The merits of the Visual Evaluation of Soil Structure method (VESS) for assessing soil physical quality in the remote, undeveloped regions of the Amazon basin

Guimaraes, RML; Neves Jr, AF; Silva, WG; Rogers, CD; Ball, BC; Montes, CR; Pereira, BF

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Corresponding Author: Dr. Rachel Muylaert Locks Guimaraes, Ph.D.

Corresponding Author's Institution: Universidade Tecnológica Federal do Paraná

First Author: Rachel Muylaert Locks Guimaraes, Ph.D.

Order of Authors: Rachel Muylaert Locks Guimaraes, Ph.D.; Afrânio F Neves Jr, PhD; Wellington G Silva, PhD; Craig D Rogers, PhD; Bruce C Ball, PhD; Célia R Montes, PhD; Bruno F Pereira, PhD

Abstract: The Visual Evaluation of Soil Structure (VESS) is a straightforward and logistically simple method for characterising and scoring soil structural and physical quality, ideally suited to evaluate and monitor soil degradation in remote and undeveloped areas. The research presented here tested for the first time the feasibility of using VESS in the Amazon basin, under the specialised land uses and soils (Yellow Oxisol and "Terra Preta de Índio") of the region, and its relation with quantitative soil indicators. The evaluated areas, which had never been subjected to mechanisation, fertilisation nor tillage, were "Terra Preta de Índio"/ Anthropogenic Dark Earth; Regenerating Forest; Slash and Burn; Pasture; and Pristine Forest. The results showed that the quantitative indicators were less sensitive at revealing signs of degradation than VESS and that VESS brought to light evidence of historic land use change and limitations to crop productivity. VESS was significantly correlated with soil resistance to penetration. However, VESS had difficulty capturing possible low water-holding capacity and surface sealing, but the hands on approach to VESS allowed the user to identify these problems, despite not being listed in the reference chart. Overall, VESS was a more integrated soil quality indicator, exposing more aspects of soil functionality than the quantitative indicators, it was also logistically easier to perform making it ideal for tracking soil degradation and structural quality in similarly challenging situations. However, more research is required to fully enable VESS to capture structural quality in 'sandified' soils, caused by the slash and burn method widely used in the Amazon region.

The Editorial Office of Soil & Tillage Research

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1000 AD Amsterdam

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Dear Editor

Please find enclosed the manuscript entitled "**The merits of the Visual Evaluation of Soil Structure method (VESS) for assessing soil physical quality in the remote, undeveloped regions of the Amazon basin**" co-authored by Afrânio F. Neves Jr., Wellington G. Silva, Craig D. Rogers, Bruce C. Ball, Célia R. Montes and Bruno F. F. Pereira, for consideration to be published in the special issue "VSE and Compaction Res." of Soil & Tillage Research.

Yours faithfully,

Rachel Muylaert Locks Guimarães

Rachel Muylaert Locks Guimarães
Universidade Tecnológica Federal do Paraná – UTFPR
Via do Conhecimento, km 1
Pato Branco, Paraná, Brazil
CEP: 85503-390
Tel: +55-46-32202542
E-mail: rachelguimaraes@utfpr.edu.br

*Highlights

Highlights

- VESS brought to light changes between land use and limitations to crop productivity
- Quantitative indicators were less sensitive at revealing degradation than VESS
- VESS had difficulty capturing possible low water holding capacity and crusting
- VESS had a significant positive correlation with soil resistance to penetration
- VESS was a more integrated indicator, exposing more aspects of soil functionality

The merits of the Visual Evaluation of Soil Structure method (VESS) for assessing soil physical quality in the remote, undeveloped regions of the Amazon basin

Rachel M. L. Guimarães[1*], Afrânio F. Neves Jr[2], Wellington G. Silva[3], Craig D. Rogers[4], Bruce C. Ball[5], Célia R. Montes[6], Bruno F. F. Pereira[3]

[1]Federal University of Technology-Paraná, Department of Agronomy, Via do Conhecimento, km 1, 85503-390, Pato Branco, PR, Brazil

[2]Universidade Federal do Amazonas, Av. Gen. R. Otávio Jordão Ramos, 3000-Coroado I, Centro de Educação a Distância, 69077-000, Manaus, AM, Brazil.

[3]Universidade Federal do Amazonas, Av. Gen. R. Otávio Jordão Ramos, 3000-Coroado I, FCA, DEAS, 69077-000, Manaus, AM, Brazil.

[4]Independent Scholar

[5]Scotland's Rural College, Crop and Soil Systems Research Group, West Mains Road, Edinburgh, EH9 3JG, UK.

[6]Center for Nuclear Energy in Agriculture, University of São Paulo, Avenida Centenário, 303, 13416-903, Piracicaba, SP, Brazil

*Corresponding author, Tel.: +55-46-32202542

E-mail address: rachelguimaraes@utfpr.edu.br

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Abstract

The Visual Evaluation of Soil Structure (VESS) is a straightforward and logistically simple method for characterising and scoring soil structural and physical quality, ideally suited to evaluate and monitor soil degradation in remote and undeveloped areas. The research presented here tested for the first time the feasibility of using VESS in the Amazon basin, under the specialised land uses and soils (Yellow Oxisol and “Terra Preta de Índio”) of the region, and its relation with quantitative soil indicators. The evaluated areas, which had never been subjected to mechanisation, fertilisation nor tillage, were “Terra Preta de Índio”/ Anthropogenic Dark Earth; Regenerating Forest; Slash and Burn; Pasture; and Pristine Forest. The results showed that the quantitative indicators were less sensitive at revealing signs of degradation than VESS and that VESS brought to light evidence of historic land use change and limitations to crop productivity. VESS was significantly correlated with soil resistance to penetration. However, VESS had difficulty capturing possible low water-holding capacity and surface sealing, but the hands on approach to VESS allowed the user to identify these problems, despite not being listed in the reference chart. Overall, VESS was a more integrated soil quality indicator, exposing more aspects of soil functionality than the quantitative indicators, it was also logistically easier to perform making it ideal for tracking soil degradation and structural quality in similarly challenging situations. However, more research is required to fully enable VESS to capture structural quality in

‘sandified’ soils, caused by the slash and burn method widely used in the Amazon region.

Keywords: Terra Preta de Índio; Soil quality; Slash and burn; Soil degradation; Forest regeneration

1. Introduction

The vast stocks of carbon found in forests and their soils can be lost through land use change and degradation, with deforestation being considered the second greatest source of anthropogenic carbon dioxide to the atmosphere (van der Werf et al., 2009). With disturbances to tropical forest ecosystems and land use change of tropical forests accounting for approximately 20 % of the anthropogenic greenhouse gas emissions of tropical countries (Mäkipää et al., 2012).

The Amazon forest is one of the largest areas of contiguous forest in the world containing 150-200 Pg C in living biomass and soils (Feldpausch et al., 2012) and accounting for approximately 25% of Earth's terrestrial species (Malhi et al., 2008). It is a massive store of carbon, with C uptake in the Amazon basin being estimated at 0.42-0.65 Pg C yr^{-1} between 1990-2007, accounting for approximately 25% of the terrestrial carbon sink (Phillips et al., 2009; Pan et al., 2011).

The Amazon basin covers approximately 40% of South America and is spread across Bolivia, Brazil, Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname and Venezuela, with 60% falling within the borders of Brazil (Song et al., 2015). Despite the area's importance it has been subjected to extensive deforestation and has lost almost 20% of its coverage since the 1970s (INPE, 2015). The rate of deforestation has generally slowed within the Brazilian Amazon since 2004, a 77% fall in annual rates between 2004 and 2011 (Godar et al., 2014), due to a number of socioeconomic factors

(Godar et al., 2014; Nepstad et al., 2014). Since then, deforestation rates have stabilised at between 5,000–7,000 km^2 yr^{-1} in Brazil (Godar et al., 2014; INPE, 2015), however, deforestation rates in many non-Brazilian regions of the Amazon have increased (Hansen et al., 2013 Song et al., 2015). Deforestation in the Amazon basin is mainly due to land use change, deforestation for farming (Morton et al., 2006), illegal logging (Asner et al., 2005) and mining (Asner et al., 2013) as well as natural sources such as fire, drought and flooding (Espirito-Santo et al., 2014).

Despite their importance and high level of productivity, tropical rainforest soils, such as those found in the Amazon basin, are nutrient poor (Herrera et al., 1978; Laurance et al., 1999), rely on the recycling of nutrients from soil organic matter to maintain fertility (Tiessen et al., 1994), have a high turnover rate of organic matter and can be subjected to high levels of weathering (Peña-Venegas et al., 2016). This results in a fragile soil vulnerable to anthropogenic disturbance (Reichert et al., 2014), that can result in a loss in soil function and, consequently, damage to the component ecosystems and the services they provide (Foley et al., 2007).

However, throughout the Amazon basin small areas of highly fertile soil are found, this Anthropogenic Dark Earth, known as *Terra Preta de Índio* (terra preta) in Portuguese, is the result of indigenous Brazilian soil management and the employment of slash and burn (SB) (Glaser and Birk 2012). The soil contains a high level of charcoal and ash as a result of the slash and burn and also available nutrients, such as nitrogen, phosphorus, calcium, zinc and manganese, due to the incorporation of plant residues and animal waste (including feaces, urine and bone) (Smith, 1980; Kern and Kampf, 1989; Lima et al., 2002). The addition of the organic matter and charcoal to the soil also affects the physical structure of the soil, improving soil porosity and structural strength (Kern and Kampf, 1989; Teixeira and Martins, 2003).

Soil degradation, the loss of soil potential productivity due to a loss in soil fertility, greatly affects the Amazon region and can be brought about by several agricultural land use changes, such as deforestation for logging, cropping and ranching, and can be compounded through inappropriate cropping systems and management (Lal, 1997). Soil degradation can come in the form of biological (loss of soil micro and macrobiota), chemical (nutrient loss/imbalance, acidification, salinisation, decrease in cation exchange, volatilisation) and physical degradation (crusting, compaction, erosion, leaching and anaerobism) (Guimarães et al., 2015).

These degradation processes release carbon through burning, where the combustion of organic matter leads to the release of carbon dioxide (CO_2) into the atmosphere. While C is also lost to the atmosphere through volatilisation or ash convection, ash deposited and left on site as unburnt material (Beorner, 1982). This material can be lost in runoff with rainfall. Tillage also causes C release due to the increased oxidation of soil organic matter. Compaction can increase average soil wetness and restrict crop growth so that mineral nitrogen in the soil is at risk of loss by denitrification causing an increase in N_2O release (Ball, 2013). The degradation spirals as the loss of fertility leads to a further loss in vegetation, leaving the soil more vulnerable to further degradative processes of desertification and erosion. Therefore, it is important to monitor the quality of the soil so as to record degradation, identify inappropriate use and management and to allow practices to be implemented to ameliorate the problem.

The soil physical quality can be monitored using both quantitative and qualitative techniques. Quantitative techniques such as bulk density, soil resistance to penetration, macro- and micro-porosity and infiltration rate, are useful as they provide information of how the structure of soil is working to supply water, air and support to plants. However, collection of such data often requires large and/or heavy equipment to be transported to the field or soil samples to be brought back to a laboratory for analysis. The lack of transport infrastructure, specialist knowledge, equipment and facilities in many large, less developed regions, such as the Amazon basin, effectively prohibit this type of sampling. Qualitative techniques, such as visual soil evaluation methods are rapid and simple tests that offer a more holistic estimate of the soil structure (Ball et al., 2015; Batey et al., 2015). The simplest group of qualitative visual methods is the spade tests, which are designed for use by scientists, agronomists and land users like farmers (Batey et al., 2015). They combine a range of soil properties such as aggregate strength, shape and porosity alongside colour and smell to give the soil a score that indicates the structural quality of the soil.

The Visual Evaluation of Soil Structure (VESS) originally proposed by Ball et al. (2007) is a spade method which assess soil structural quality by comparing features of aggregates and roots with a description chart to attribute a soil quality score (Sq). The most up-to-date and most widely available scoring chart, including the progressive reductive breakdown of aggregates in scoring, was published by Guimarães et al. (2011). The scores produced by this simple and rapid visual test can be subjected to statistical analysis (Batey et al., 2015) and have been correlated with many measured physical qualities including tensile strength, bulk density, resistance to penetration, least limiting water range, hydraulic properties and air permeability (Guimarães et al., 2011, 2013; Giarola et al., 2013, Moncada et al., 2014ab), demonstrating its reliability for assessing soil structural quality. VESS has proven to be very efficient at distinguishing soil structural qualities under different uses and managements (Batey et al., 2015). The method has had limited testing under tropical soils (Guimarães et al., 2011; Giarola et al., 2013; Moncada et al., 2014b); at the 2014 ISTRO working group F meeting in Brazil, one of the outcomes was that visual methods developed under temperate conditions need further testing in tropical soils to enable them to be used more widely.

VESS has a very low startup cost, requiring only a spade, the VESS chart and no consumables. This makes it an ideal tool for characterising and monitoring soil degradation in remote areas with poor infrastructure and limited resources, such as the

Amazon basin. However, it has not been tested under such conditions and on the specialised soils and management practices of the region.

The objective of this work was to test, for the first time, the feasibility of using VESS in an inaccessible region of the Amazon basin susceptible to soil degradation; correlate VESS soil quality scores with quantitative soil quality indicators; and assess the ability of VESS to evaluate the soil structural quality of Yellow Oxisol and Terra Preta soils under different land uses.

2. Material and Methods

2.1 Experimental area

The study site was located near Santa Isabel do Rio Negro, Amazonas, Brazil, (0º 24' 40.07" S; 65º 00' 35.15" W, 49 m a.s.l) in an agricultural area previously occupied and worked by indigenous Brazilians (> 1000 years) and more recently by a Portuguese settler family since ~1850. The region has an average minimum temperature of 22 ºC and average maximum temperature of 31 ºC, with an annual rainfall of 3014 mm.

The soil in the area is classified as a Yellow Oxisol and has been cultivated and used for foraging and hunting through regional techniques since first settlement. The site was only accessible via a one hour boat ride and had never been subjected to mechanised agricultural practices, tillage, liming nor fertilisation.

The study site was zoned into five areas based on land use: i) Terra Preta de Índio (TPI): containing fruit tree and vegetable production in an Anthropogenic Dark Earth (0.3 ha, 40 m a.s.l), with more than 1000 years of use; ii) Pasture (PA): grassland (*Brachiaria humidicola*) area occupied by cattle and buffalo (~ 10 ha, 45 m a.s.l) for meat production (stock rate: 1 animal ha^{-1}) with 26 years under this use; iii) Slash and Burn (SB): area cultivated with cassava and pineapple (~ 0.5 ha, 46 m a.s.l) under annual burning of weeds and crop residues; with 9 years under this use; iv) Regenerating Forest (RF): area previously cultivated under the slash and burn system, but now abandoned for more than 30 years (~ 1 ha, 55 m a.s.l); v) Pristine Forest (PF): used for hunting and to extract seeds, fruits and medicines (57 m a.s.l).

For each area a transect line was laid out and ten sampling points (n = 10) were marked out along it. The length of each transect and distance between sampling points was proportional to the size of each area, and were respectively: TPI - 40 m (4 m); PA - 300 (30 m); SB - 50 m (5 m); RF - 100 m (10 m); and PF - 300 m (30 m).

Table 1 presents the particle size distribution of these five areas and the water content at the time of sampling. Particle size distribution (pipette method – Camargo et al., 2009) was performed to characterise the areas, with samples taken from two depths (0-10 and 10-20 cm), except for the pristine forest area where only the 0-20 cm layer was sampled.

2.2 Evaluations

At each sampling point a VESS sample, a soil resistance to penetration measurement, an undisturbed sample for bulk density and total porosity, and a disturbed sample for total carbon were taken.

For analysis of soil structure, using the VESS method, a soil slice of approximately 10 cm thick, 20 cm wide and 25 cm deep, was extracted from each of the sampling positions along the transect of each area (n=10 per area). For the PF and RF the surface litter and root matter was removed for the evaluation. The depth of the soil slice and of the layers identified with contrasting soil quality, after initial manual break-up, were measured and a soil quality score, Sq, was attributed to each layer using the VESS reference chart (Guimarães et al., 2011) - Sq varies from 1 (good soil quality) to 5 (poor soil quality). The characteristics observed for the attribution of a score included size and shape of aggregates; external and internal porosity of aggregates, difficulty of breaking the aggregates; shape and position of roots, among others. The overall score for each sample point was obtained by calculating the weighted average using the depth of each layer and the Sq of the corresponding layer.

For soil resistance to penetration (SRP) one measurement per point, at 0-20 cm depth, was taken using an impact penetrometer (SONDATERRA®, Model PI-60). To determine soil bulk density (Bd) and total porosity (Tp) one undisturbed soil sample was collected at each sampling point, using soil cores of 100 cm^3, from the layer 7.5 to

12.5 cm deep. In the laboratory, for Bd the samples were dried at 105^{o}C for 48 hours and were then weighed (Blake & Hartge, 1986). Total porosity was calculated using the equation [Tp=1-(Bd/particle density)], where 2.65 Mg m^{-3} was the value used for particle density.

In close proximity to each VESS sampling point, 14 disturbed soil subsamples were collected from the 0–20 cm layer using a Dutch auger to form a composite soil sample. Soil samples were dried at 40ºC and sieved through a 2 mm mesh. Total carbon was determined using a CN analyser (Carlo Erba, model EA 1110, Milan, Italy).

2.3 Statistical analysis

Data sets were tested for normal distribution using the Ryan–Joiner normality test ($P \leq 0.1$), before being subjected to a one-way ANOVA. If the ANOVA were significant ($p<0.05$) the means were compared using the *post hoc* Tukey's test ($P \leq 0.05$), to identify significant differences between the treatments. Regression analysis was used to correlate the quantitative soil quality indicators with VESS. All statistical analysis was conducted in Minitab Statistical Software version 16 (Minitab Ltd.).

3. Results

3.1 Visual Evaluation of Soil Structure (VESS)

The overall VESS Sq for each of the evaluated areas indicated that the quality of the soil was best in SB, PF and RF (Fig. 1). The Sq score for the TPI indicated soil structure of significantly lower quality than the three best areas (SB, PF and RF), while the Pasture was the lowest, significantly, of the areas (Fig. 1). Nevertheless, despite these differences between the Sq scores, all the soils were of good structural quality based on overall scores.

When considering the average individual layer score and thickness (Fig. 2), the Pasture contained a compacted layer (Sq 3.4), from 5 to 20 cm with half of the samples scoring Sq4. This compacted layer was characterised by large angular clods, and was under a surface layer of Sq 1 that was stabilised by roots (Fig. 3E). The first layer of the slash and burn was structureless (Fig. 3A), consisting almost exclusively of single grains. The Pristine and Regenerating Forest sites displayed similar soil structures though the Regenerating Forest, had a shallower top layer of Sq 1 (Fig. 2, 3BC). The TPI was the area that presented the highest Sq close to the surface (Sq1.6) and presented an average Sq for the second layer of 2.6 (Fig. 2).

3.2 Resistance penetration, bulk density and total porosity

The resistance to penetration results followed the same pattern as VESS (SB=PF<RF<TPI<PA) (Fig. 4). The values for the SB and PF were significantly lower than the other treatments. The resistance to penetration values for the other treatments

were all significantly distinct from each other.

The Bd was significantly higher in the SB area than in all other treatments except for the TPI, which was not significantly greater than at the other sites (Fig. 5A). The Tp mirrored the pattern of the Bd, but in reverse, with SB being lower (Fig. 5B).

3.3 Total carbon

The PA presented the lowest total carbon content, which was lower than all other sites except for the SB, while the total carbon content for the other sites were not significantly distinct from each other (Fig. 6).

3.4 Correlations

The correlations made between VESS and SRP, Bd, Tp and C are shown in Table 2. There was a significant correlation between VESS and the indicators SRP and C but not between VESS and the indicators Bd and Tp. SRP and VESS were highly correlated (R^2=0.68) (Fig. 7), while C was weakly correlated with VESS despite being significant.

4. Discussion

All quantitative soil quality indicators showed that the soil from each of the study areas was of adequate quality. However, the VESS method was more sensitive, allowing a more detailed picture of soil physical quality.

The VESS score for the PF and RF were statistically the same, 1.2 and 1.3 respectively, showing that the quality of the soil was almost indistinguishable after more than 30 years of regeneration after a return to forest from slash and burn. However, when the depths of contrasting layers of soil quality were compared (Fig 2, 3), VESS revealed the land use history by showing that the top layer of the best quality soil was still shallower in the RF area.

According to VESS and SRP the area of slash and burn had the best soil structural quality, (Sq 1.1; SRP 0.6 MPa), but when manipulating the soil slice to perform the VESS analysis, it was noted that the top layer of soil was structureless as it was a predominantly sandy soil, almost single grain (Fig. 3). The site had an unusually sandy top layer (Table 1), probably caused by the slash and burn agricultural technique. The SB and the RF areas presented the highest sand contents and the largest fall (~9%), in sand content from the first 0-10 cm to the second (10-20 cm) layers (Table 1). This was probably due to both sites being subjected to the slash and burn process, as the heat caused by burning is more intense nearer to the soil surface. The high sand content has been shown to be caused by the slash and burn agricultural technique, as fire alters the properties of the soil along a thermal gradient, starting at 50 °C, which causes a decrease in the quantity of fungi. While temperatures above 200 °C result in an increase in soil water repellency and soil organic matter starts to be destroyed (Certini, 2005; Ketterings and Bigham, 2000; Mataix-Solera et al., 2011; Neary et al., 1999). The exposure of the soil to higher temperatures, around 600 °C, results in a sand content increase and a silt and clay content decrease, as the high temperature fuses the clay and silt into sand sized particles (Sertsu and Sanchez 1978; Ketterings and Bigham, 2000).

The 'sandification' of the soil reduces water-holding ability (Ulery and Graham 1993). This could explain why the Bd was highest and Tp was lowest in the SB treatment, as soil texture has a direct affect on soil bulk density and porosity. The Bd and Tp were not sensitive enough to identify problems with the soil structure in the SB due to the greater sand content. The VESS method, suggested that the soil quality in this area was good, and, although robust enough to accurately assess the low resistance to penetration, was unable to identify the problem with possible low water-holding capacity. This reflects one of the limitations of visual methods, especially spade methods, that tend to identify fine, loose structures as having a 'good' structural quality (Ball and Munkholm, 2015). A positive aspect regarding the use of VESS in this instance was that the hands on approach, where the user is in direct contact with soil, allowed identification of a problem with the structure even though it was not specified in the chart, something that may not occur when taking other types of sample.

The PA, according to the quantitative indicators (Bd, Tp and SRP), was within the boundaries of good soil quality (Arshad et al., 1996; Camargo and Alleoni, 1997;

Taylor et al., 1966). However, the PA presented SRP=2.0 MPa, considered at the limit for adequate plant growth, as the soil dries the SRP will increase and possibly impose restrictions to plant growth in this area. The VESS method, when taken as the soil quality of the overall depth (Sq 2.8), also showed that the structural quality of the pasture soil was acceptable. However, when looking at the individual layers within the soil profile, 50 % of the samples contained a layer of Sq 4, which, according to Ball et al. (2007) is of poor quality and in need of marked changes to the management to sustain high productivity. The C in PA was significantly lower than at the other sites, except for the SB. Pasture areas can maintain carbon stocks similar to those of native forests within the same biome as long as the soil structural quality is being maintained through appropriate management practices (Franzluebbers et al., 2012). Areas where carbon stocks are depleted, in comparison to local native forest soils, may have been subject to soil degradation, which can be revealed by very distinct zones of markedly different structure (Guimarães et al., 2011; Giarola et al., 2013; Munkholm and Holden, 2015).

VESS when used to observe individual layers of structure within the soil profile could give an early sign of structural change due to degradative processes. While, waiting for the degradative process to elevate the overall Sq high enough to indicate a poorer condition in need of amelioration could result in further damage, meaning more drastic measures are needed to correct the problem.

Both quantitative and visual soil indicators showed that the area of TPI had good overall score quality (Sq 2.2), however, some layers in some of the samples scored Sq3 (moderate soil quality) (Fig. 3D). Despite the impression of good soil quality given by the indicators, ponding was readily observed at this site after heavy rain events. Preliminary work (not published) conducted in the same area indicated low infiltration rates for the TPI, the soil also appeared to have a thin crust on the surface, possibly due to the exposure of the unprotected soil to sealing, through raindrop impact, causing the blockage of pores at the soil surface. The TPI would have been more susceptible to this process due to the lack of soil coverage, as it is the custom of the local farmers to keep the area under and between the trees completely uncovered of any cover crop or plant debris. The organic debris that eventually fall to the ground are removed. However, VESS was not capable of capturing the thin sealing layer at the surface.

In this experiment VESS only correlated well with SRP. Resistance is one of the key parameters evaluated when applying VESS (Ball et al., 2007), and this result confirmed a strong influence of SRP on the VESS score. The Bd and Tp did not correlate with overall Sq scores due to the direct influence of soil texture on these quantitative indicators brought about by the high sand content. Work from Giarola et al. (2013) did not find an influence of soil texture on VESS scores. In other studies VESS has been shown to correlate well with Bd and SRP (Guimarães et al., 2013; daSilva et al., 2014; Moncada et al., 2014b), porosity (Munkholm et al., 2013; Moncada et al

2014ab) and soil organic carbon (Moncada et al., 2014ab; Askari et al. 2015). As the overall Sq score in the present study was used for VESS, the lack of correlation with Bd and Tp could have been due to not including the distinct layering that was evident within the soil profiles.

Soil carbon and organic matter has been associated with physical, biological and chemical qualities (Ghani et al., 2003; Tiessen et al., 1994) and with VESS (Abdollahi et al., 2013; Mueller et al., 2013). A weak correlation was found between VESS Sq score and total C, with the angular coefficient (Table 2) showing a negative correlation between these variables (C = 2.03 – 0.163 x VESS). Lower Sq scores were associated with higher total C concentration in soil and vice versa. PF and RF had lower Sq values (Fig. 1) and higher total C concentrations (Fig. 6). The inverse tendency was observed for the PA. TPI and SB areas did not follow this tendency. Soil burning increases recalcitrant carbon fraction in soil, called “black carbon” or charcoal resistant to oxidation and biological degradation (Gonzáles-Pérez et al., 2004). Fractions such as hot water extractable C have being correlated with other key indicators of soil quality (Ghani et al., 2003) and, therefore, could be better correlated with VESS Sq.

The VESS methodology was found to be well suited to monitoring soil degradation and structural quality at the Amazon site. This was principally due to very little equipment being required, allowing users to apply the method in areas where access was challenging, such as in the dense pristine forest. Also, as the farm site visited in the study was only accessible by boat, the fact that no VESS samples were required for further analysis in the laboratory, made the visual methodology logistically easier than the quantitative indicators used in this study. From the start of digging the access pit to attaining the final Sq score took ~5 minutes with one operator to dig and another to apply VESS. The exception to this was for the PF, where thick roots made digging and soil slice extraction more difficult and time consuming, as these roots needed to be cut with a knife to allow the sample to be taken.

5. Conclusions

The quantitative indicators each showed one aspect of the soil's structural quality and generally showed that the soils were of adequate structural quality, with the drop in total carbon for the PA being the only quantitative indication that some degradation had taken place. VESS, however, gave a more holistic view of the soil's structure, allowing the changes between land uses to be identified and the limitations to crop productivity within the profile to be brought to light, such as the compacted layer in the PA. This combined with its ease of use and immediate results make it a suitable tool for soil quality monitoring in remote and inaccessible regions such as the Amazon basin. This was a pioneering study using VESS in the Amazon basin, the methodology was a more integrated indicator, exposing more aspects of the functionality of the soil structure and confirmed the loss of structure and physical fertility associated with ‘sandification’ due to slash and burn. However, it showed limitations as it did not indicate the possible low water-holding capacity of the SB and the crusting in the TPI. Further studies and development of VESS are required to fully enable VESS scores to accurately reflect soil structural function under these types of soils and uses, which is important for the expansion of the use of VESS in similar environmental conditions such as in Africa, where slash and burn and anthropogenic dark earth is a widely found.

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List of Tables

Table 1.

Area	Depth 0-10 cm			Depth 10-20			
	Clay (%)	Sand (%)	Silt (%)	Clay (%)	Sand (%)	Silt (%)	Water content (m^3 m^{-3}) ±SD*
Slash and Burn (SB)	6.4	92.6	1.0	9.8	83.6	6.6	0.20±0.04
Regenerating Forest (RF)	11.4	81.5	7.1	16.8	72.9	10.3	0.21±0.04
Terra Preta (TPI)	14.2	73.9	11.9	14.4	74.1	11.5	0.15±0.08
Pasture (PA)	13.0	77.9	9.1	14.8	72.2	13.0	0.15±0.01
	Depth 0-20 cm						
Pristine Forest (PF)	22.8	52.1	25.1				0.22±0.09

SD = Standard Deviation

Table 2.

Relationship	Equation	R^2	n	Significance
SRP versus VESS	SRP = 0.115 + 0.626 (VESS)	0.68	50	<0.001
Bd versus VESS	Bd = 1.16 + 0.0058 (VESS)	0.00	50	NS
Tp versus VESS	Tp = 0.563 – 0.00219 (VESS)	0.00	50	NS
C versus VESS	C = 2.03 – 0.163 (VESS)	0.17	50	=0.003

SRP = soil resistance to penetration; Bd = bulk density; Tp = total porosity; C = total carbon; VESS = visual evaluation of soil structure; R^2 = coefficient of determination; n = sample size; NS = not significant.

Figure Captions

Fig. 1. Mean overall VESS scores (Sq) for areas of Slash and Burn (SB), Pristine (PF), Regenerating Forest (RF), Terra Preta (TPI) and Pasture (PA). Significant statistical differences between areas are indicated by uppercase letters, identified through Tukey test ($P \leq 0.05$).

Fig. 2. Mean depths of layers observed in soil slices and their average VESS Sq for Slash and Burn (SB), Pristine Forest (PF), Regenerating Forest (RF), Terra Preta (TPI) and Pasture (PA). The bars represent the standard deviation (SD) of the mean depth, where the first upper bar belongs to the first layer, the lower bar belongs to the second layer and, when present, the second upper bar belongs to the third layer.

Fig. 3. Photographs of soil slices, assessed by the VESS method, that are exemples of typical samples from the areas evaluated. Slash and Burn = Sq1; Pristine Forest = Sq1 first layer, Sq2 second layer; Regenerating forest Sq1 first layer, Sq2 second layer; Terra Preta = Sq1 first layer, Sq3 second layer; and Pature = Sq1 first layer (held by roots), Sq4 second layer.

Fig. 4. Soil resistance to penetration (SRP) for the 0-20 cm layer for Slash and Burn (SB), Pristine Forest (PF), Regenerating Forest (RF), Terra Preta (TPI) and Pasture (PA). Significant statistical differences between areas are indicated by uppercase letters, identified through Tukey's test ($P \leq 0.05$).

Fig. 5. (A) Soil bulk density (Bd) and (B) total porosity (Tp), for the 7.5-12.5 cm depth, for areas of Slash and Burn (SB), Pristine Forest (PF), Regenerating Forest (RF), Terra Preta (TPI)

and Pasture (PA). Significant statistical differences between areas are indicated by uppercase letters, identified through Tukey test ($P \leq 0.05$).

Fig. 6. Total carbon (%) (0-20 cm depth) for areas of Slash and Burn (SB), Pristine Forest (PF), Regenerating Forest (RF), Terra Preta (TPI) and Pasture (PA). Significant statistical differences between areas are indicated by uppercase letters, identified through Tukey test ($P \leq 0.05$).

Fig. 7. Correlation between soil resistence to penetration (SPR) at 0-20 cm depth and visual evaluation of soil structure (VESS) overall soil quality score (Sq).

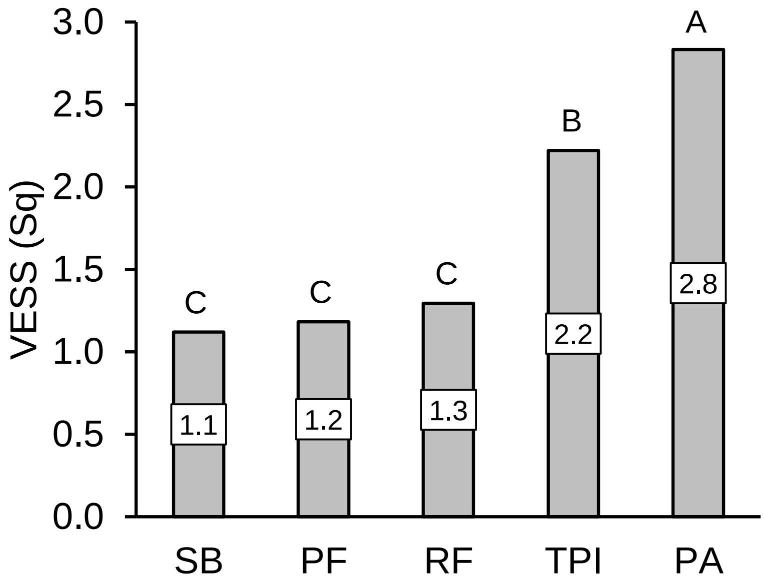

Fig. 1

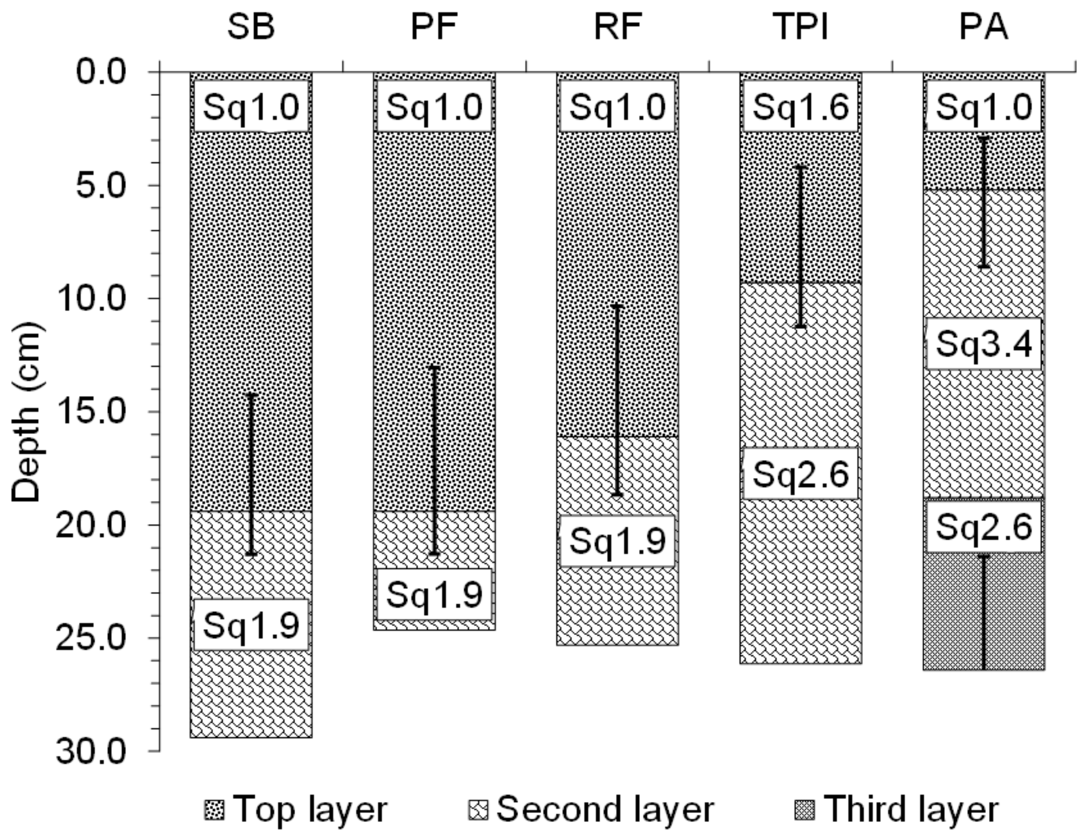
SB
PF
RF
TPI
PA
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Depth (cm)
Sq1.0
Sq1.0
Sq1.0
Sq1.6
Sq1.0
Sq3.4
Sq2.6
Sq1.9
Sq2.6
Sq1.9
Sq1.9
Top layer
Second layer
Third layer

Fig. 2

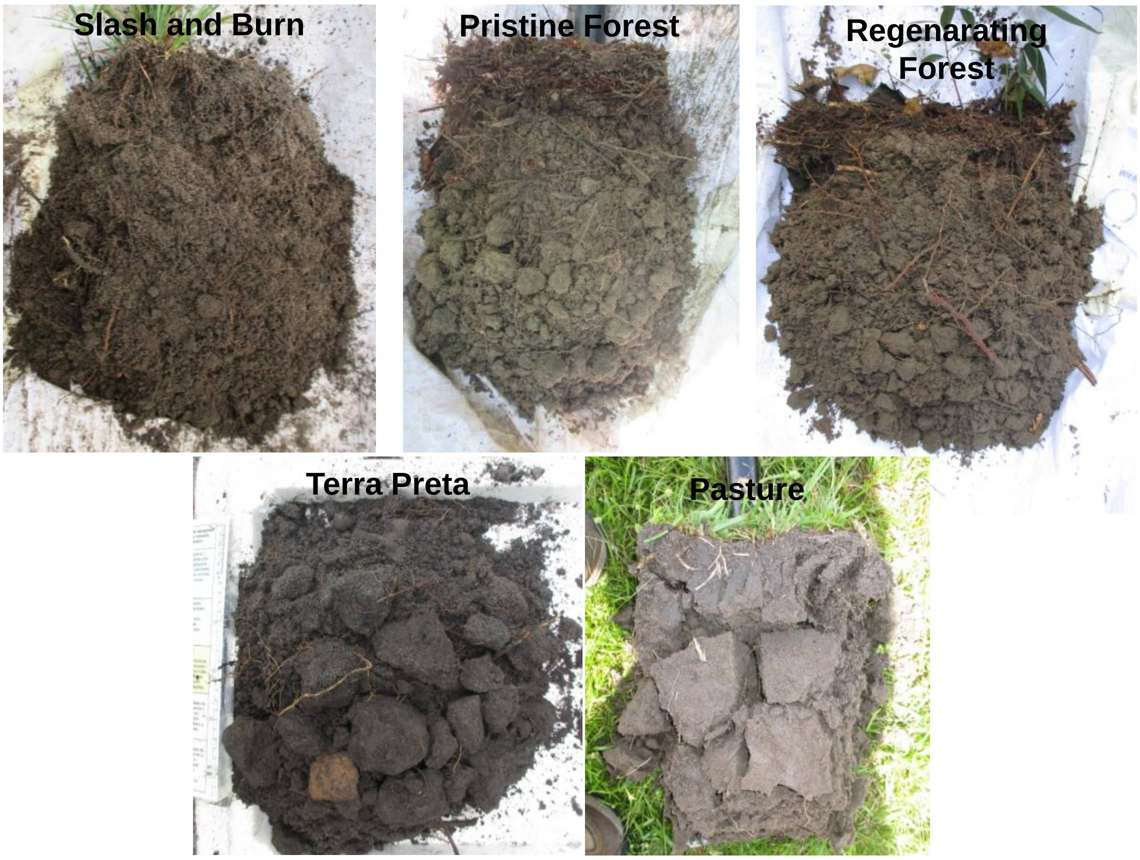
Slash and Burn
Pristine Forest
Regenarating
Forest
Terra Preta
Pasture

Fig 3

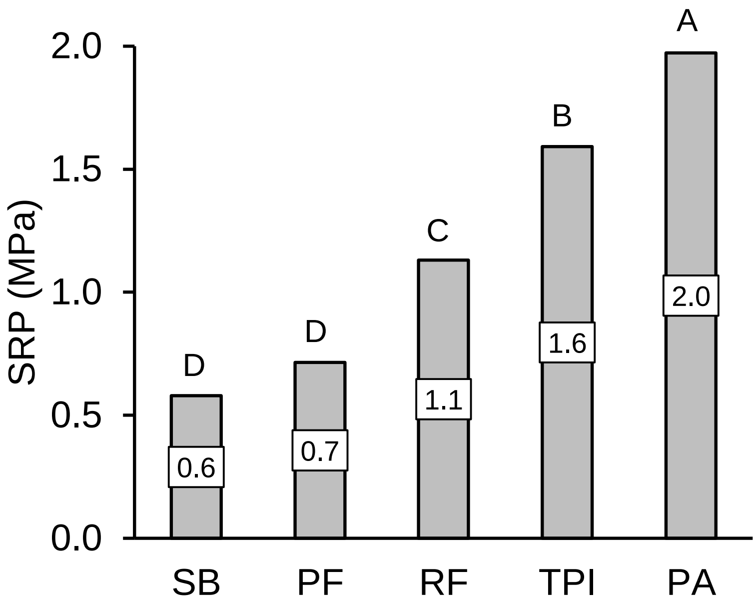

Fig 4

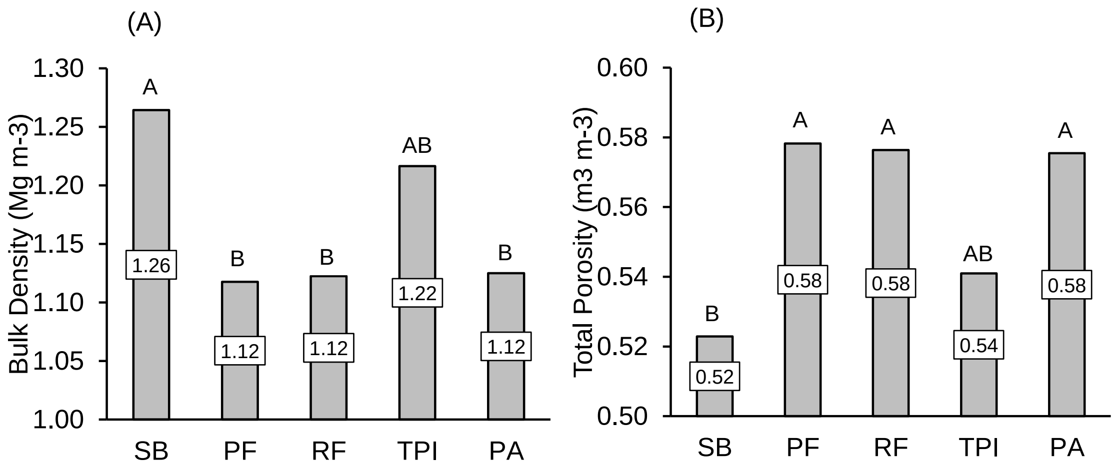
(A)
Bulk Density (Mg m-3)
1.30
1.25
1.20
1.15
1.10
1.05
1.00
A
1.26
B
1.12
B
1.12
AB
1.22
B
1.12
SB
PF
RF
TPI
PA
(B)
Total Porosity (m3 m-3)
0.60
0.58
0.56
0.54
0.52
0.50
B
0.52
A
0.58
A
0.58
AB
0.54
A
0.58
SB
PF
RF
TPI
PA

Fig 5

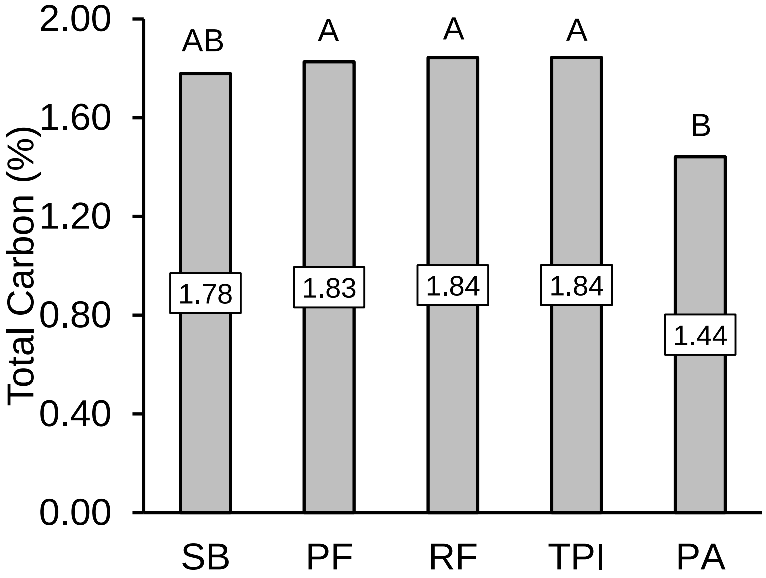
Total Carbon (%)
2.00
1.60
1.20
0.80
0.40
0.00
AB
A
A
A
B
1.78
1.83
1.84
1.84
1.44
SB
PF
RF
TPI
PA

Fig. 6

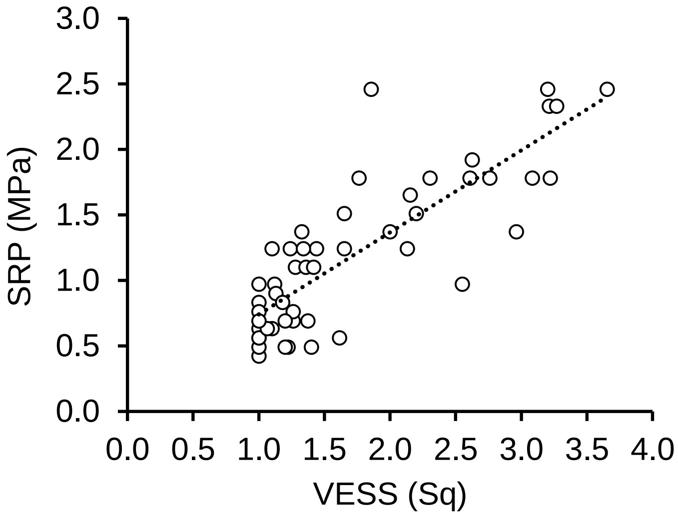

Fig. 7