SQI values in the chakra systems and the forest in the surface horizon were slightly higher than the rest of the uses, which implies that the agroforestry chakra model was able to improve the quality of the soil. In summary, our study confirms that the SQI method is a useful and practical tool for evaluating and monitoring soil quality because of its flexibility and quantitative precision. However, in order to assess soil quality more completely and accurately, it is necessary for future SQI studies to also consider other chemical and biological properties of soils.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

All authors contributed equally in all aspects that led to the development of this publication.

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Table 1. Selected land uses in the area under study (Pastaza Province, Ecuadorian Amazon Region)

Land Use	**Crops**	Coordinates **WGS 84/UTM, Zona 18 S**	Coordinates **WGS 84/UTM, Zona 18 S**
		X coordinate	Y coordinate

Land Use	**Crops**	Coordinates **WGS 84/UTM, Zona 18 S**	Coordinates **WGS 84/UTM, Zona 18 S**
*Chakra_A	Cocoa (*Theobroma cacao L)*), Papa china (*Colocasia esculenta*), yuca (*Manihot esculenta*), plantain banana (*Musa paradisiaca*), maize (*Zea mays*),	169679	9855138
Chakra_B	Cocoa (*Theobroma cacao L*), Papa china (*Colocasia esculenta*),	168550	9855016
Ckakra_C	Papa china (*Colocasia esculenta*), Plantain banana (*Musa paradisiaca*), coffee (*Coffea arabico*), sugar cane (*Saccharum officinarum)*	168144	9854641
Cattle_A	Brachiaria grass (*Brachiaria decumbens*) with trees.	168517	9854737
Cattle_B	Gramalote grass (*Axonopus Scoparius*) with trees	168378	9854606
Cattle_C	Grasses (*Brachiaria decumbens, Axonopus Scoparius*) without trees	168488	9854268
Primary forest	High biodiversity and predominance of species from the families of Fabaceae (*Inga vismifolia*), Sapotaceae (*Pouteria torta*) and Arecaceae (*Iriartea deltoidea*)	168431	9855456

***** Chakra system is a polycultured agrarian systems in Ecuadorian Amazonia (also called chakras or swollen gardens) are characterised by a market-oriented crop for the generation of monetary income, for example, cocoa, other agricultural products (e.g., banana and cassava), and livestock for family farm consumption (Coq-Huelva et al., 2017).

Table 2. Average values of physical properties of soil quality under different land uses in the Boayacu Community.

Variables /Treatment	Bulk density (Mg m-^{3})	Saturated hydraulic conductivity (cm h^{-1})	Total porosity (%)	Aeration porosity (%)	Retention porosity (%)
Depth of 0-10 cm	**Depth of 0-10 cm**	**Depth of 0-10 cm**	**Depth of 0-10 cm**	**Depth of 0-10 cm**	**Depth of 0-10 cm**
Chakra A	0.37± 0.05a	50.02± 19.23a	89.65±2.69 a	17.58±3.15 ab	72.07± 2.68ab
Chakra B	0.47±0.05a	68.18± 17.17a	84.70±2.18 a	16.82±3.50 ab	67.88± 4.25ab
Chakra C	0.51±0.09 a	21.59 ±5.37b	84.90±5.33 a	21.01±7.15a	63.89± 6.43b
Cattle A	0.43±0.09 a	13.14±4.12 c	89.85±4.15 a	11.94± 2.74b	77.91±3.57 a
Cattle B	0.44±0.05 a	23.09± 8.33b	90.82±3.43 a	12.74± 1.10ab	78.08±3.61 a
Cattle C	0.38± 0.12a	33.28± 8.96a	90.88±3.42 a	15.53± 5.34ab	75.36±2.10 a
Forest	0.30±0.07b	66.85±14.9**0**a	89.98±3.26a	24.46±5.89a	65.52±8.46b
Depth of 10-30 cm	**Depth of 10-30 cm**	**Depth of 10-30 cm**	**Depth of 10-30 cm**	**Depth of 10-30 cm**	**Depth of 10-30 cm**
Chakra A	0.48±0.02 a	1.46±0.47 c	89.12±2.21 a	8.96±1.23 a	80.16±1.08a
Chakra B	0.51±0.06 a	15.05±3.38 b	83.89±2.12 a	14.42±3.02 a	69.48±8.03 a
Chakra C	0.57±0.08 a	10.43±2.14 b	83.66±2.13 a	11.01±2.75 a	72.66±3.70 a
Cattle A	0.54±0.11 a	3.57±1.05 c	85.98±3.42 a	10.26±1.21 a	75.73±2.68 a
Cattle B	0.52±0.03 a	3.40±1.24 c	89.35±2.89 a	9.33±0.81a	80.02±2.62 a
Cattle C	0.49±0.15 a	13.35±3.10 b	80.63±7.92 a	12.39± 3.50a	68.24±6.77 a
Forest	0.45±0.09a	51.95±10.03a	89.39±4.39a	13.31±1.84a	76.08±3.75a

Notes: Values are means ± standard deviation. Different lowercase among differente land use types at the same depth (one-way ANOVA, p<0.05); **Chakra_A** : papa china-yuca-plantain banana-cocoa, **Chakra_-B** : Papa china-cocoa, **Chakra_C** : papa china-plantain banana-coffee-sugar cane, **Cattle_A** :*Brachiaria Decumbens* grass, **Cattle_B** : *Axonopus scoparius* grass, **Cattle_C** : *Brachiaria Decumbens* &*Axonopus Scoparius* grasses, and **Forest** : Secondary Forest.

Table 3. Principal component analysis of soil quality indicators.

Principal Component	PC-1	PC-2	PC-3	PC-4
Eigenvalues	5.52	3.88	3.10	1.93
Variance (%)	32.48	22.83	18.24	11.33
Accumulative variance (%)	32.48	55.31	73.54	84.87
BD (Mg m^{-3})	-0.62	0.27	*-0.61*	-0.05
K_{sat} (cm h^{-1})	*0.80*	-0.42	-0.31	-0.05
TP (%)	0.33	0.16	**0.80**	0.09
AP (%)	*0.81*	-0.53	-0.08	-0.02
RP (%)	-0.48	0.54	0.56	0.08
TOC (%)	0.48	*-0.75*	0.53	0.05
pH	-0.29	*0.70*	-0.31	0.38
Exchangeable acidity	**0.77**	0.22	0.38	-0.36
Al^{3+}, meq 100 g s^{-1}	0.32	**0.69**	-0.02	-0.45
P mg kg^{-1}	**0.75**	0.22	-0.51	-0.10
K^{+}, meq 100 g s^{-1}	0.56	0.58	0.42	0.24
Ca^{2+}, meq 100 g s^{-1}	0.70	0.52	-0.11	0.36
Mg^{2+}, meq 100 g s^{-1}	0.64	0.63	0.14	0.29
Cu, mg kg^{-1}	0.15	0.22	-0.47	0.52
Zn, _mg kg^{-1}	**0.79**	0.04	-0.50	-0.03

Principal Component	PC-1	PC-2	PC-3	PC-4
Biomass (kg ha^{-1})	-0.10	-0.29	0.37	*0.75*
Worms	-0.14	0.56	0.25	**-0.57**

Note: Bold factor are considered highly weighted; underline and bold factors are retained in the minimum data set (MDS). PC-1, PC-2, PC-3 and PC-4 indicate first principal component, second principal component, third principal component, and forth principal component respectively. BD: bulk density (Mg m^{-3}); K_{sat}: Saturated hydraulic conductivity (cm h^{-1}); TP: Total porosity (%); AP: Aeration porosity (%); TOC: Total organic carbon (%); EA: Exchangeable acidity (meq 100 g s^{-1}); Al^{+3}: Exchangeable aluminium (meq 100g s^{-1}); P: Available phosphorus (mg kg^{-1}); K+: Exchangeable potassium (meq 100g s^{-1}); Ca2+: Exchangeable calcium (meq 100g s^{-1}); Mg^{2+}: Exchangeable magnesium (meq 100g s^{-1}); Cu: Available copper (mg kg s^{-1}); Zn: Available zinc (mg s^{-1}).

Table 4. Correlation coefficient of soil properties determined in different land uses

	BD	K_{sat}	TP	AP	RP	TOC	pH	EA	Al^{3+}	P	K^+	Ca^{2+}	Mg^2
BD	1.00												
K_{sat}	-0.35	1.00											
TP	-0.63*	0.00	1.00										
AP	**-0.63***	**0.85****	0.07	1.00									
RP	0.14	-0.71**	0.55*	-0.79**	1.00								
TOC	**-0.80****	0.48	0.41	**0.71****	-0.34	1.00							
pH	0.44	-0.51	-0.26	-0.57*	0.31	**-0.79****	1.00						
EA	-0.65*	0.39	0.49	0.51	-0.12	0.43	-0.27	1.00					
Al^{3+}	-0.06	-0.05	0.16	-0.12	0.20	-0.33	0.29	0.59*	1.00				
P	-0.09	**0.70****	-0.06	0.50	-0.45	-0.10	0.07	0.39	0.44	1.00			
K^+	-0.38	0.08	0.57*	0.12	0.25	0.15	0.18	0.64*	0.38	0.26	1.00		
Ca^{2+}	-0.23	0.34	0.23	0.26	-0.08	-0.05	0.38	0.43	0.46	**0.72****	**0.72****	1.00	
Mg^{2+}	-0.27	0.20	0.41	0.18	0.10	-0.02	0.32	.574*	0.41	0.49	**0.93****	**0.82****	1.00
Cu	0.19	0.13	-0.22	0.09	-0.21	-0.27	0.44	-0.08	-0.01	0.17	0.15	0.27	0.35
Zn	-0.16	*0.83***	-0.05	0.67**	-0.58*	0.06	-0.08	0.42	0.32	**0.95***	0.23	0.66**	0.45
LL	-0.31	-0.11	0.19	0.02	0.10	0.37	0.08	-0.24	-0.52	-0.37	0.06	0.06	-0.0
NW	0.08	-0.38	0.05	-0.34	0.32	-0.32	0.26	0.38	0.45	-0.11	0.28	-0.08	0.20

BD: Bulk density (Mg m^{-3}); K_{sat}: Saturated hydraulic conductivity (cm h^{-1}); TP: Total porosity (%); AP: Aeration porosity (%); TOC: Total organic carbon (%); EA: Exchangeable acidity (meq 100 g s^{-1}); Al^{+3}: Exchangeable aluminium (meq 100g s^{-1}); P: Available phosphorus (mg kg^{-1}); K+: Exchangeable potassium (meq 100g s^{-1}); Ca2+: Exchangeable calcium (meq 100g s^{-1}) ; Mg^{2+}: Exchangeable magnesium (meq 100g s^{-1}); Cu: Available copper (mg kg s^{-1}); Zn: Available zinc (mg s^{-1}); LL: Leaf litter (Mg ha^{-1}); NW: Number of worms.

* Correlation is significant at the 0.05 level (bilateral).

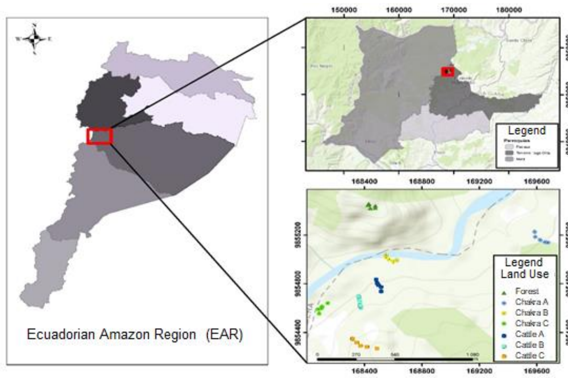
** Correlation is significant at the level 0.01 (bilateral)

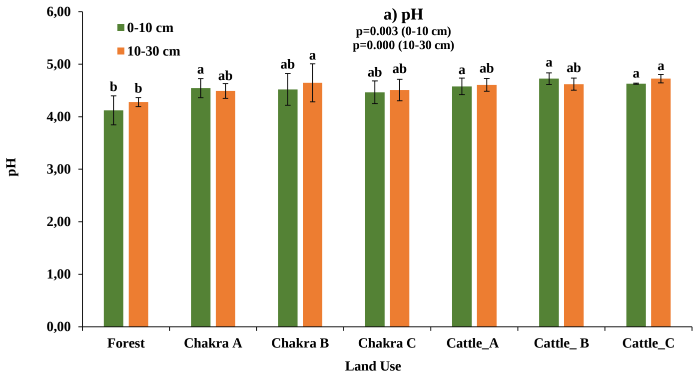
Table 5 . Normalisation equation of scoring curves

Parameter	AP	Zn	TOC	BD	Leaf Litter
Average	14.27	1.94	6.74	0.46	5.80
Curve type	More is better	More is better	More is better	Less is better	More is be

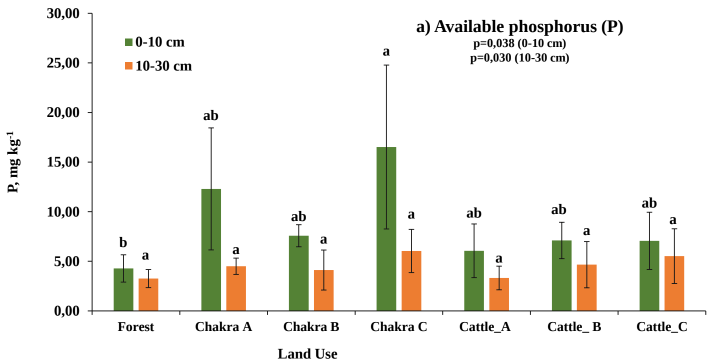
Parameter	AP	Zn	TOC	BD	Leaf Litter
Slope (b)	-2.5	-2.5	-2.5	-2.5	-2.5
Normalisation equation	$S=a/[1+(x/14.27)]^b$	$S=a/[1+(x/1.94)]^b$	$S=a/[1+(x/6.74)]^b$	$S=a/[1+(x/0.46)]^b$	$S=a/[1+(x$
Weighting value	0.38	0.38	0.27	0.22	0.13

AP: Aeration porosity; Zn: Available zinc content; TOC: Total organic carbon; BD: Bulk density.

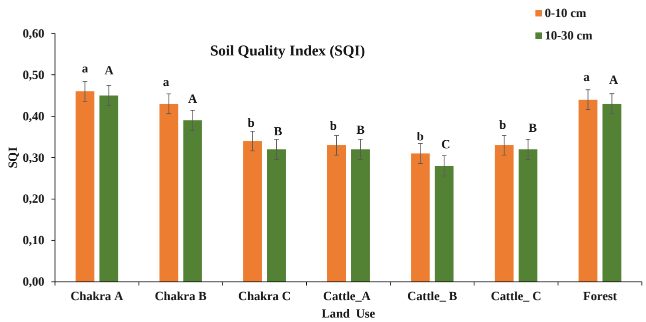




a) pH
p=0.003 (0-10 cm)
p=0.000 (10-30 cm)
0-10 cm
10-30 cm
pH
6,00
5,00
4,00
3,00
2,00
1,00
0,00
b
b
a
ab
ab
a
ab
ab
a
ab
a
ab
a
a
Forest
Chakra A
Chakra B
Chakra C
Cattle_A
Cattle_ B
Cattle_C
Land Use



a) Available phosphorus (P)
p=0,038 (0-10 cm)
p=0,030 (10-30 cm)
0-10 cm
10-30 cm
P, mg kg-1
30,00
25,00
20,00
15,00
10,00
5,00
0,00
b
a
ab
a
ab
a
a
a
ab
a
ab
a
ab
a
Forest
Chakra A
Chakra B
Chakra C
Cattle_A
Cattle_ B
Cattle_C
Land Use


Soil Quality Index (SQI)
0-10 cm
10-30 cm
SQI
0,60
0,50
0,40
0,30
0,20
0,10
0,00
a
A
a
A
b
B
b
B
b
C
b
B
a
A
Chakra A
Chakra B
Chakra C
Cattle_A
Cattle_ B
Cattle_ C
Forest
Land Use