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Agroforestry systems improve soil physical quality in northwestern Colombian Amazon

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Abstract Land use change is a global threat to soil quality and related ecosystem services. In Colombian Amazon, forest-cleared lands are predominantly covered by low-input and degraded pastures; but gradually, agroforestry systems (AFS) have been introduced as a sustainable alternative for soil reclamation and increasing land productivity. Although soil physical quality changes can be monitored by multiple indicators, the Visual Evaluation of Soil Structure (VESS) method has emerged as a straightforward, reliable and low-cost tool for assessing and monitoring the impacts of land uses and management agricultural practices on soil quality in different parts of the world. However, the VESS has never been tested in AFS and in Colombian soils. Thus, we conducted a pioneering assessment of soil physical quality in six typical land uses (i.e., forest, pasture and four AFS) using the VESS method in northwestern Colombian Amazon. The VESS assessment takes account characteristics of soil aggregate and biological activity (roots and macrofauna) to assign scores ranging from Sq 1 (good) to Sq 5 (poor physical quality). Moreover, quantitative soil indicators (i.e., bulk density, soil resistance to penetration, soil moisture and soil organic C) were evaluated to correlate with VESS scores. Soil physical changes induced by land use change were efficiently detected by VESS scores. The VESS scores were significantly correlated with key indicators of soil quality. Conversion from Amazon forest to low-input pasture intensively degraded soil physical quality (overall Sq 1.3 vs Sq 4.0). Nevertheless, the adoption of AFS improves soil physical quality (overall Sq 3.2, 2.8, 2.4 and 2.2) in areas previously occupied with pasture, indicating greater potential of soil reclamation under more diversified systems. This study shows that adopting AFS can be a strategy for recovering soil quality and reincorporating degraded lands into productive and sustainable production systems in Amazon regions, and the VESS method can be an useful tool to monitoring soil physical changes in these areas.

Keywords Land use change · VESS method · Soil structure · Soil organic C · Quantitative soil physical attributes · Soil quality

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Introduction

As the largest tropical forest in the world, the Amazon region plays an essential role to the Earth, influencing global carbon fluxes, water cycle and biodiversity. In Colombia, the Amazon covers 42% of the country's territory (Etter et al. 2006), accounting for 67% of the national's area covered by forests. However, despite the relevance of this ecosystem, land use changes in this region have resulted in high deforestation rates (45,302 ha year^{-1}), contributing with 46% of the total deforested area in the country in 2015 and 2.5% of the total habitat loss in the Amazon basin (SIAC 2017).

Extensive cattle ranching, expansion of the agricultural frontier and logging for the illicit cultivation of coca bush (*Erythroxylum coca*) are the main drivers of deforestation in Colombia, especially in Caquetá state, an important hotspot of deforestation in Amazon basin, together with the so-called "arc of deforestation" in Brazil (Coca-Castro et al. 2013). Conversion from Amazon forest to low-management pasture or agriculture causes not only degradation of aboveground vegetation but also negative changes in soil properties and ecosystem services (Lavelle et al. 2014; Celentano et al. 2017). Deforestation and cultivation may induce significant soil C depletion (Fujisaki et al. 2015; Durigan et al. 2017), which coupled with intensive machinery traffic or animal trampling drives negative soil physical changes, increasing bulk density and soil resistance to penetration, reducing soil aeration, aggregate stability and water infiltration and consequently, increasing the soil risks to degradation by erosion (Cherubin et al. 2016b, 2017).

The adoption of agroforestry systems (AFS) is being promoted as a sustainable productive alternative for local communities (Nair 2011; Somarriba et al. 2012), which can partially offset the negative impacts of long-term extensive pasture and low-input agriculture land uses. It is estimated that agroforestry covers between 88 and 315 million hectares in South America (Somarriba et al. 2012). In Colombian Amazon, AFS involve annual crops, fruits and trees with varying ages of adoption and grades of integration (Miller and Nair 2006; Somarriba et al. 2012; Bucheli and Bokelmann 2017). In addition to social-economic aspects (Bucheli and Bokelmann 2017), AFS provides several environmental benefits on preserving or improving soil quality (Silva et al. 2011; Guimarães et al. 2014; De Stefano and Jacobson 2017) and ecosystem services (Somarriba et al. 2012; Bucheli and Bokelmann 2017). Thus, soil quality changes must be continuously monitored to design even more sustainable landscape managements in Amazon region.

In this context, since soil structure is highly related to many key soil processes, observable soil structural attributes enable to evaluate changes on multiples soil-related ecosystem services (Robot et al. 2018). Alternative methods (e.g., visual soil assessments) capable of producing quick and accurate results could be a useful tool for researchers, advisers and farmers from this remote region (Guimarães et al. 2017a, b), since monitoring alterations of soil physical quality by traditional quantitative methods is relatively time consuming and requires expensive equipment and laboratory infrastructure (Emmet-Booth et al. 2016). Visual soil methods provide useful diagnosis related to shape and stability of soil structure, as well as indicatives of structural resilience based on biological indicators (Guimarães et al. 2017a), which are related to soil functions such as physical stability and support, storage and filtering of water, biomass production (Robot et al. 2018) and soil biological abundance (Franco et al. 2016). Despite this, as any methodology, visual evaluation approaches present drawbacks mainly related to considerable subjectivity for assigning scores according to the experience of operator, difficulty in breaking soil manually along planes of weakness and the influence of soil texture and moisture (Robot et al. 2018). For more details about potentialities and limitations of the soil visual evaluation methods consult recent reviews conducted by Emmet-Booth et al. (2016) and Ball et al. (2017a).

The Visual Evaluation of Soil Structure (VESS), however, has been recognized as one of the simplest methods that provides a first indicative of overall soil quality (Ball et al. 2017a; Cherubin et al. 2017; Guimarães et al. 2017b). It has been widely applied for assessing soil physical changes induced by land uses (Moncada et al. 2014; Cherubin et al. 2017; Guimarães et al. 2017b); tillage and crop managements (Ball et al. 2007; Guimarães et al. 2013; Tormena et al. 2016) and pasture management systems (Ball et al. 2007; Cui et al. 2014). Recently, Guimarães et al. (2017b) verified that VESS can efficiently detect physical quality changes in soils of the Brazilian Amazon biome. Nevertheless, there is no applications of the

VESS method for evaluating tropical agroforestry systems, as those present in northwestern Colombian Amazon.

In this sense, the objective of this study was to evaluate soil physical quality changes associated with land use change including agroforestry systems in Colombian Amazon region using the VESS method. We tested the hypotheses that: (1) the introduction of agroforestry systems, especially long-term diversified systems, can be an alternative to attenuate soil physical degradation induced by land use change from Amazon forest to extensive pasture; (2) the VESS method is capable to detect efficiently soil structure changes in Colombian Amazon, being an useful and straightforward indicator to monitor soil quality changes.

Materials and methods

Study sites

The study was carried out in the research center of the University of Amazon "Cesar Augusto Estrada Gonzalez" (1°37′N; 75°37′W; 300 meters above sea level), located in Caquetá state in Colombia, the state with the biggest deforestation rate of the country and an important hotspot of deforestation within the Amazon basin. The regional climate is classified as tropical rainforest—Af type (Koppen classification), with mean annual temperature of 25.5 °C and annual precipitation of 3793 mm.

We selected six areas for this study, which represent the main land uses, including four AFS, existing in that region, as follows:

1. "Forest", area covered by pristine rainforest that belongs to the Amazon biome;
2. "AFS_Peach palm": agroforestry system implanted in the late 1990s composed of peach palm tree (*Bactris gasipaes*) as the principal species, rubber tree (*Hevea brasiliensis*) and strawberry guava tree (*Eugenia stipitata*). In addition, a mix of spontaneous species of herbs and shrubs is growing underneath of the trees.
3. "AFS_Cupuassu": agroforestry system implanted in the late 1990s composed of cupuassu tree (*Theobroma grandiflorum*) as the principal species, rubber tree and parica (*Shizolobium amazonicum*);
4. "AFS_Rubber tree": agroforestry system implanted in the late 1990s composed of rubber tree as the principal species and strawberry guava tree;
5. "AFS_Cocoa": agroforestry system implanted since 2013 composed of cocoa tree (*Theobroma cacao*) as the principal species and banana tree (*Musa* spp.). It is worth highlighting this is the youngest AFS evaluated in this study, being 3-year old at the soil sampling date (November 2016);
6. "Pasture", area covered predominantly by the African grass *Urochloa humidicola* (Syn. *Brachiaria humidicola*) since 1990 characterized by extensive management (i.e., absence of fertilizations or animal rotations) and low productivity (< 1 animal unit per ha).

The AFS had different grades of integration, with plants density varying from high to low density, following the sequence AFS_Peach palm > AFS_Cupuassu > AFS_Rubber tree > AFS_Cocoa. All the AFS were implanted in areas previously occupied by extensive pasture without soil disturbance, except in the tree planting pits. Study sites were located adjacent to each other in the same landscape position, preventing undesired variation in the climate, relief and soil conditions among areas.

The soil in the areas was classified as a Typic Kandiudox (Soil Survey Staff 2014) with clay loam texture (37% of clay). The soil is highly weathered, typical of the tropical Colombian Amazon region.

Applying of the Visual Evaluation of Soil Structure (VESS) method

Soil sampling was performed in November 2016, when the soil water content was near field capacity. Within each land use, we selected semi-randomly three representative sampling points to take the soil samples. We positioned the sampling points approximately in the same landscape position to prevent undesired changes in the soil type among land use systems. In addition, following recommendation of Cherubin et al. (2017), we avoided to sample close to big tree trunks, nests of ants or termites and armadillo borrows in the undisturbed Amazon forest and agroforestry systems, as well as, on preferential cattle trampling paths in pasture.

The VESS assessment was performed following the methodology proposed by Ball et al. (2007) and improved by Guimarães et al. (2011). In each sampling point, a mini trench (i.e., 30 × 30 × 30 cm deep) was dug out to extract an undisturbed sample (soil block of ~ 20 × 10 × 25 cm deep to ~ 5000 cm^3 volume) using a spade. Then, the sample was carefully transferred to a light-colored plastic tray. Initially, the intact soil sample was measured to verify the exact soil layer assessed. The ease of block extraction was the first signal (or criteria) for assisting the user to assign the score (Ball et al. 2007; Guimarães et al. 2011), which was much difficult if the score was higher (i.e., lower soil physical quality). Then, the sample was gently manipulated and broken up to reveal the characteristics of the main structural units (i.e., shape, size and visible porosity of soil aggregates), identify layers of contrasting aggregation and verify roots distribution (inter- or intra-aggregate spaces) and biological activity signs (e.g., presence of earthworms and burrows).

Afterwards, VESS scores (Sq scores), ranging from 1 to 5, were assigned for each layer identified as having a distinct soil structure using the visual interpretation chart proposed by Guimarães et al. (2011). Scores 1 and 2 indicate good physical quality and therefore, the land use or management practices adopted offer suitable conditions to plant growth. Score 3 also indicate good soil physical quality (Ball et al. 2017a), nevertheless it is a threshold (Cherubin et al. 2017), suggesting that management practices need to be improved to prevent further degradation of soil quality. Finally, the scores 4 and 5 indicate poor soil physical quality, the therefore, management practices should be urgently changed to improve soil condition to plant growth. A detailed interpretation of VESS scores and respective recommendations of soil management are available in Ball et al. (2007) and Guimarães et al. (2011).

An overall weighted Sq score was calculated for each sample based on the individual score and thickness of each contrasting soil layers, according to Eq. 1.

$$\text{VESS Sq}_{\text{score}} = \sum_{i=1}^{n} \frac{Sq_i T_i}{TT} \qquad (1)$$

where VESS Sq_{score} is the overall VESS score of the sample, Sq_i and T_i are respectively the score and thickness of each identified soil layer, and TT is the total thickness of soil sample.

Weighted VESS scores for the top (0–10 cm) and bottom (10–25 cm) soil layers were also calculated for comparing and correlating VESS data with other soil parameters taken in this specific soil layers, as recommended by Cherubin et al. (2017).

In the last step, the sample was identified and pictures were taken to further confirm of the scores assigned in the field (Tormena et al. 2016; Ball et al. 2017a). A trained person completed all the VESS assessments, in order to standardize score assigning, preventing potential variations induced by different people and consequently, reducing the subjectivity of the method (Cherubin et al. 2017).

Soil sampling and determination of quantitative soil parameters

In the same mini trenches used for VESS assessment, we collected undisturbed soil samples in the center of the 0–10 and 10–25 cm layers using a metallic ring (5 × 5 cm to 98 cm^2) and disturbed samples from the same soil depths. In the laboratory, undisturbed samples were weighed, dried in a forced-air oven at 105 °C for 48 h, and weighed again. Bulk density (BD, Mg m^{-3}) was calculated by dividing the soil dry mass by volume of the cylinder; whereas soil moisture (%) was determined by the equation: soil moisture = [(dry soil mass/wet soil mass) − 1] × 100. Disturbed soil samples were dried, grounded and sieved at 2 mm. Soil C concentration was estimated by a modified wet oxidation method, without external heating procedure, followed by colorimetric method using a UV–visible spectrophotometer (Heanes 1984).

In addition, measurements of soil resistance to penetration (SRP) were performed using a hand penetrometer (Eijkelkamp®) around the soil sampling trenches down to 30 cm with angle and surface area of cone of 60° and 2 cm^2, respectively.

Data analysis

The data were subjected to analysis of variance (ANOVA) using completely randomized design to test the land use system effects on VESS scores and quantitative soil attributes. When ANOVA F-test was significant ($p < 0.05$) mean values within each soil layer were compared according the Tukey's test ($p < 0.05$). Furthermore, Person's linear correlation analysis was performed between VESS scores and quantitative soil attributes. All statistical analyses were completed using the Statistical Analysis System—SAS v.9.3 software (SAS Inc., Cary, USA).

Results and discussion

VESS assessment

The VESS method allowed identifying soil physical quality changes induced by conversion from pristine forest to extensive pasture, as well as by introduction of diversified agroforestry systems in the Colombian Amazon region.

The complete VESS test of each sample required about 20 min, similar to reported in the literature (Tormena et al. 2016; Cherubin et al. 2017; Guimarães et al. 2017a). Soil slices were easily extracted in the forest and AFS areas, although the tree roots had to be carefully cut with a knife to facilitate the extraction of intact soil samples. The same procedure was adopted by Guimarães et al. (2017b) and Cherubin et al. (2017) sampling soils under pristine Amazon forest and Cerrado in Brazil, respectively. In contrast, severe soil compaction was the major restriction to extract and breakdown samples under pasture, providing clear indication of soil physical degradation (Ball et al. 2007; Guimarães et al. 2011). We also highlighted the importance of sampling soil for VESS assessment within the friable range of water contents (i.e., when the soil crumbles under an applied load), avoiding extreme wet or dry soil conditions (Ball et al. 2017a; Guimarães et al. 2017a). It eases the sample extraction and allows a more accurate signature of Sq scores (Cherubin et al. 2017).

The scores ranged from Sq 1 to 4.5 (Fig. 1). Reducing the size of larger soil aggregates to approximately 1.5 cm diameter (Guimarães et al. 2011) was helpful for distinguishing between two Sq scores, especially between Sq 3 and 4 (Tormena et al. 2016; Cherubin et al. 2017). In addition, an even force was applied by closing the palm of the hand to the larger aggregates, where, an Sq 3 score was given if the aggregate crumbles, whilst a higher score (i.e., Sq 4–4.5 score) was assigned if it did not crumble (Ball et al. 2017a).

Two distinct layers were identified for the samples extracted under forest, AFS_Peach palm, AFS_Rubber tree and AFS_Cocoa, whilst three distinct layers were identified under pasture and AFS_Cupuassu soils (Figs. 2, 3). According to Ball et al. (2017a), no more than three layers are possible to be identified within a spade depth of 25 cm using VESS method, in which any further division is impractical on the basis of insufficient samples to be rated.

Effects of land use on soil physical quality based on VESS scores

The highest soil physical quality was found in the pristine Amazon forest samples (Fig. 1), which can be considered a reference of soil's capacity to sustain suitable conditions to support plant growth. Overall, a mix of porous and rounded aggregates and roots throughout the soil profile was characteristic of the structure of forest soil (Fig. 3). The VESS scores under native forest soils typically range between Sq 1 and 2 (e.g., Guimarães et al. 2013, 2017b; Auler et al. 2017; Cherubin et al. 2017), presenting a deeper top layer of better soil quality (Sq 1) followed by a layer with scores slightly higher (Sq 1.5). Nevertheless, bottom layer scores also indicate suitable soil conditions to root growth (Fig. 2).

The permanent soil cover by litter, continuous inputs of organic C in the soil and absence of disturbance are key drivers of soil aggregation and enhanced physical quality under native vegetation (Auler et al. 2017; Cherubin et al. 2017; Guimarães et al. 2017b). Litter coverage protects the soil against the direct impact of raindrop, preventing soil disaggregation, surface sealing and consequently, reducing soil losses by erosion. Soil C increases the complexity and stability of soil aggregates (Tisdall and Oades 1982), whereas absence of soil disturbance reduces C losses by accelerated microbial respiration (Cherubin et al. 2017).

In addition, forest/native vegetation areas are associated with higher diversity and activity of soil

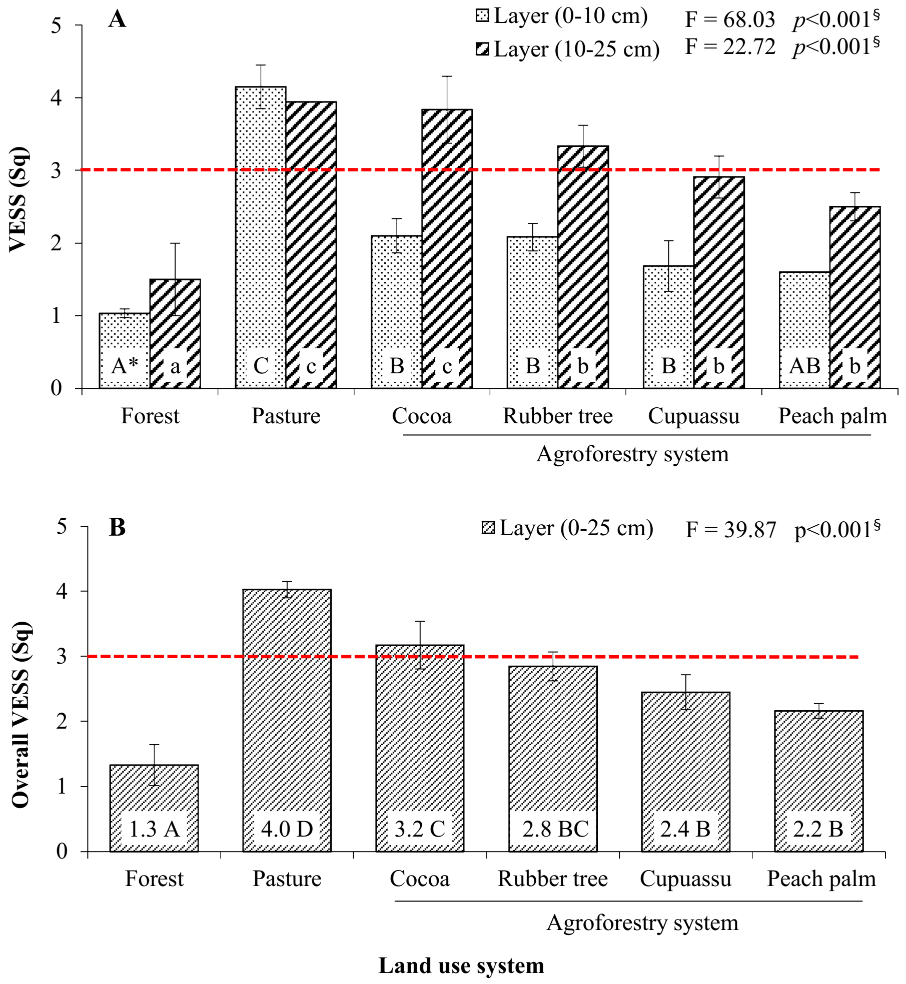

Fig. 1 VESS scores (Sq) for the top (0–10 cm) and bottom (10–25 cm) layers and overall Sq for total layer (0–25 cm) under land-use systems in Colombian Amazon. Dashed line indicated the VESS score (Sq = 3.0) considered as a threshold for suitable root growth. §F and p values derived from ANOVA analysis for each soil layer. *Means followed by the same letter [uppercase for the 0–10-cm soil layer and lowercase for the 10–25-cm soil layer (**a**); uppercase for the 0–25-cm soil layer (**b**)] did not differ among themselves according to Tukey's test ($p < 0.05$)

biota compared to agricultural land uses (Franco et al. 2016). Soil biota acts positively on soil aggregation by exudation of biopolymers, entanglement of particles and incorporation of fresh organic matter at depth by digging channels and galleries (Lehmann et al. 2017). We did not systematically evaluate soil biota, but the presence of biopores (i.e., created by soil fauna activity and root growth) is one of criteria to assign lower VESS scores (Guimarães et al. 2011), as observed in the forest samples. Recently, Franco et al. (2017) confirmed that lower VESS scores (i.e., better soil physical quality) was significantly correlated with higher abundance of isopterans and coleopterans (groups known as soil engineers). More studies on soil biota may be necessary to investigate its linkage with soil structural changes assessed by VESS, as well as to provide more robustness to the results obtained by VESS or other visual soil methods.

Long-term conversion from forest to pasture versus soil physical quality

Historically, poor-managed pasture is the first land use after deforestation in Amazon region (Armenteras et al. 2006). The long-term conversion from pristine Amazon forest to extensive pasture induced severe

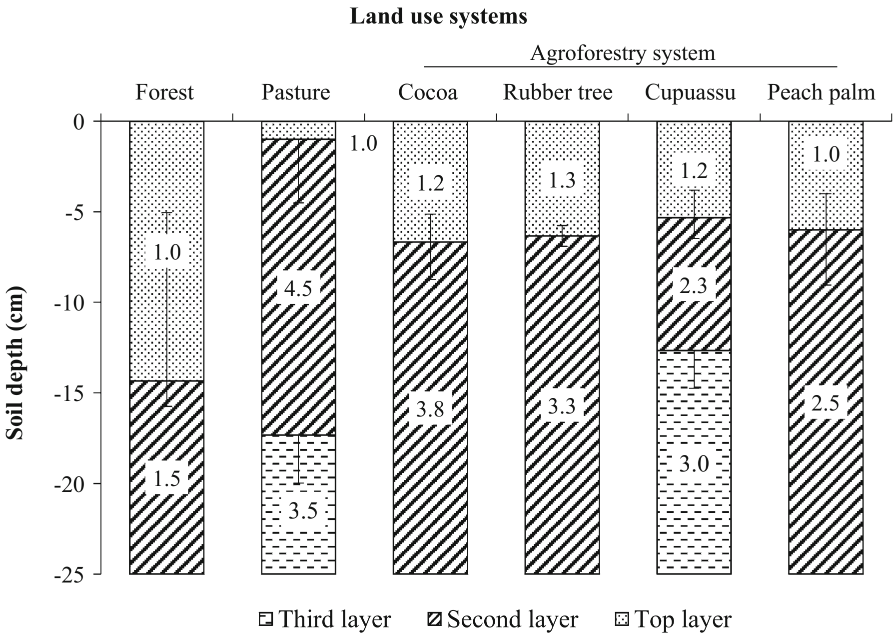

Fig. 2 Average depth and Sq score (inside the bars) of each contrasting soil layers observed in samples from the land use systems [i.e., forest, pasture and agroforestry systems (cocoa, rubber tree, cupuassu and peach palm)] in Colombian Amazon. Error bars presented inside each soil layer (first, second and third) denote standard deviation of the average depths observed by VESS

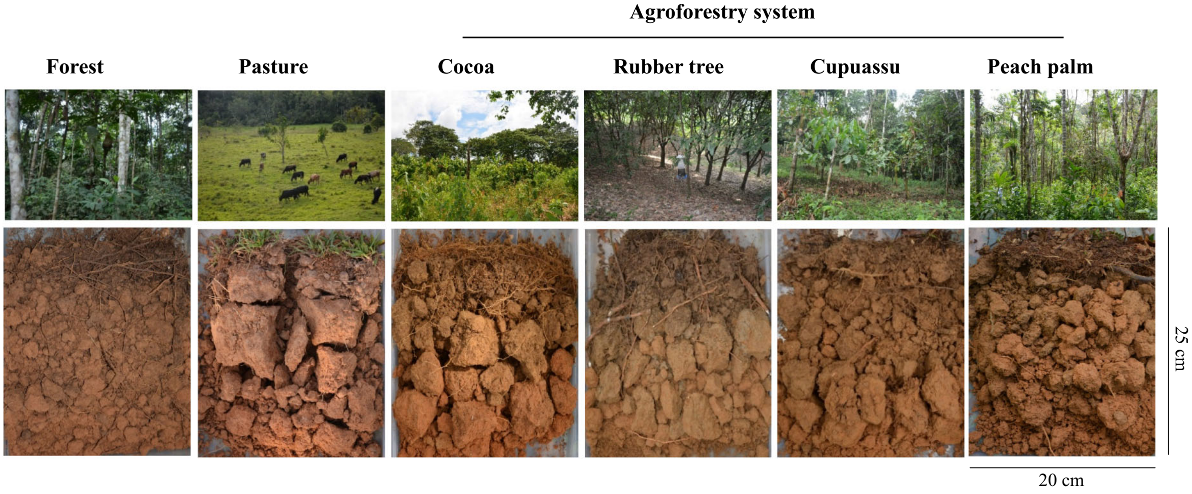

Fig. 3 Representation of the soil physical quality changes detected by VESS method due to effects of land-use systems in Colombian Amazon. The photos taken after VESS assessment revealed contrasting soil physical quality, in which lower VESS scores (better soil physical quality) were signed to soil layers that presented a mix of porous, easy to break and rounded aggregates, presence of roots and signal of higher biological activity (e.g., forest soil). In contrast, higher VESS scores (poorer soil physical quality) were related with soil layers that presented large, angular and hard to break clods with very low visible porosity and practically absence of roots (e.g., pasture soil). For more detail about criteria of score assignment and other photos, see the VESS chart in Guimarães et al. (2011)

degradation on soil physical quality for the 0–25-cm layer (Fig. 1), increasing overall Sq scores from 1.3 to 4.0 (Fig. 1b). High Sq scores (> 3) are widely reported in both tropical (Auler et al. 2017; Cherubin et al. 2017) and temperate pasturelands (Cui et al. 2014; Ball et al. 2017a; Emmet-Booth et al. 2018).

Many studies have shown that conversion from Amazon forest to deep-rooted pasture did not change or even increase soil C in the surface layers (Fujisaki et al. 2015; Durigan et al. 2017), in which corroborates with the results of this study (Table 1). Higher soil C stocks in pasture areas are favored by large activity

Table 1 Bulk density, soil resistance to penetration, soil moisture content and soil organic C content under land use systems [i.e., forest, pasture and four agroforestry systems (cocoa, rubber tree, cupuassu and peach palm)] in Colombian Amazon

Soil layer (cm)	Land use system					
	Forest	Pasture	Agroforestry system			
			Cocoa	Rubber tree	Cupuassu	Peach palm
Bulk density (Mg m^{-3})						
0–10	0.78a*	1.33b	0.98ab	1.22ab	1.05ab	0.84a
10–25	1.14a	1.36ab	1.23ab	1.46b	1.39ab	1.28ab
Soil resistance to penetration (MPa)						
0–10	1.94a*	7.49c	3.86b	1.73a	2.19a	2.84ab
10–25	2.86a	4.42b	3.35a	2.65a	3.11a	3.51ab
Soil moisture content (%)						
0–10	31a*	17c	22bc	26ab	22bc	30ab
10–25	24a	19a	22a	20a	21a	25a
Soil organic C content (g kg^{-1})						
0–10	29.88a*	20.82ab	20.78ab	17.48b	18.48ab	19.55ab
10–25	14.66a	11.12ab	11.01ab	10.63ab	9.95b	10.40b

*Means followed by the same letter did not differ among themselves according to Tukey's test ($p < 0.05$)

and turnover of the vigorous and deep root system of perennial tropical grasses, which input enough C to offset the native-C mineralization (Fujisaki et al. 2015). Furthermore, the absence of soil disturbance in pasture soils reduces C losses by microbial respiration due to exposure of protected C within soil aggregates (Cherubin et al. 2017). However, although deep-rooted gasses can increase soil C that acts positively on soil aggregation (Tisdall and Oades 1982) and increases soil resistance and resilience to degradation, forces applied by continuous cattle trampling exceeded the loading-support capacity of these soils, leading to intense soil compaction, as confirmed by higher values of bulk density and soil resistance to penetration found in the pasture (Table 1). Moreover, southwestern Colombia rural areas are predominantly occupied by smallholders, who, in general, have low capacity for investments and access to technical information for better management of the soil, pasture and animals, in order to reverse the soil degradation processes. These are perhaps the major drivers of soil compaction and consequent structural degradation in low-input pastureland not only in Colombian, but also in other regions of the world (Newell-Price et al. 2013; Cui et al. 2014; Cherubin et al. 2017; Emmet-Booth et al. 2018).

In the soil surface layer (0–10 cm), these impacts were even more intense, increasing Sq from 1.0 in the forest to 4.2 in the pasture soil (Fig. 1a). Despite the perennial grasses typically present a massive volume of roots in the first 5–10 cm of soil (Emmet-Booth et al. 2018), intense mechanical stress induced by high soil compaction limits root growth in depth, confining most of roots in a very thin surface layer (~ 1 cm). Underneath this 1-cm root zone, a compacted layer (Sq 4.5) of 16 cm, in average, was characterized by hard and large angular clods with very low visible porosity and practically absence of roots, as clearly shown in Fig. 3.

Livestock trampling, especially under wet soil conditions (Drewry 2006), induces a widespread degradation in the soil surface structure in pastures (Ball et al. 2017a; Emmet-Booth et al. 2018), differently from soil compaction caused by heavy machinery in arable fields, where soils are gradually compacted at greater depths (Ball et al. 2017a). Because of that, assigning VESS scores for different soil layers, weighed (Fig. 1a) or naturally identified (Fig. 2) provides more specific information for targeted management actions compared to information provided only by an overall block score (Ball et al. 2017a). In this case, although we could identify more intense soil compaction in the surface layers (Figs. 1, 2, 3), the overall Sq score 4 (Fig. 1b), that considers the entire soil layer (0–25 cm), also provides a clear diagnosis of soil compaction and poor soil physical quality. Therefore, both individualized scores by soil layers and overall score indicated an urgent need to change the management for improving the soil quality and consequently the pasture and livestock productivity.

Our results showed that VESS method can be a practical and low-cost tool to diagnose and exchange knowledge about the soil degradation problems in pastures of the northwestern Colombia. Nevertheless, this action must be associated with adoption of technical strategies for reclamation and improving land productivity (Cui et al. 2014; Auler et al. 2017), such as (1) division of area in the paddocks for adopting a grazing rotation plan according to the grass biomass production; (2) reduce grazing intensity; (3) avoid cattle grazing under wet soil conditions, (4) grass reseeding or seeding a mix of species (including legume species); and (5) mineral or organic N-fertilizer inputs.

Agroforestry systems versus soil physical quality changes

The introduction of agroforestry systems (AFS) attenuated the degradation of soil physical quality imposed by historical improper land use and management with extensive pasture. In general, scores for both layers (Fig. 1a) and overall block (Fig. 1b) were lower in the AFS compared to pasture, although they remained higher than those found under forest. The Sq scores decreased from AFS_Cocoa (overall Sq 3.2) to AFS_Peach palm (overall Sq 2.2), suggesting that soil physical quality improved as the system became older and more diversified.

The benefits of AFS adoption were more significant for the surface soil layer, which presented high abundance of roots mixed with a soft layer composed primarily of porous and rounded aggregates (Fig. 3). The Sq scores ranged from 2.2 to 1.6 for the weighed 0–10-cm layer (Fig. 1a) or from 1.3 to 1.0 when considered the natural top layer identified in the field (Fig. 2). Both approaches showed Sq scores below critical level (i.e., Sq < 3) for the surface soil layer, indicating positive impact of AFS adoption on soil structure over time. In this case, management decisions based on scores of the individual layers differ from those of the overall block scores. According to Guimarães et al. (2017b), to observe individual layers by VESS could provide an early sign of physical limiting conditions to plant growth, allowing us to recommend adoption of best management practices that prevents further degradation in the overall soil profile. Therefore, overall Sq scores could be used to consider longer-term changes in management to improve soil quality (Ball et al. 2017a).

Agroforestry system soils tend to have similar physical quality as that of forest soils over time, when the system reaches an equilibrium and starts functioning similar to a forest, which is evident from the VESS scores (Fig. 1). The youngest system, AFS_Cocoa, presented a significant improvement in the soil surface physical quality compared to pasture, decreasing Sq from 4.15 to 2.10 for the 0–10 cm (Fig. 1a). It likely is associated with withdrawal of cattle from the area that causes surface soil compaction (Drewry 2006) and C inputs by tree litter in the soil surface. However, the system with small trees and heterogeneous soil coverage was unable to alleviate soil compaction in subsurface layer (Sq 3.83). Despite that, long-term cocoa agroforestry system can sustain improved soil physical and chemical quality (Arévalo-Gardini et al. 2015). Our results also showed that soil physical quality improvements were increasing in AFS_Rubber tree, AFS_Cupuassu and AFS_Peach palm (Fig. 1).

The greatest VESS scores found in AFS_Peach palm, likely is related to greater diversity of species in that system, including tree species (i.e., peach palm, rubber and strawberry guava) and a complete soil coverage by herbs and shrubs, that were introduced into the system by birds, wildlife and wind. In well-established agroforestry systems, high C inputs on the soil surface by litter of diverse species, favor soil biodiversity, C accumulation (De Stefano and Jacobson 2017) and indirectly, soil physical quality (Silva et al. 2011; Arévalo-Gardini et al. 2015) and other related ecosystem services (Nair 2011; Bucheli and Bokelmann 2017). In addition, vigorous root system may benefit soil aggregation by entanglement of particles, root penetration, changes in soil water status (wetting–drying cycles) and exudation of organic molecules (Six et al. 2004), enhancing soil physical quality in subsurface layers (Figs. 1a, 2). Therefore, adoption of diversified AFS is an effective strategy for reclamation of soil quality in degraded and low-productivity pasture areas, as those typically found in Amazon basin.

VESS scores versus quantitative soil attributes

Soil changes detected by VESS scores were also detected by traditional indicators used to evaluate soil

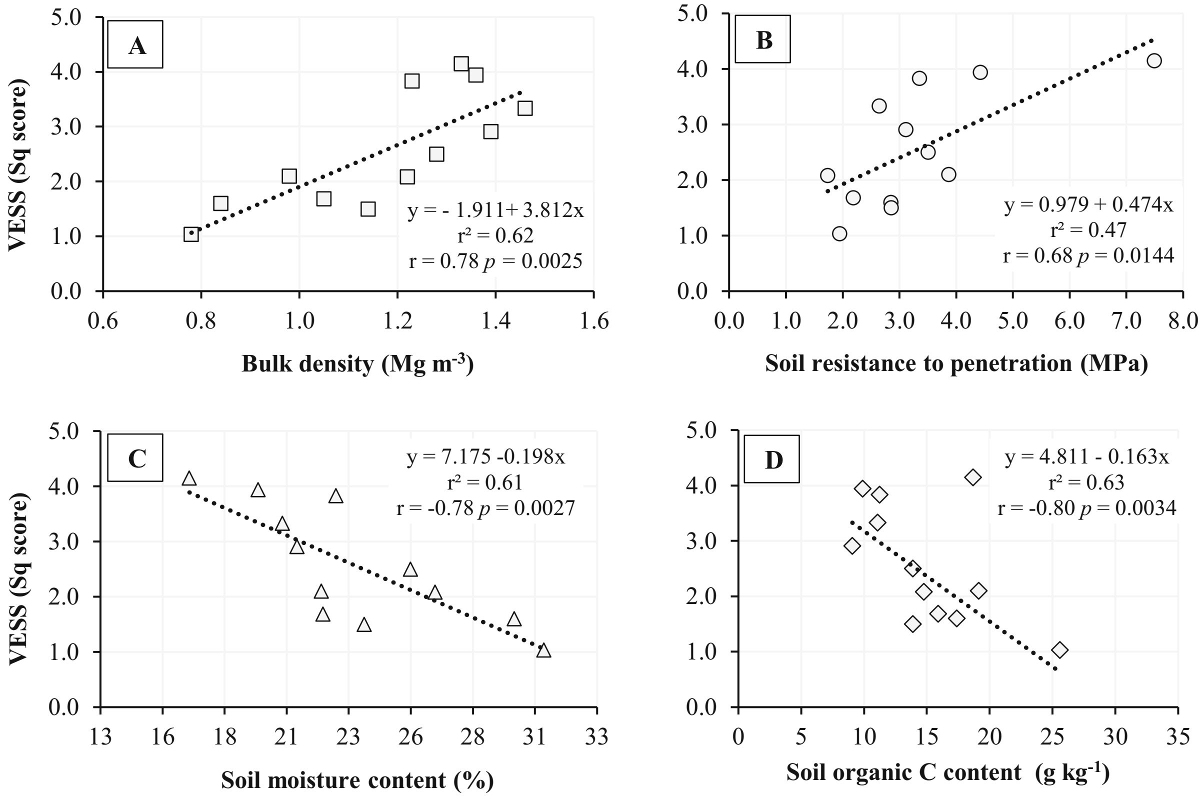

Fig. 4 Relationship between visual evaluation soil structure (VESS) scores and bulk density (**a**), soil resistance to penetration (**b**), soil moisture content (**c**) and soil organic C content (**d**) in land use systems in Colombian Amazon. n = 12, except for VESS versus soil C content, which n = 11

compaction and soil physical degradation (Table 1). Conversion of Amazon forest to pasture induced stark increases (70 and 286%) in bulk density and resistance to penetration, and caused reduction of 45% soil moisture in the surface layers (0–10 cm). A similar pattern was observed for subsurface (10–25 cm), but with changes of smaller magnitudes (Table 1). Contrarily, soils under AFS generally had similar bulk density, resistance to penetration and moisture as that of forest soils ($p > 0.05$), except AFS_Cocoa that presented higher soil resistance to penetration and lower soil moisture compared to forest for the 0–10 cm layer. Similar to the VESS results, quantitative parameters showed similar soil physical quality between forest and AFS_Peach palm.

In general, forest soils had higher C content compared to AFS with lower diversity (AFS_Rubber tree), but did not differ from the pasture and other AFS. As reported by previous studies, conversions from native vegetation to pasture did not have a noticeable effect on soil C content (Fujisaki et al. 2015; Durigan et al. 2017). Vigorous root systems of perennial grasses, C recycling by animal manure and lack of disturbance at pastures, even under process of degradation, likely drive C sequestration processes (Paustian et al. 2000). On the other hand, when AFS are established the continuous input of organic material provided by litterfall allows to maintain the SOC content. Both high diversity of species and biomass input in this systems are comparable to natural ecosystems, resulting in higher potential to storage C (De Stefano and Jacobson 2017). Fresh organic matter added into the AFS is an ideal substrate for microbial activity, acting as an agent for improving the stability of the aggregates (Tisdall and Oades 1982; Guimarães et al. 2014) and promotes better pore distribution, improving soil physical quality (Silva et al. 2011).

Our findings confirmed close correlations between VESS scores and key indicators of soil physical quality (Cherubin et al. 2016b; Bünemann et al. 2018).

Higher VESS scores were associated with higher bulk density (r = 0.78) and soil resistance to penetration (r = 0.68) and lower soil moisture content (r = − 0.78) (Fig. 4). These results are in line with previous studies (Guimarães et al. 2013; Moncada et al. 2014; Cherubin et al. 2017), indicating that VESS is able to integrates attributes related to essential physical functions of soils (e.g., water availability, aeration and root growth) (Cherubin et al. 2016a, 2017). Furthermore, although traditional soil aggregate stability analysis (e.g., wet sieving) was not performed in this study, previous studies have shown that VESS scores were significantly correlated with MWD and tensile strength of aggregates, as summarized by Ball et al. (2017a).

In addition, VESS scores were well correlated with soil C content (r = − 0.80) (Fig. 4), which is consistent with previous studies conducted in Venezuelan tropical soils (Moncada et al. 2014) and Irish temperate soils (Cui et al. 2014). Soil organic C plays multiple functions to sustain chemical, physical and biological properties and processes in the soil, and thus, it is considered the main indicator for soil quality assessments (Cherubin et al. 2016a; Bünemann et al. 2018). Therefore, VESS scores can integrate in one single value not only soil physical aspects but also it can be one of the 'core indicators' of soil quality (Cherubin et al. 2016a, 2017; Ball et al. 2017a).

Thinking beyond technical efficiency, VESS method also has benefits of easy comprehension, minimal equipment and ability to be used in remote locations such as the Amazon basin (Guimarães et al. 2017a, b). Thus, VESS can be useful tool for assessing soil degradation by improper land management or monitoring soil reclamation induced by the introduction of more sustainable systems, such as agroforestry, silvopastoral (see Tovar et al. 2017) or even, in coca plantation areas that recently have been repossessed through the peace agreement signed between the Colombian government and the Revolutionary Armed Forces of Colombia (FARC).

Finally, the VESS method application can strengthen the people's connection to the soil increasing their awareness on soils simply by digging it up and looking at it (Ball et al. 2017b). Therefore, the VESS method can be used for multiple proposes, such as scientific investigations, teaching to transference of knowledge on soils to farmers and stakeholders, extension agents, policy makers, scientists, students and society as a whole (Ball et al. 2017b; Bünemann et al. 2018).

Conclusions

This pioneering VESS assessment in northwestern Colombian Amazon revealed that conversion from forest to low-input pasturelands led to intensive degradation of soil physical quality, which is likely directly associated with the low productivity of the lands. In contrast, the adoption of agroforestry systems improves soil physical quality in areas previously occupied with pasture, showing greater benefits for longer-term and more diversified systems. Thus, agroforestry systems can be an alternative for recovering soil quality and reincorporating degraded lands into productive and sustainable production systems in Amazon regions.

The VESS Sq scores offer a potent low cost and straightforward option to efficiently detect soil physical changes induced by land use and management. Thus, it can be used by scientists, consultants and/or extension agents for assessing soil quality changes and transferring knowledge to increase the awareness about soil degradation in Amazon regions.

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