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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

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Published in:
Soil and Tillage Research

DOI:
[10.1016/j.still.2016.10.014](https://doi.org/10.1016/j.still.2016.10.014)

First published: 13/11/2016

Document Version
Peer reviewed version

[Link to publication](#)

Citation for published version (APA):

Guimaraes, RML., Neves Jr, AF., Silva, WG., Rogers, CD., Ball, BC., Montes, CR., & Pereira, BF. (2016). 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. *Soil and Tillage Research*, 173, 75 - 82. Advance online publication. <https://doi.org/10.1016/j.still.2016.10.014>

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Manuscript Number:

Title: 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

Article Type: SI: VSE and Compaction Res.

Keywords: Soil quality; visual soil evaluation; soil structure

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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.

The Editorial Office of Soil & Tillage Research

P.O. Box 181

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The Netherlands

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

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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

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

3
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21 Type of Paper: Original Research Article "SI: VSE and Compaction Res."

22

23 **Abstract**

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27 research presented here tested for the first time the feasibility of using VESS in the
28 Amazon basin, under the specialised land uses and soils (Yellow Oxisol and “Terra
29 Preta de Índio”) of the region, and its relation with quantitative soil indicators. The
30 evaluated areas, which had never been subjected to mechanisation, fertilisation nor
31 tillage, were “Terra Preta de Índio”/ Anthropogenic Dark Earth; Regenerating Forest;
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33 indicators were less sensitive at revealing signs of degradation than VESS and that
34 VESS brought to light evidence of historic land use change and limitations to crop
35 productivity. VESS was significantly correlated with soil resistance to penetration.
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40 quantitative indicators, it was also logistically easier to perform making it ideal for
41 tracking soil degradation and structural quality in similarly challenging situations.
42 However, more research is required to fully enable VESS to capture structural quality in

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44 region.

45

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

47 regeneration

48

49 **1. Introduction**

50 The vast stocks of carbon found in forests and their soils can be lost through
51 land use change and degradation, with deforestation being considered the second
52 greatest source of anthropogenic carbon dioxide to the atmosphere (van der Werf et al.,
53 2009). With disturbances to tropical forest ecosystems and land use change of tropical
54 forests accounting for approximately 20 % of the anthropogenic greenhouse gas
55 emissions of tropical countries (Mäkipää et al., 2012).

56 The Amazon forest is one of the largest areas of contiguous forest in the world
57 containing 150-200 Pg C in living biomass and soils (Feldpausch et al., 2012) and
58 accounting for approximately 25% of Earth's terrestrial species (Malhi et al., 2008). It is
59 a massive store of carbon, with C uptake in the Amazon basin being estimated at 0.42-
60 0.65 Pg C yr⁻¹ between 1990-2007, accounting for approximately 25% of the terrestrial
61 carbon sink (Phillips et al., 2009; Pan et al., 2011).

62 The Amazon basin covers approximately 40% of South America and is spread
63 across Bolivia, Brazil, Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname and
64 Venezuela, with 60% falling within the borders of Brazil (Song et al., 2015). Despite the
65 area's importance it has been subjected to extensive deforestation and has lost almost
66 20% of its coverage since the 1970s (INPE, 2015). The rate of deforestation has
67 generally slowed within the Brazilian Amazon since 2004, a 77% fall in annual rates
68 between 2004 and 2011 (Godar et al., 2014), due to a number of socioeconomic factors

69 (Godar et al., 2014; Nepstad et al., 2014). Since then, deforestation rates have stabilised
70 at between 5,000–7,000 km² yr⁻¹ in Brazil (Godar et al., 2014; INPE, 2015), however,
71 deforestation rates in many non-Brazilian regions of the Amazon have increased
72 (Hansen et al., 2013 Song et al., 2015). Deforestation in the Amazon basin is mainly due
73 to land use change, deforestation for farming (Morton et al., 2006), illegal logging
74 (Asner et al., 2005) and mining (Asner et al., 2013) as well as natural sources such as
75 fire, drought and flooding (Espírito-Santo et al., 2014).

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

84 However, throughout the Amazon basin small areas of highly fertile soil are
85 found, this Anthropogenic Dark Earth, known as *Terra Preta de Índio* (terra preta) in
86 Portuguese, is the result of indigenous Brazilian soil management and the employment
87 of slash and burn (SB) (Glaser and Birk 2012). The soil contains a high level of
88 charcoal and ash as a result of the slash and burn and also available nutrients, such as

89 nitrogen, phosphorus, calcium, zinc and manganese, due to the incorporation of plant
90 residues and animal waste (including faeces, urine and bone) (Smith, 1980; Kern and
91 Kampf, 1989; Lima et al., 2002). The addition of the organic matter and charcoal to the
92 soil also affects the physical structure of the soil, improving soil porosity and structural
93 strength (Kern and Kampf, 1989; Teixeira and Martins, 2003).

94 Soil degradation, the loss of soil potential productivity due to a loss in soil
95 fertility, greatly affects the Amazon region and can be brought about by several
96 agricultural land use changes, such as deforestation for logging, cropping and ranching,
97 and can be compounded through inappropriate cropping systems and management (Lal,
98 1997). Soil degradation can come in the form of biological (loss of soil micro and
99 macrobiota), chemical (nutrient loss/imbalance, acidification, salinisation, decrease in
100 cation exchange, volatilisation) and physical degradation (crusting, compaction,
101 erosion, leaching and anaerobism) (Guimarães et al., 2015).

102 These degradation processes release carbon through burning, where the
103 combustion of organic matter leads to the release of carbon dioxide (CO₂) into the
104 atmosphere. While C is also lost to the atmosphere through volatilisation or ash
105 convection, ash deposited and left on site as unburnt material (Beorner, 1982). This
106 material can be lost in runoff with rainfall. Tillage also causes C release due to the
107 increased oxidation of soil organic matter. Compaction can increase average soil
108 wetness and restrict crop growth so that mineral nitrogen in the soil is at risk of loss by

109 denitrification causing an increase in N₂O release (Ball, 2013). The degradation spirals
110 as the loss of fertility leads to a further loss in vegetation, leaving the soil more
111 vulnerable to further degradative processes of desertification and erosion. Therefore, it
112 is important to monitor the quality of the soil so as to record degradation, identify
113 inappropriate use and management and to allow practices to be implemented to
114 ameliorate the problem.

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

129 soil a score that indicates the structural quality of the soil.

130 The Visual Evaluation of Soil Structure (VESS) originally proposed by Ball et
131 al. (2007) is a spade method which assess soil structural quality by comparing features
132 of aggregates and roots with a description chart to attribute a soil quality score (Sq). The
133 most up-to-date and most widely available scoring chart, including the progressive
134 reductive breakdown of aggregates in scoring, was published by Guimarães et al.
135 (2011). The scores produced by this simple and rapid visual test can be subjected to
136 statistical analysis (Batey et al., 2015) and have been correlated with many measured
137 physical qualities including tensile strength, bulk density, resistance to penetration, least
138 limiting water range, hydraulic properties and air permeability (Guimarães et al., 2011,
139 2013; Giarola et al., 2013, Moncada et al., 2014ab), demonstrating its reliability for
140 assessing soil structural quality. VESS has proven to be very efficient at distinguishing
141 soil structural qualities under different uses and managements (Batey et al., 2015). The
142 method has had limited testing under tropical soils (Guimarães et al., 2011; Giarola et
143 al., 2013; Moncada et al., 2014b); at the 2014 ISTRO working group F meeting in
144 Brazil, one of the outcomes was that visual methods developed under temperate
145 conditions need further testing in tropical soils to enable them to be used more widely.

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

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

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

156

157

158 **2. Material and Methods**

159 *2.1 Experimental area*

160 The study site was located near Santa Isabel do Rio Negro, Amazonas, Brazil, (
161 0° 24' 40.07" S; 65° 00' 35.15" W, 49 m a.s.l) in an agricultural area previously occupied
162 and worked by indigenous Brazilians (> 1000 years) and more recently by a Portuguese
163 settler family since ~1850. The region has an average minimum temperature of 22 °C
164 and average maximum temperature of 31 °C, with an annual rainfall of 3014 mm.

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

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

179 For each area a transect line was laid out and ten sampling points (n = 10) were
180 marked out along it. The length of each transect and distance between sampling points
181 was proportional to the size of each area, and were respectively: TPI - 40 m (4 m); PA -
182 300 (30 m); SB - 50 m (5 m); RF - 100 m (10 m); and PF - 300 m (30 m).

183 Table 1 presents the particle size distribution of these five areas and the water
184 content at the time of sampling. Particle size distribution (pipette method – Camargo et
185 al., 2009) was performed to characterise the areas, with samples taken from two depths
186 (0-10 and 10-20 cm), except for the pristine forest area where only the 0-20 cm layer
187 was sampled.

188

189 *2.2 Evaluations*

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

193 For analysis of soil structure, using the VESS method, a soil slice of
194 approximately 10 cm thick, 20 cm wide and 25 cm deep, was extracted from each of the
195 sampling positions along the transect of each area (n=10 per area). For the PF and RF
196 the surface litter and root matter was removed for the evaluation. The depth of the soil
197 slice and of the layers identified with contrasting soil quality, after initial manual break-
198 up, were measured and a soil quality score, Sq, was attributed to each layer using the
199 VESS reference chart (Guimarães et al., 2011) - Sq varies from 1 (good soil quality) to
200 5 (poor soil quality). The characteristics observed for the attribution of a score included
201 size and shape of aggregates; external and internal porosity of aggregates, difficulty of
202 breaking the aggregates; shape and position of roots, among others. The overall score
203 for each sample point was obtained by calculating the weighted average using the depth
204 of each layer and the Sq of the corresponding layer.

205 For soil resistance to penetration (SRP) one measurement per point, at 0-20 cm
206 depth, was taken using an impact penetrometer (SONDATERRA[®], Model PI-60). To
207 determine soil bulk density (Bd) and total porosity (Tp) one undisturbed soil sample
208 was collected at each sampling point, using soil cores of 100 cm³, from the layer 7.5 to

209 12.5 cm deep. In the laboratory, for Bd the samples were dried at 105°C for 48 hours
210 and were then weighed (Blake & Hartge, 1986). Total porosity was calculated using the
211 equation [$Tp=1-(Bd/particle\ density)$], where 2.65 Mg m^{-3} was the value used for
212 particle density.

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

217

218 2.3 Statistical analysis

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

225

226

227 3. Results

228 3.1 Visual Evaluation of Soil Structure (VESS)

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

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

244

245 *3.2 Resistance penetration, bulk density and total porosity*

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

249 were all significantly distinct from each other.

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

253

254 *3.3 Total carbon*

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

258

259 *3.4 Correlations*

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

265

266

267 **4. Discussion**

268 All quantitative soil quality indicators showed that the soil from each of the

269 study areas was of adequate quality. However, the VESS method was more sensitive,
270 allowing a more detailed picture of soil physical quality.

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

277 According to VESS and SRP the area of slash and burn had the best soil
278 structural quality, (Sq 1.1; SRP 0.6 MPa), but when manipulating the soil slice to
279 perform the VESS analysis, it was noted that the top layer of soil was structureless as it
280 was a predominantly sandy soil, almost single grain (Fig. 3). The site had an unusually
281 sandy top layer (Table 1), probably caused by the slash and burn agricultural technique.
282 The SB and the RF areas presented the highest sand contents and the largest fall (~9%),
283 in sand content from the first 0-10 cm to the second (10-20 cm) layers (Table 1). This
284 was probably due to both sites being subjected to the slash and burn process, as the heat
285 caused by burning is more intense nearer to the soil surface. The high sand content has
286 been shown to be caused by the slash and burn agricultural technique, as fire alters the
287 properties of the soil along a thermal gradient, starting at 50 °C, which causes a
288 decrease in the quantity of fungi. While temperatures above 200 °C result in an increase

289 in soil water repellency and soil organic matter starts to be destroyed (Certini, 2005;
290 Ketterings and Bigham, 2000; Mataix-Solera et al., 2011; Neary et al., 1999). The
291 exposure of the soil to higher temperatures, around 600 °C, results in a sand content
292 increase and a silt and clay content decrease, as the high temperature fuses the clay and
293 silt into sand sized particles (Sertsu and Sanchez 1978; Ketterings and Bigham, 2000).

294 The ‘sandification’ of the soil reduces water-holding ability (Ulery and Graham
295 1993). This could explain why the Bd was highest and Tp was lowest in the SB
296 treatment, as soil texture has a direct affect on soil bulk density and porosity. The Bd
297 and Tp were not sensitive enough to identify problems with the soil structure in the SB
298 due to the greater sand content. The VESS method, suggested that the soil quality in this
299 area was good, and, although robust enough to accurately assess the low resistance to
300 penetration, was unable to identify the problem with possible low water-holding
301 capacity. This reflects one of the limitations of visual methods, especially spade
302 methods, that tend to identify fine, loose structures as having a ‘good’ structural quality
303 (Ball and Munkholm, 2015). A positive aspect regarding the use of VESS in this
304 instance was that the hands on approach, where the user is in direct contact with soil,
305 allowed identification of a problem with the structure even though it was not specified
306 in the chart, something that may not occur when taking other types of sample.

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

309 Taylor et al., 1966). However, the PA presented SRP=2.0 MPa, considered at the limit
310 for adequate plant growth, as the soil dries the SRP will increase and possibly impose
311 restrictions to plant growth in this area. The VESS method, when taken as the soil
312 quality of the overall depth (Sq 2.8), also showed that the structural quality of the
313 pasture soil was acceptable. However, when looking at the individual layers within the
314 soil profile, 50 % of the samples contained a layer of Sq 4, which, according to Ball et
315 al. (2007) is of poor quality and in need of marked changes to the management to
316 sustain high productivity. The C in PA was significantly lower than at the other sites,
317 except for the SB. Pasture areas can maintain carbon stocks similar to those of native
318 forests within the same biome as long as the soil structural quality is being maintained
319 through appropriate management practices (Franzluebbers et al., 2012). Areas where
320 carbon stocks are depleted, in comparison to local native forest soils, may have been
321 subject to soil degradation, which can be revealed by very distinct zones of markedly
322 different structure (Guimarães et al., 2011; Giarola et al., 2013; Munkholm and Holden,
323 2015).

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

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

341 In this experiment VESS only correlated well with SRP. Resistance is one of
342 the key parameters evaluated when applying VESS (Ball et al., 2007), and this result
343 confirmed a strong influence of SRP on the VESS score. The Bd and Tp did not
344 correlate with overall Sq scores due to the direct influence of soil texture on these
345 quantitative indicators brought about by the high sand content. Work from Giarola et al.
346 (2013) did not find an influence of soil texture on VESS scores. In other studies VESS
347 has been shown to correlate well with Bd and SRP (Guimarães et al., 2013; daSilva et
348 al., 2014; Moncada et al., 2014b), porosity (Munkholm et al., 2013; Moncada et al

349 2014ab) and soil organic carbon (Moncada et al., 2014ab; Askari et al. 2015). As the
350 overall Sq score in the present study was used for VESS, the lack of correlation with Bd
351 and Tp could have been due to not including the distinct layering that was evident
352 within the soil profiles.

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

365 The VESS methodology was found to be well suited to monitoring soil
366 degradation and structural quality at the Amazon site. This was principally due to very
367 little equipment being required, allowing users to apply the method in areas where
368 access was challenging, such as in the dense pristine forest. Also, as the farm site visited

369 in the study was only accessible by boat, the fact that no VESS samples were required
370 for further analysis in the laboratory, made the visual methodology logistically easier
371 than the quantitative indicators used in this study. From the start of digging the access
372 pit to attaining the final Sq score took ~5 minutes with one operator to dig and another
373 to apply VESS. The exception to this was for the PF, where thick roots made digging
374 and soil slice extraction more difficult and time consuming, as these roots needed to be
375 cut with a knife to allow the sample to be taken.

376

377

378 **5. Conclusions**

379 The quantitative indicators each showed one aspect of the soil's structural
380 quality and generally showed that the soils were of adequate structural quality, with the
381 drop in total carbon for the PA being the only quantitative indication that some
382 degradation had taken place. VESS, however, gave a more holistic view of the soil's
383 structure, allowing the changes between land uses to be identified and the limitations to
384 crop productivity within the profile to be brought to light, such as the compacted layer
385 in the PA. This combined with its ease of use and immediate results make it a suitable
386 tool for soil quality monitoring in remote and inaccessible regions such as the Amazon
387 basin. This was a pioneering study using VESS in the Amazon basin, the methodology
388 was a more integrated indicator, exposing more aspects of the functionality of the soil

389 structure and confirmed the loss of structure and physical fertility associated with
390 'sandification' due to slash and burn. However, it showed limitations as it did not
391 indicate the possible low water-holding capacity of the SB and the crusting in the TPI.
392 Further studies and development of VESS are required to fully enable VESS scores to
393 accurately reflect soil structural function under these types of soils and uses, which is
394 important for the expansion of the use of VESS in similar environmental conditions
395 such as in Africa, where slash and burn and anthropogenic dark earth is a widely found.

396

397

398 **Funding:** Project financed by the National Counsel of Technological and Scientific

399 Development - CNPq # 470143/2013-4

400

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1 **List of Tables**

2

3 **Table 1.** Particle size distribution and the water content at the time of sampling.

4

5 **Table 2.** Correlation between VESS and the quantitative indicators soil resistance to
6 penetration, bulk density, total porosity and total carbon.

7

8 **Table 1.**

9

Area	Depth 0-10 cm			Depth 10-20			Water content (m ³ m ⁻³) ±SD*
	Clay (%)	Sand (%)	Silt (%)	Clay (%)	Sand (%)	Silt (%)	
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

10 SD = Standard Deviation

11

12 **Table 2.**

13

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

14 SRP = soil resistance to penetration; Bd = bulk density; TP = total porosity; C = total carbon;

15 VESS = visual evaluation of soil structure; R² = coefficient of determination; n = sample size;

16 NS = not significant.

17

18

1 **Figure Captions**

2

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

6

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

12

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

17

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

22

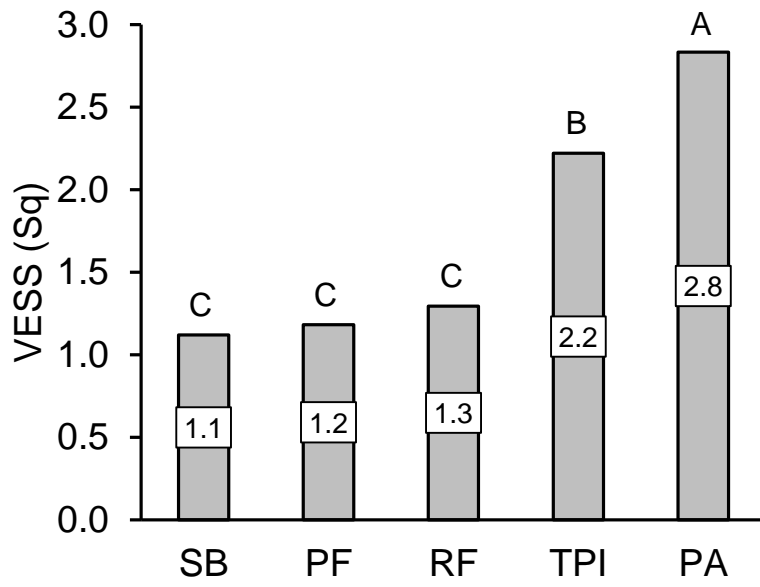
23 **Fig. 5.** (A) Soil bulk density (Bd) and (B) total porosity (Tp), for the 7.5-12.5 cm depth, for
24 areas of Slash and Burn (SB), Pristine Forest (PF), Regenerating Forest (RF), Terra Preta (TPI)

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

27
28 **Fig. 6.** Total carbon (%) (0-20 cm depth) for areas of Slash and Burn (SB), Pristine Forest (PF),
29 Regenerating Forest (RF), Terra Preta (TPI) and Pasture (PA). Significant statistical differences
30 between areas are indicated by uppercase letters, identified through Tukey test ($P \leq 0.05$).

31
32 **Fig. 7.** Correlation between soil resistance to penetration (SPR) at 0-20 cm depth and visual
33 evaluation of soil structure (VESS) overall soil quality score (Sq).

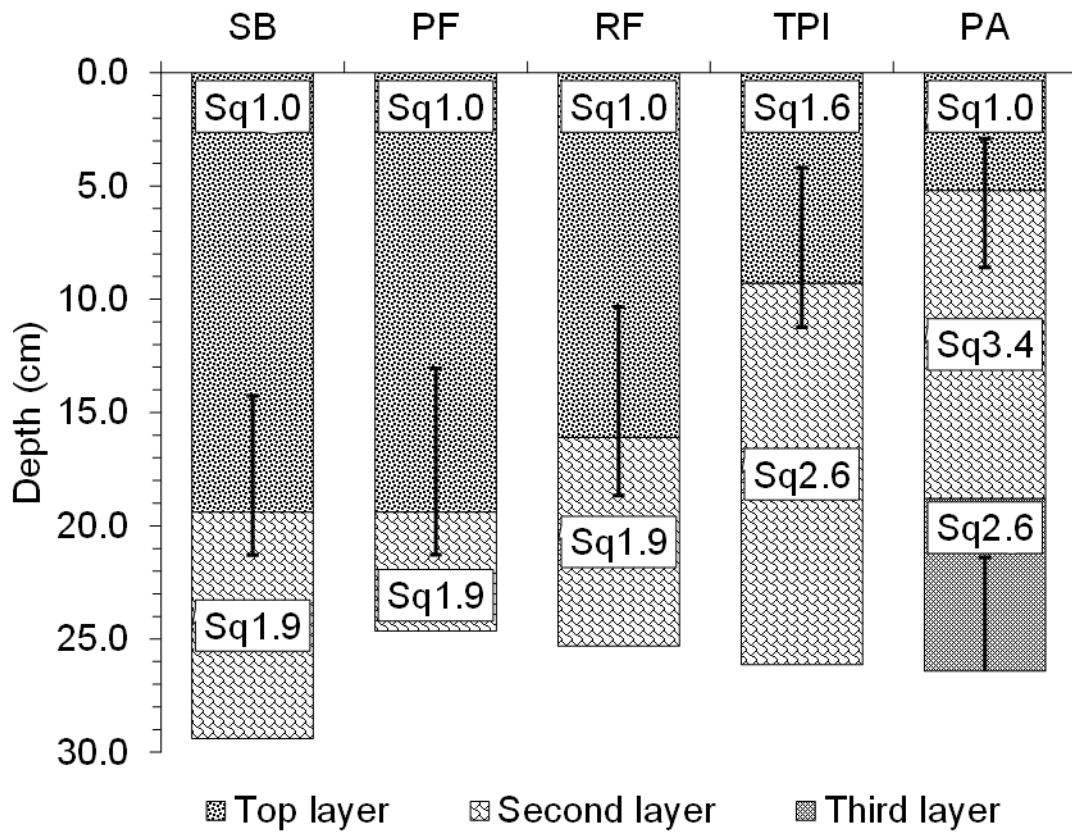
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37 **Fig. 1**

38



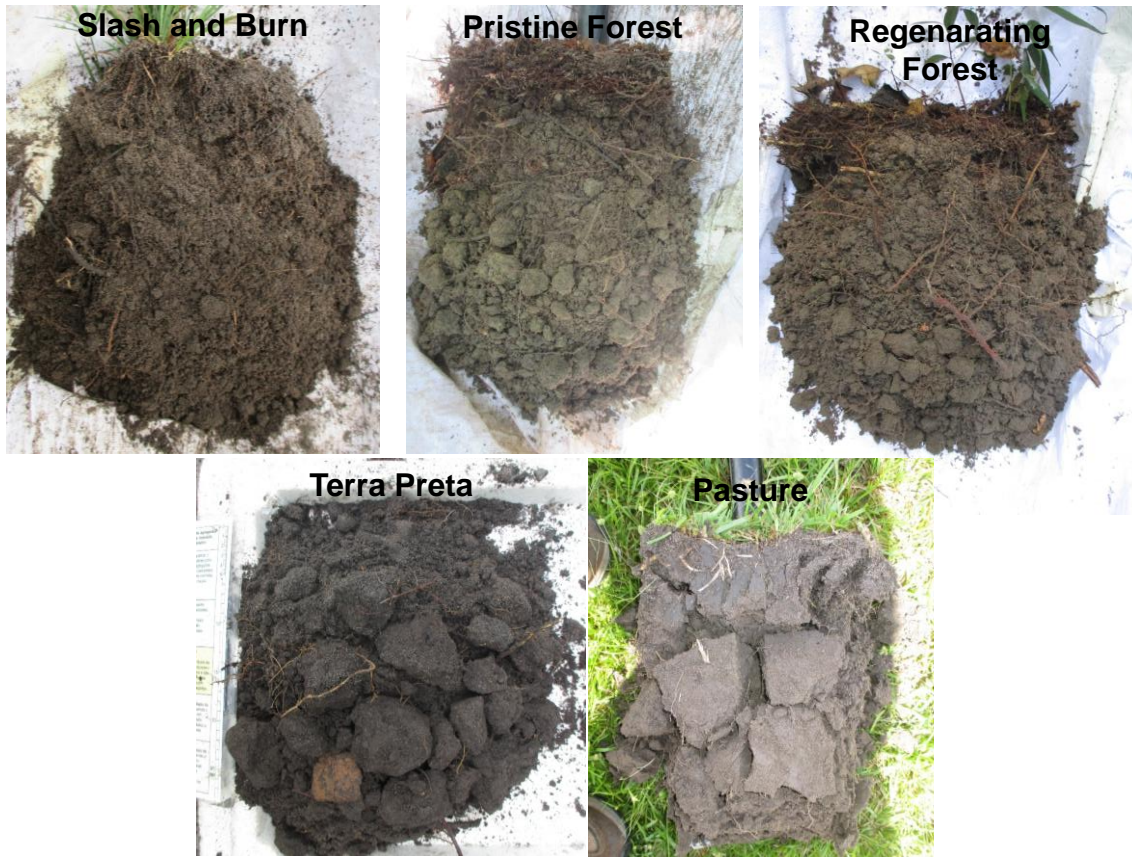
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41 **Fig. 2**

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43

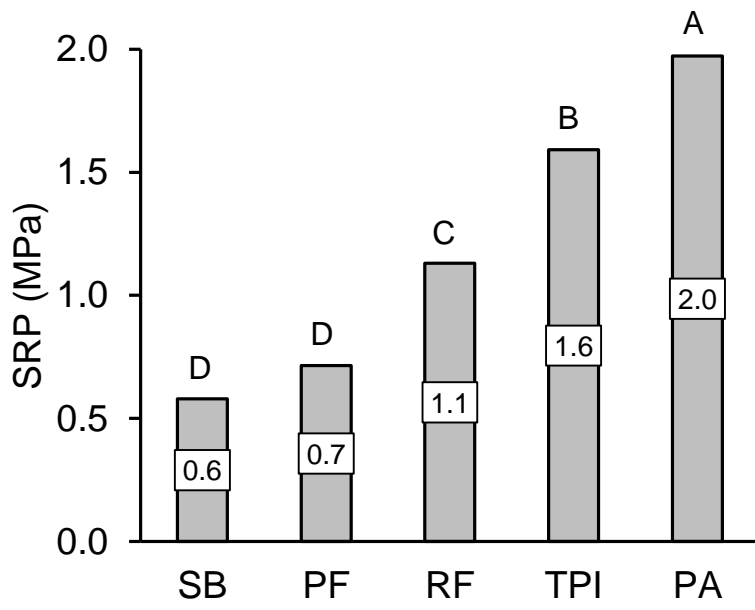
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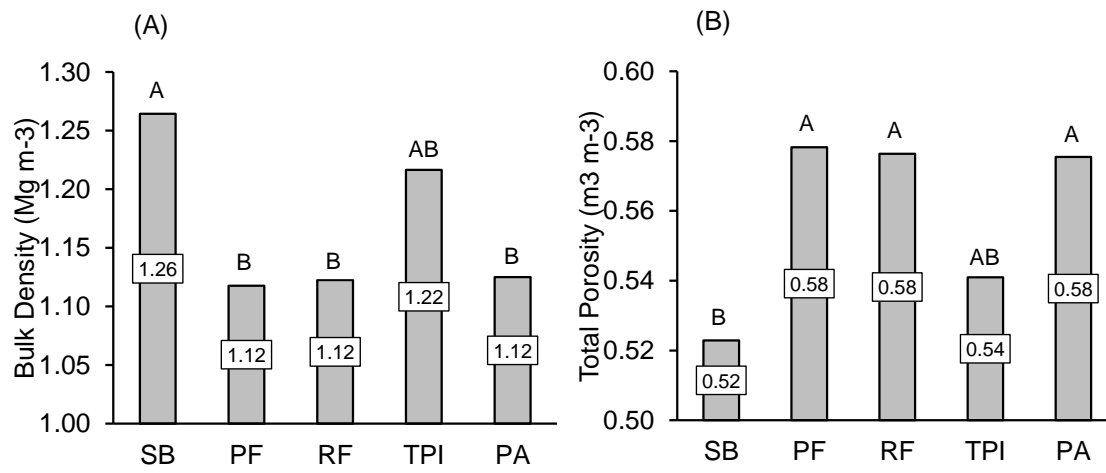
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47 **Fig 3**



50 Fig 4

51

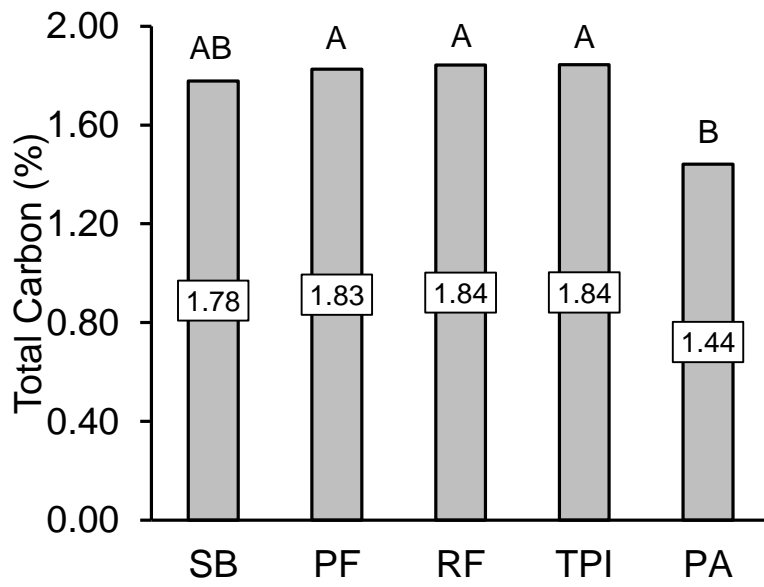


52

53 **Fig 5**

54

55

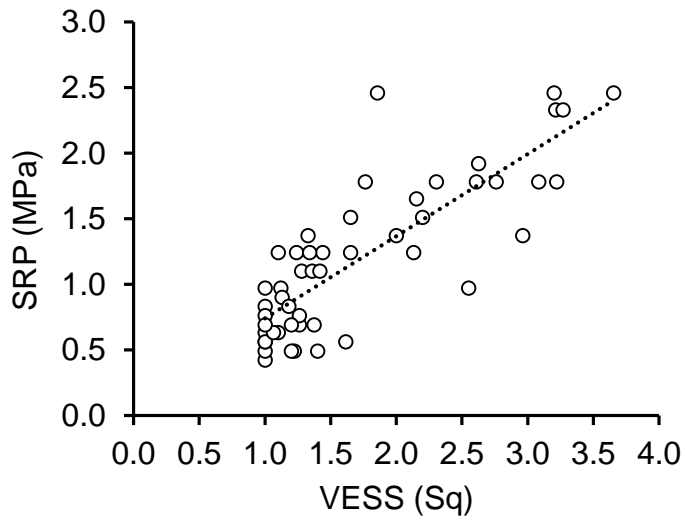


56

57 **Fig. 6**

58

59



60

61 **Fig. 7**