Soil & Tillage Research 139 (2014) 8–18

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Visual field assessment of soil structural quality in tropical soils

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ARTICLE INFO

Article history:
Received 16 January 2013
Received in revised form 14 January 2014
Accepted 26 January 2014

Keywords:
Soil structure
Soil quality
Physical soil properties
Visual examination

ABSTRACT

Visual field assessments have already been tested for 'temperate' soils, but there is scant information about their applicability to 'tropical' soils. This survey contributes to the validation of the visual field assessments by comparing the performance of three of such methods on 'tropical' soils. This study was conducted across six different soils with contrasting soil type and land use, in the central-northern part of Venezuela between November 2011 and January 2012. Scores provided by the soil quality scoring procedure (SQSP), the visual evaluation of soil structure (VESS), and the visual soil assessment (VSA), as well as soil physical properties were measured to assess the soil's structural quality. All methods showed that soil structural quality was unfavourable on a loamy soil (Alfisol) with continuous cereal growth, conventional tillage and low soil organic carbon (SOC), as well as on a silty clay soil (Alfisol) under natural vegetation and cattle production. Where SQSP scores ranged between 1 (extremely firm) and 2 (firm), VESS scores ranged from 4 (compact) to 5 (very compact), and VSA scores were between 0 (poor) and 0.5 (moderately poor). The sandy clay loam (Ultisol) and clay loam (Mollisol) soils under no-tillage and with high SOC had the best soil quality. In our 'tropical' Venezuelan soils there was also high correlation ($P < 0.01$) between the visual assessment scores and soil physical properties such as bulk density (BD), porosity, SOC, and saturated hydraulic conductivity (Ksat), as has been reported for 'temperate' soils. A visual poor condition of soil structure corresponded to BD values higher than 1.4 Mg m^{-3}, porosity lower than 0.5 m^3 m^{-3}, SOC below 25 g kg^{-1}, and Ksat (log) values under 0.5 cm h^{-1}. In those cases where the rooting system could not be evaluated because of fallow, VSA and VESS appeared to be the most appropriate methods for assessing the soil structure. The rating of the indicator 'number of earthworms' should be adjusted for 'tropical' soils; this shall improve the accuracy of the VSA method. These methods were capable of distinguishing the different soil structural quality, and are therefore suitable for assessing soil structural quality of 'tropical' soils with contrasting soil type and land use.

1. Introduction

Soil structure is considered a key factor in the functioning of soil, as its ability to support plant and animal life, and moderate environmental quality (Bronick and Lal, 2005). Several methods of soil structure assessment have been proposed and tested around the world. In general, methods of soil structure assessment are divided in to direct and indirect methods. Indirect characterization of soil structure includes its estimation from soil properties such as hydraulic conductivity, infiltration rate, bulk density (BD) and pore-size distribution (Pagliai et al., 2004; Kodesova et al., 2011; Guimaraes et al., 2013). Direct methods involve observation of morphological structural features by microscopy, analysis of images (e.g., CT scans) for quantification of spatial pores arrangement, measuring soil aggregation and aggregate stability under laboratory conditions, and visual field description of structural form (Lal and Shukla, 2004; Pagliai et al., 2004).

With reference to the visual field assessments, they can be subdivided in to soil profile description and topsoil examination (Peerlkamp, 1959; Scholefield et al., 1985; McKeague et al., 1986; Munkholm, 2000; McKenzie, 2001; Ball and Douglas, 2003; Roger-Estrade et al., 2004; Ball et al., 2007; Shepherd, 2009). The visual

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http://dx.doi.org/10.1016/j.still.2014.01.002

field assessments have been developed to satisfy the requirement of a simple and repeatable methodology for monitoring soil degradation and soil organic matter decline, to evaluate small areas in detail and large areas quickly (McGarry, 2006), as well as a methodology well related to crop growth and soil aeration, strength and density measurements (Ball and Douglas, 2003). According to Batey (2000), the advantages of making assessment of soil physical quality including soil structure directly in the field are: (i) the relatively short time consumed and the immediate availability of the results, (ii) the use of simple equipment, (iii) the observation of slight changes in physical conditions that may be difficult to determine by other means, and (iv) the flexibility to deal with a wide range of situations. Some of the disadvantages of the visual field assessments are: (i) they demand field training and some experience for effective use, (ii) cross-checking of the results by two or more assessors is necessary when there is an absence of confidence for accurate evaluation, and (iii) the process of sample extraction required for destruction of significant area in experimental plots (Balarezo Giarola et al., 2013; Kerebel and Holden, 2013).

Several studies about the use and the refinement of these visual field assessments have been published (Munkholm, 2000; Mueller et al., 2009, 2013; Guimaraes et al., 2011; Boizard et al., 2013; Guimaraes et al., 2013; McKenzie, 2013; Munkholm et al., 2013; Murphy et al., 2013). These assessments have been developed for 'temperate' soils, but there is scant information about their applicability to 'tropical' soils. Balarezo Giarola et al. (2013) tested the method described by Ball et al. (2007) in a sub-tropical area with a humid climate in Brazil. The authors described the method as sufficiently sensitive to identify changes in structural quality of Oxisols under different soil managements. Moreover, other similar methodologies such as 'Le profil cultural' method by Roger-Estrade et al. (2004) were tested for soil physical evaluation under 'tropical' environments (Tavares et al., 1999).

Three widely used methods that have been evaluated on different 'temperate' soils but not on tropical areas are the soil quality scoring procedure (SQSP), the visual evaluation of soil structure (VESS) and the visual soil assessment (VSA). These field assessments could be used as alternatives to the most frequently used soil physical properties for evaluating soil structure. However, before the visual field assessments of soil structural quality can be applied under tropical environments, validation is needed. The hypothesis assessed in this study is that the SQSP, the VESS and the VSA methods are applicable on 'tropical' soils and they are related to quantitative soil physical properties. Our objective is therefore to compare the performance of the SQSP, VESS, and VSA methods in assessing the soil structural quality on Venezuelan 'tropical' soils with contrasting soil type and land use. Additionally, soil physical properties were measured and correlated with the soil structure scores.

2. Materials and methods

2.1. Soil sampling

This study was conducted across six different soils (V1–V6) in the central-northern part of Venezuela between November 2011 and January 2012. Soils selected represent the dominant soils in this agricultural area, where a large part of the country cereal and vegetable production takes place. These soils thus represent the soil structural quality at the moment of sampling under different agricultural conditions very well. The six sites selected differ in factors that affect soil quality such as soil type, soil management, vegetation type, and root growth stage. This provided a wide range of soil quality, which enables to test the different visual field assessments that were selected for this study.

Soil V1 is located at 1861 MAMSL, where the mean annual temperature and the mean annual rainfall are 17 °C and 1154 mm, respectively. V2 is at 436 MAMSL with 25 °C of mean annual temperature and 979 mm of mean annual rainfall. V3 is at 320 MAMSL, and the mean annual temperature and the mean annual rainfall are 27 °C and 1212 mm, respectively. Soils V4, V5 and V6 are located in the same geographical area at 120 MAMSL, with 27 °C of mean annual temperature and 1336 mm of mean annual rainfall.

At the time of sampling V1 soil was under permanent trees (*Prunus persica* (L.) Batsch) with grass between trees rows, V2 soil was under permanent pasture (*Morus* spp. and *Cynodon nlemfuensis*), V3 soil was under maize crop (*Zea mays* L.) with conventional tillage, V4 soil was under pasture (*Brachiaria brizantha*), and V5 soil as well as V6 soil were in fallow with natural vegetation. Soil use and management, soil description and general characterization are detailed in Table 1.

Three transects were randomly located along the plots. At each transect two sampling locations were selected, in which the visual field assessment of soil structural quality was undertaken. Disturbed samples were taken from the upper layer to a depth of 200 mm, and ~100 cm^3 core samples (inner diameter of 51 mm and a height of 50 mm) from a depth of 100 mm. For the visual field assessment two blocks of soil (200 mm deep, 100 mm thick and 200 mm long) were taken at each sampling location. One block was broken by hand and the other by dropping one to three times from

Table 1
Description and characteristics of the tropical soils from Venezuela (V1–V6).

Soil	Textural class	Geographic coordinates	Location	USDA class (Soil Survey Staff, 2010)	Drainage status[a]	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})	SOC (g kg^{-1})	pH$_{KCl}$	Soil use and management[b]
V1	Sandy clay loam	10° 22′ N 67° 12′ W	La Colonia Tovar, Aragua	Typic Kandiustult	Well drained	285.2	198.6	516.2	42.6	3.65	Fruit cropping, no tillage
V2	Clay loam	10° 15′ N 67° 37′ W	Maracay, Aragua	Fluventic Haplustoll	Well drained	291.0	282.3	426.7	24.4	7.67	Grass, no tillage, no trampling
V3	Loam	10° 21′ N 68° 39′ W	Danac, Yaracuy	Typic Endoaqualf	Imperfectly drained	172.8	350.7	476.5	7.5	4.90	Maize mono-cropping, conventional tillage[c]
V4	Loam	8° 46′ N 67° 45′ W	La Fundación, Guárico	Aquic Haplustoll	Moderately well drained	229.5	485.8	284.7	20.3	5.19	Grazing, no tillage
V5	Silty loam	9° 0′ N 67° 41′ W	El Cujicito, Guárico	Typic Rhodustalf	Well drained	261.0	583.0	156.0	29.1	4.84	Cereal cropping with fallow periods, conventional tillage
V6	Silty clay	9° 02′ N 67° 41′ W	Las Nubes, Guárico	Aquic Haplustalf	Moderately well drained	423.1	501.3	75.6	16.1	4.67	Grazing with natural vegetation

SOC, soil organic carbon.

[a] The soil drainage class indicates the possibility to evacuate excess moisture form a soil based on the soil unit's classification name. The FAO soil drainage classes are: not applicable; excessively drained; soils extremely drained; well drained; moderately well drained; imperfectly drained; poorly drained; very poorly drained; water bodies.

[b] Current and over the last 10 years.

[c] Conventional tillage in Venezuela can be described as multiple passes of the harrow and plough during each cultivation period as well as a yearly or a two years subsoiling.

a height of 1 m into a plastic tray. The water content at sampling was 0.40, 0.20, 0.18, 0.27, 0.23 and 0.22 kg kg^{-1} for soils V1–V6, respectively.

2.2. Visual soil structure assessment

The visual field assessment of soil structural quality was conducted by three methods: the SQSP (Ball and Douglas, 2003), the VESS (Ball et al., 2007), and the VSA (Shepherd, 2009).

The SQSP was conducted by describing the condition of the soil block broken by hand and the condition of the soil surface. The horizontal layers of contrasting structure present in each soil block were identified and depth of each layer was measured. The degree of firmness was the criterion used to identify the contrasting layers present in the soil block. In each layer, soil structure (type, size and rupture resistance of aggregates) and rooting (quantity, distribution, bending and thickness) were evaluated using the explanatory notes proposed by Ball and Douglas (2003), as well as the soil surface condition (vegetation and surface soil relief) in each area where the soil blocks were extracted. The scale of scoring (semi-quantitative evaluation of soil physical quality and rooting) was ranked from 1 to 5, where scores of 1 and 2 represent incoherent or poorly developed structure and scores of 3–5 refer to distinct aggregates and good physical condition for crop growth.

The VESS was simultaneously conducted with the SQSP, meaning that we used the same soil block to perform both methods. The evaluation of the soil blocks was conducted according to the methodology described by Ball et al. (2007), which allows to assess the soil structural quality based on a visual key linked to criteria chosen to be as objective as possible. This methodology consists of identifying any layers of contrasting structure and given a structural quality score (Sq) by comparing the appearance of the soil block after hand breaking with a visual key proposed by Guimaraes et al. (2011). In this visual key the attributes evaluated are size and appearance of aggregates, visible porosity and roots, appearance after break up, distinguishing features, as well as appearance and description of natural or reduced fragment of 15 mm in diameter. The blocks of soil were graded on a scale from Sq1 to Sq5 where 1 was best. Scores were fitted between structural quality categories when the soil block had the properties of both. The assigned score was confirmed or increased from factors such as difficulty in extracting the soil block, aggregate shape and size, presence of large worm holes, root clustering, thickness and deflections, soil colour and smell, and the necessity to break large aggregates to small fragments to reveal their type. Soils with scores of 1–3 have acceptable condition of soil structure whereas those with scores of 4–5 have a limiting condition and require change of management.

The soil block broken by dropping was used in order to conduct the VSA as described by Shepherd (2009). This method was conducted following the visual assessment of the key indicators (soil texture, soil structure, soil porosity, number and colour of soil mottles, soil colour, earthworms, soil smell, potential rooting depth, surface ponding, surface cover, surface crusting, and soil erosion) presented on the scorecard suggested by the author. The fresh face of three of the large clods from the soil structure test was examined for soil porosity by comparing it with the reference photographs from the field guide manual. Pores visible to the naked eye and earthworm burrows were also considered before giving a visual score (VS) for soil porosity.

Each indicator was given a VS of 0 (poor), 1 (moderate), 2 (good), or an in-between score (0.5 = moderately poor and 1.5 = moderately good), based on the soil quality observed when comparing the soil with the description of the indicator and the photographs in the field guide manual. The ratings for each attribute were then weighted and summed up to derive a final overall score for soil structural quality. The field guide manual for cropping land was used in soils V1 and V3, whereas in the other soils that for pastoral grazing was applied. Soils with a sum of visual scores ranking <20 (under both grazing and cropping) have a poor soil quality, and soils with values >35 (under grazing) or >37 (under cropping) have a good soil quality. Values between these ranges are considered to be of a moderate soil quality.

2.3. Soil physical analysis

The saturated hydraulic conductivity (Ksat) was determined on the core samples using a closed permeameter system (Eijkelkamp Agrisearch Equipment, the Netherlands). The soil water retention curve (SWRC) was constructed by measuring soil water content at eight soil-matric potentials using the same cores. For the matric potential ranging from −1 to −10 kPa, the sand box apparatus (Eijkelkamp Agrisearch Equipment, the Netherlands) was used, whereas pressure chambers were used to measure the water content at −33 kPa, −100 kPa and −1500 kPa (Soilmoisture Equipment, Santa Barbara, CA, USA), following the procedure described by Cornelis et al. (2005). The measured water retention data were fitted using the function of van Genuchten (1980). Total porosity ($\theta_{h=0\ \mathrm{kPa}}$), air capacity (AC, $\theta_{h=0\ \mathrm{kPa}} - \theta_{h=-10\ \mathrm{kPa}}$), field capacity (FC, $\theta_{h=-33\ \mathrm{kPa}}$), permanent wilting point (PWP, $\theta_{h=-1500\ \mathrm{kPa}}$), plant available water capacity (PAWC, $\theta_{h=-33\ \mathrm{kPa}} - \theta_{h=-1500\ \mathrm{kPa}}$), and relative water capacity (RWC, $\theta_{h=-33\ \mathrm{kPa}}/\theta_{h=0\ \mathrm{kPa}}$) were calculated from SWRC, with h denoting matric potential. Soil dry BD was determined at −10 kPa matric potential. Shrinkage was observed in some of the rings as well as some stones; hence a correction on the volume was made for the calculation of BD. The volume of the stones was calculated by Archimedes' principle.

These soil physical properties, as well as the slope at the inflection point of the SWRC named as S index (Dexter, 2004) and the structural stability index (StI) (Pieri, 1992) were calculated and compared to the score of the visual field assessment methods. This comparison was performed with the aim to establish relationships between simple visual assessments and quantitative indicators of soil quality, which can demonstrate the strengths and weaknesses of the methods (Mueller et al., 2009; Guimaraes et al., 2013).

Eqs. (1) and (2) were used to calculate the StI and the S index, respectively:

$$\mathrm{StI} = \frac{1.72 \times \mathrm{SOC}}{\mathrm{Clay} + \mathrm{Silt}} \times 100 \qquad (1)$$

where SOC is the soil organic carbon content (%) and Clay + Silt is the soil's clay and silt content (%).

$$S = -n(\theta_{\mathrm{sat}} - \theta_{\mathrm{res}}) \left[\frac{2n-1}{n-1}\right]^{((1/n)-2)} \qquad (2)$$

The SWRCs were used for deriving the parameters of the van Genuchten equation (van Genuchten, 1980) by curve-fitting with the $m = 1 - 1/n$ constraint:

$$\theta(h) = \theta_{\mathrm{res}} + \frac{\theta_{\mathrm{sat}} - \theta_{\mathrm{res}}}{[1 + |\alpha h|^{n}]^{m}} \qquad (3)$$

where θ_{sat} ($m^3\ m^{-3}$) is the soil water content at saturation; θ_{res} ($m^3\ m^{-3}$) is the residual soil water content; h is equal to the modulus of the matric potential (hPa); α, n and m are fitting parameters. These parameters were estimated with the retention curve program (RETC, 2008).

2.4. Data analysis

An evaluation of individual indicators and indices of the visual field assessment was simultaneously conducted on each soil.

Methods were compared from score data of all soils. To test the relationships between the visual field assessment scores and soil physical properties measurements, correlation coefficients were calculated using Spearman's statistic for mean rank data. A criterion of $P < 0.01$ was selected to represent statistical significance. If a visual field method was consistently correlated with all the soil physical properties measured, then this method was seen as an adequate indicator of the soil structural quality. Regressions between variables were conducted in order to postulate thresholds of soil physical properties that correspond to a deterioration of the soil structural quality (visually evaluated). These analyses were performed using the statistical package SPSS (version 15.0, SPSS Inc., USA).

3. Results

3.1. Soil structural quality as evaluated by different visual field assessments

The evaluation of soil structural quality using the SQSP, the VESS and the VSA was conducted on different soils and simultaneously.

3.1.1. Soil quality scoring procedure (SQSP)

In general, the absence of roots or the low density of plants in soils under fallow (natural vegetation) made the evaluation of rooting in the SQSP (Ball and Douglas, 2003) difficult. The identification and description of the different indicators and features used in this method are summarized in Tables 2 and 3.

3.1.1.1. Surface condition. Soils V1, V2, V4 and V5 did not show evidence of crusting and sealing, neither of visible nor slight micro relief, but decomposing vegetation was present on the soil surface, which provides a 'good' surface score for these soils (Table 3). In contrast, soils V3 and V6 had a 'bad' surface score. The soil surface of these soils had little vegetation, mossy spots, and soils crusting along the plot. These are features commonly present in soil with a 'poor' physical quality.

3.1.1.2. Structure block score. All soils had two visible layers to a depth of 200 mm. V1 and V5 had an upper layer of 50 mm in depth. But for V2 the blocks of soils had an upper layer of 100 mm and for the other soils a layer between 50 and 100 mm. The features used to differentiate the contrasting layers were the type, size, and rupture resistance of the aggregates. Results in Tables 2 and 3 showed that the score quality of the soil structure was 'good' in soils V1 and V2. This is attributed to the dominance of a fine crumbly structure with low resistance to rupture in the upper layer (0–50 mm and to 100 mm, respectively) and the friable sub-angular blocky structure underneath. In V4 and V5 soils, the dominance of friable, sub-angular or angular blocky aggregate types with visible macropores in the upper layer as well as the prevalence of firm angular blocky structure in the under layer (50 or 100 mm to 200 mm), result in a 'moderate' soil structure score for these soils. In some blocks, macropores were not visible to the naked eye, but few earthworm burrows were present. A 'bad' soil structure score was given to V3 and V6 soils because of the dominance of angular blocky structure type, the high resistance against rupture of the field moist aggregates, and the low porosity observed in the faces of the aggregates (non-visible porosity).

3.1.1.3. Rooting block score. The amount of roots, distribution and bending were important features to distinguish scores in each soil block. Reference photograph are given in Fig. 1. The root distribution was uniform along the soil blocks in V1 and V2, the root growth was not restricted. In the V3 and V6 soils, however, roots were concentrated at the upper layer (0 to ~100 mm) of the soil blocks as evidenced by a compacted layer underneath (~100–200 mm).

Table 2
Scores given to the indicators and index of the three visual field assessments for Venezuelan tropical soils.

Soil	SQSP				VESS Structure quality	VSA		
	Surface condition	Structure score	Rooting score	Block score		Soil structure	Soil porosity	Soil quality
V1	3 (0)[a]	3.5 (0.4)	3.7 (0.4)	3.0 (0.2)	2.5 (0.5)	1.3 (0.5)	1.6 (0.2)	35 (2.0)
V2	4 (0)	4.0 (0.0)	4.1 (0.5)	4.1 (0.3)	2.0 (0.0)	1.6 (0.2)	1.9 (0.2)	40 (1.3)
V3	2 (0)	1.3 (0.4)	1.6 (0.8)	1.5 (0.6)	4.2 (0.4)	0.0 (0.0)	0.2 (0.3)	15 (1.2)
V4	4 (0)	2.3 (0.1)	3.7 (0.4)	3.0 (0.2)	3.3 (0.4)	0.7 (0.3)	1.1 (0.2)	31 (2.3)
V5	3 (0)	2.6 (0.4)	3.0 (0.0)	2.8 (0.2)	3.5 (0.3)	1.0 (0.0)	1.4 (0.2)	27 (0.9)
V6	2 (0)	2.0 (0.0)	2.0 (0.0)	2.0 (0.0)	4.4 (0.4)	0.3 (0.4)	0.3 (0.3)	11 (2.7)

SQSP, soil quality scoring procedure by Ball and Douglas (2003); VESS, visual evaluation of soil structure by Ball et al. (2007); VSA, visual soil assessment by Shepherd (2009). With SQSP and VSA, lower values refer to poorer soil quality, whereas with VESS lower values indicate better soil quality. See Table 5.

[a] Standard deviation is given in parenthesis (±).

Table 3
Global comparison of indicators and indices of the three visual field assessments for soils from the northern part of Venezuela.

Soil	SQSP				VESS Structure quality	VSA		
	Soil surface	Soil structure	Rooting	Soil quality		Soil structure	Soil porosity	Soil quality
V1	No relief/smooth	Firm/friable	None restriction	Good structural development	Intact/firm	Moderately good	Moderately good	Moderately good
V2	No relief	Friable/firm	None restriction	Good structural development	Intact	Moderately good	Moderately good	Good
V3	Crusting	Firm/extremely firm	Restricting roots	Structure deteriorated	Compact	Poor	Poor	Poor
V4	No relief	Firm/friable	Weak restriction	Good structural development	Firm	Moderately poor	Moderate	Moderate
V5	Rough/high covert	Firm/friable	Weak restriction	Moderate structural development	Firm/compact	Moderate	Moderately good	Moderate
V6	Smooth with ridges	Firm	Restricting roots	Structure deteriorated	Compact	Poor	Poor	Poor

SQSP, soil quality scoring procedure by Ball and Douglas (2003); VESS, visual evaluation of soil structure by Ball et al. (2007); VSA, visual soil assessment by Shepherd (2009).

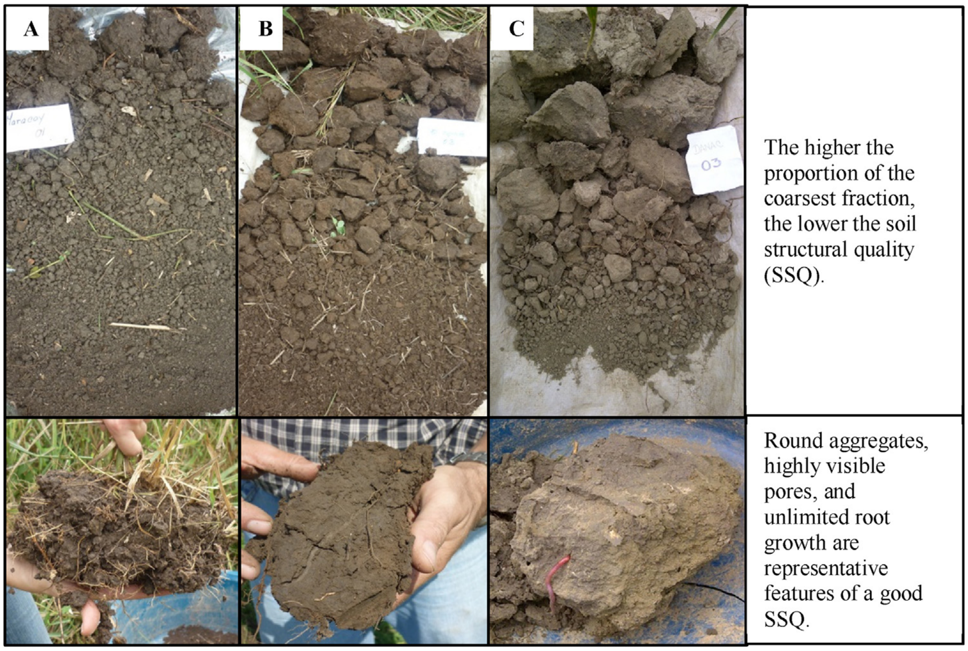

Fig. 1. Three soils with different soil structural quality classes. From left to right, the photographs show 'good', 'moderate' and 'poor' soil structural quality. (A) is from a clay loam-Mollisol under permanent pasture, high SOC, no-tillage and no-trampling, (B) is from a loam-Mollisol under pasture, medium SOC, and permanent trampling, and (C) is from a loam-Alfisol, under cereal growth, conventional tillage and low SOC.

In the V4 and V5 soils, the evenness of the root distribution and the absence of thickening and bending indicated that roots were not restricted by unfavourable soil structure (Table 3). However, the vegetation present in V5 and V6 soils was heterogeneous and had a poor root density making it difficult to describe the distribution of the roots and the other specific features such as thickening and bending.

3.1.1.4. Block score. The 'block score', from the soil structure score and soil rooting score, was 'good' for V1, V2 and V4 soils; 'moderate' for V5 soil; and 'bad' for V3 and V6 soils (Table 3). This means that the interaction between the soil use and management with the soil features prevalent in each soil contribute in maintaining a 'good' quality of soil structure. No physical limitations were present for plant growth in V1, V2 and V4 soils. In V3 soil, the 'block score' revealed a 'poor' soil physical quality. Evidence of soil compaction, soil crusting and soil erosion were present in this soil. The degradation condition of this soil restricts the root development of the crop. In the clayey soil, V6, the 'block score' suggests that this soil has a 'poor' soil physical quality condition as well. This can result in a high risk of water logging. Soil V5 under fallow condition had a 'moderate' soil structural quality, suggesting that action should be taken to improve the function of soil.

3.1.2. Visual evaluation of soil structure (VESS)

The visual key of VESS (Ball et al., 2007) was very practical and made the evaluation of the soil structural quality less time-consuming. Low scores in the visual key, Sq = 1 and Sq = 2, refer to a high soil quality. A crucial factor to identify the score in some soil blocks was the shape of the aggregate fragments (photographically evaluated); e.g., this factor provides in most of the cases Sq = 4 to soils where the other attributes such as size of aggregates and visible porosity match with the description of Sq = 3.

In the clayey soil (V6), it was difficult to test the methods SQSP and VESS. Much effort was needed to extract the block and break up the aggregates. In this soil the features such as massive structure, absence of roots, abundance of soil mottles and visible cracks, match with the Sq = 5 description of the visual key, which means a low physical quality for crop production.

In the upper layer (0 to ∼100 mm) of V3 the seedbed created by tillage had Sq = 3, but an abrupt change was observed in the under layer (∼100–200 mm) where Sq = 5 (Table 2). The whole block had a degraded quality despite the condition of the upper layer. The compacted layer had evidences of restricted root growth and water movement (deformed roots and mottled soil).

In V4 and V5 soils, the aggregate fragments were easily obtained. Most aggregates were round-shaped in the upper layer (0 to ∼100 mm in V4, and 0–50 mm in V5) and cube-shaped in the under layer. The evidence of earthworm burrows in soil V5 and the evenness of root distribution in soil V4 were considered as positive features in the description of porosity and roots. But the few visible pores and the cube-shaped in the aggregate fragments of the under layer (∼100–200 mm) of the blocks soils were features for increasing the scores. Therefore, the structural quality of these soils was between Sq = 3 and Sq = 4 (Table 2).

The differences in size and appearance of aggregates in soil V1 were the most important features to distinguish Sq as visual key. This soil had Sq = 2.5 (moderate quality). In soil V2 the majority of the aggregates obtained were fragile, round and in most of the cases were held together by roots. No clods were present, most aggregates were porous and roots were well distributed along the block, consequently, this soil had Sq = 2 (Table 2).

3.1.3. Visual soil assessment (VSA)

The indicators of the score card were identified in the soils using the comparative photographs of the field guide manual proposed by Shepherd (2009). Dropping of the soil block was difficult to do with compacted and heavy soils. Dropping the soil block and arranging the distribution of aggregates for the VSA method consume more time than breaking up the soil block by hand as was conducted in the other methods. However, from a visual point of view, VSA was the easiest method to provide soil quality scores to the indicators such as soil structure, soil porosity and surface condition, because of the three reference photographs and the criteria given in the field guide. The soil quality of specific

Table 4
Summary of the visual scores given to the indicators of soil quality of the visual soil assessment (VSA) for the evaluated Venezuelan ‘tropical’ soil.

Visual indicator of soil quality	V1	V2	V3	V4	V5	V6
Soil texture	1	2	1	2	1	0
Soil structure	1	2	0	1	1	0
Soil porosity	2	2	0	1	2	0
Number and colour of soil mottles	2	2	1	1	2	1
Soil colour	1	2	0	1	2	1
Earthworms	0	0	0	0	0	0
Soil smell	2	2	1	2	2	1
Potential rooting depth	2	2	0	2	2	1
Surface condition	2	2	1	2	1	0

0 = average from ≥ 0 to ≤ 0.5 (condition from poor to moderately poor); 1 = average from >0.5 to <1.5 (condition from moderately poor to moderately good); 2 = average from ≥ 1.5 to 2 (condition from moderately good to good).

indicators and the overall soil quality index were evaluated as summarized below (Tables 2–4).

3.1.3.1. Soil structure. The soil fragments obtained after dropping the soil block were used to visually describe the aggregate size distribution (Table 2 and Fig. 1). In soils under grass, large fragments remained after the second or the third drop because they were held together by roots and no force was applied to separate them. In the tilled soil (V3) and the clayey soil (V6) most of the soil blocks did not break apart in more than three or four parts after being dropped. The coarsest fraction (firm and angular in shape) of the aggregates was larger than the finest fraction (friable and rounded or sub-angular) in soils V5, V4, V3 and V6 (50, 60, 70 and 90%, respectively). The higher the proportion of the coarsest fraction, the lower the quality of the soil structure. Hence structure in V1 and V2 soils was ‘moderately-good’, in V5 ‘moderate’, in V4 ‘moderate-poor’ and in V3 and V6 soils was ‘poor’ (Table 3).

3.1.3.2. Soil porosity. Soil V2 showed ‘good’ porosity (VS = 2), V1 and V5 soils had ‘moderate-good’ porosity (VS = 1.6 and VS = 1.4, respectively), V4 soil had ‘moderate’ porosity (VS = 1.1) and V3 and V6 soils had ‘poor’ porosity (VS = 0.3 and VS = 0.2, respectively) (Tables 2 and 3). In V1, V2, V4 and V5 soils, the presence of biopores (formed by roots or fauna activities) in the majority of the blocks contributed to a higher score for soil porosity than when they were not visible.

3.1.3.3. Soil quality. After dropping of the soil block, the contrasting layers present in the soil block could not be observed. But, an overall estimation over the entire soil block could be obtained immediately. The advantage of this is that the ‘score’ is the interpretation of the physical and biological properties in the first 200 mm of the soil as well as the soil surface condition.

With the VSA, the features most difficult to evaluate and with the lowest score along the soils were the potential rooting depth and the earthworm numbers respectively. These are indicators with a high weighting factor in the scorecard. Identifying the potential rooting depth requires digging very deep, at least to a depth of 800 mm that is the range established by Shepherd (2009) for a ‘good’ condition. This demands much effort and time especially in clayey soils. With respect to earthworm number, all soils were classified as having a ‘poor’ condition (Table 4). This score did not significantly correlate with any of the visual scores or soil physical properties (Tables 5 and 6).

3.2. Overall assessment of each soil

Table 3 shows the description of the scores given to all soils under study. Soil structural quality was unfavourable in soils V3 and V6, where SQSP scores ranged between 1 (extremely firm) and 2 (firm), VESS scores ranged from 4 (compact) to 5 (very compact), and VSA scores were between 0 (poor) and 0.5 (moderately poor). For the other soils, the structural status was favourable or moderate with slight restrictions for root growth according to the three methods. Photographs of investigated soil structure are provided in Fig. 1.

However, in soil V4 a different rating was given for SQSP compared to VESS and VSA. The shape and the distribution of the aggregates were the features that mainly influenced the rating of ‘moderate’ soil quality using VESS and VSA criteria. On the contrary, the overall classification of SQSP method was ‘good structural development’ for these soils, in spite of ‘smooth’, ‘firm/friable’ or ‘weak restriction’ conditions described by the indicators of SQSP. This method comprises a wide range of ‘good’ quality, from 3 to 5, and soil V4 received a score equal to 3 (Tables 2 and 3). Consequently, for soils with ‘moderate’ soil quality as determined by VESS and VSA, the SQSP tends to overestimate the soil quality. Regardless of the differences in rating found for soil V4, relation between the methods applied was found when all soils were considered (Fig. 2, Table 5).

Soil taxonomy allows comparison of the structural quality within soil orders. Irrespective of differences in factors such as texture, drainage, land use and management, all three visual field assessments indicated a compacted or poor condition of soil structure of the Alfisols (soils V3, V5 and V6). When Mollisols were considered (V2 and V4), a better condition of soil structure was observed. However, weak restrictions for rooting and evidence of

Table 5
Correlation matrix (Spearman ρ) of the visual field assessments. Data set involve six different soils from the northern part of Venezuela ($n = 36$).

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
M1	1									
M2	0.71**	1								
M3	0.87**	0.81**	1							
M4	0.86**	0.88**	0.94**	1						
M5	−0.75**	−0.84**	−0.85**	−0.84**	1					
M6	0.66**	0.88**	0.75**	0.82**	−0.77**	1				
M7	0.72**	0.88**	0.78**	0.82**	−0.88**	0.89**	1			
M8	0.74**	0.83**	0.77**	0.81**	−0.85**	0.83**	0.87**	1		
M9	0.00	0.13	−0.01	0.02	−0.11	−0.01	0.14	0.17	1	
M10	0.83**	0.87**	0.87**	0.86**	−0.90**	0.84**	0.89**	0.84**	0.09	1
M9$_{\text{mod}}$	0.42**	0.73**	0.45**	0.54**	−0.67**	0.59**	0.74**	0.72**	0.45**	0.62**
M10$_{\text{mod}}$	0.81**	0.88**	0.86**	0.85**	−0.90**	0.84**	0.84**	0.85**	0.12	0.98**

M1 = surface condition (soil quality scoring procedure, SQSP), M2 = structure score (SQSP), M3 = rooting score (SQSP), M4 = block score (SQSP), M5 = structure quality (visual evaluation of soil structure, VESS), M6 = soil structure (visual soil assessment, VSA), M7 = soil porosity (VSA), M8 = soil colour, M9 = earthworms score, M10 = soil quality (VSA), M9$_{\text{mod}}$ = visual score given to earthworms number based on criteria showed in Table 4, M10$_{\text{mod}}$ = overall score of VSA including M9$_{\text{mod}}$.

** Correlation is significant at $P = 0.01$.

Table 6
Correlation coefficient between scores of the visual field assessments and soil physical properties ($n = 36$).

	BD	Porosity[a]	AC	PAWC	RWC	SOC	Ksat	Clay	Silt	Sand	NE	*S* index	StI
M1	-0.46^{**}	0.29	0.12	0.47^{**}	−0.13	0.44^{**}	0.39^{*}	−0.05	−0.12	0.13	0.46^{**}	0.52^{**}	0.57^{**}
M2	-0.52^{**}	0.43^{**}	0.22	0.04	−0.17	0.75^{**}	0.73^{**}	0.29	-0.44^{**}	0.30	0.68^{**}	0.12	0.84^{**}
M3	-0.62^{**}	0.49^{**}	0.26	0.20	−0.25	0.57^{**}	0.55^{**}	0.06	-0.38^{*}	0.32	0.44^{**}	0.46^{**}	0.72^{**}
M4	-0.49^{**}	0.37^{*}	0.13	0.23	−0.11	0.58^{**}	0.58^{**}	0.12	−0.30	0.21	0.51^{**}	0.34^{*}	0.71^{**}
M5	0.60^{**}	-0.43^{**}	-0.39^{*}	−0.07	0.39^{*}	-0.66^{**}	-0.68^{**}	−0.07	0.49^{**}	-0.46^{**}	-0.64^{**}	−0.24	-0.80^{**}
M6	-0.37^{*}	0.28	0.11	−0.07	−0.15	0.68^{**}	0.64^{**}	0.18	-0.34^{*}	0.26	0.55^{**}	0.11	0.75^{**}
M7	-0.40^{*}	0.23	0.14	−0.02	−0.22	0.74^{**}	0.65^{**}	0.15	-0.34^{*}	0.29	0.71^{**}	0.13	0.82^{**}
M8	-0.38^{*}	0.30	0.10	−0.02	−0.09	0.62^{**}	0.67^{**}	0.29	−0.29	0.19	0.68^{**}	0.05	0.70^{**}
M9	−0.08	0.07	0.07	−0.04	0.00	0.28	0.24	0.08	−0.04	0.04	0.41^{*}	−0.29	0.19
M10	-0.62^{**}	0.43^{**}	0.41^{*}	0.18	-0.43^{**}	0.59^{**}	0.68^{**}	−0.02	-0.53^{**}	0.51^{**}	0.66^{**}	0.44^{**}	0.75^{**}
$M9_{mod}$	−0.22	0.13	0.08	−0.13	−0.12	0.60^{**}	0.60^{**}	0.32	−0.32	0.22	0.94^{**}	−0.20	0.62^{**}
$M10_{mod}$	-0.60^{**}	0.42^{**}	0.38^{*}	0.10	-0.40^{*}	0.63^{**}	0.72^{**}	0.03	-0.52^{*}	0.49^{**}	0.72^{**}	0.32	0.76^{**}

BD, bulk density; AC, air capacity; PAWC, plant available water capacity; RWC, relative water capacity; SOC, soil organic carbon; Ksat, saturated hydraulic conductivity; NE, number of earthworms; StI, structural stability index; NE, number of earthworms.
See Table 6 for abbreviations.

[a] Porosity was calculated taking into account particle density values. Particle density was measured using the well-known picnometer method.

[*] Correlation is significant at $P = 0.05$ level.

[**] Correlation is significant at $P = 0.01$ level (2-tailed).

deterioration in shape and size of aggregates were observed in the Mollisol that was only under one pasture species and subjected to trampling (V4).

3.3. Relationships between the visual field assessment scores and soil physical properties values

When comparing the scores of the indices and indicators of the visual field assessments with soil physical properties determined in the laboratory, significant correlations were found (Table 6), but not all correlations were strong ($P > 0.01$, $r < 0.7$). This significant correlation indicates that most indices and indicators of the visual field assessments refer to diagnostic features. The visual field assessments, based on the arrangement of soil structure, consider a low mass/volume relation as a 'good' quality condition. In this study, soils with low BD, high SOC, and high AC had high number of earthworms (reflect pores visible to the naked eye), abundant small round-shaped aggregates and no-limitation of root growth, which represent a 'good' visual soil structural quality.

Table 6 shows, that there were significant correlations ($P < 0.01$) between the overall visual scores and BD, porosity, SOC, and Ksat. Besides, the overall score of VESS and VSA were significantly correlated with porosity, AC and RWC. For the soils used in this study, with a silt and clay content ranging from 20 to 58% and from 23 to 42%, respectively, significant correlations were found between silt content and indicators of the visual field assessments, except with the SQSP overall score. This confirms that the SQSP tends to overestimate the soil quality of the studied soils. On the other hand, no correlations were found with clay content. This indicates that the higher the content of silt, the lower the soil structural quality in the evaluated soils.

The relationships between the visual field assessment scores and some of the soil physical properties are presented in Fig. 3 and Table 7. These relationships based on the data set of all soils were in many cases significant. The strongest relationships were those between VESS and VSA with the soil physical properties such as porosity, BD, SOC, and Ksat as well as StI. The *S* index was not significantly related to any of the visual scores.

4. Discussions

4.1. Comparison of soil quality classification

It is important to emphasize that land use and soil type are not considered as factor in this study, but are mentioned because they refer to the condition of the soil at the time of sampling.

Overall the three visual field assessments enabled to distinguish the different soil structural quality classes present at the evaluated soils, which is in agreement with our hypothesis. From the aspect of soil quality, sandy clay loam and clay loam soils (V1 and V2) were the best. Both soils V1 and V2 had high SOC and no-tillage management. The worst soil quality was found on a loamy soil (V3), characterized by continuous cereal growth, conventional tillage and low SOC, as well as on silty clay soil (V6) under natural vegetation and cattle production (Fig. 1). This indicates that no matter the differences in texture and other factors, these Alfisols (V3 and V6) are susceptible to compaction by mechanical or animal traction. These results correspond with those reported

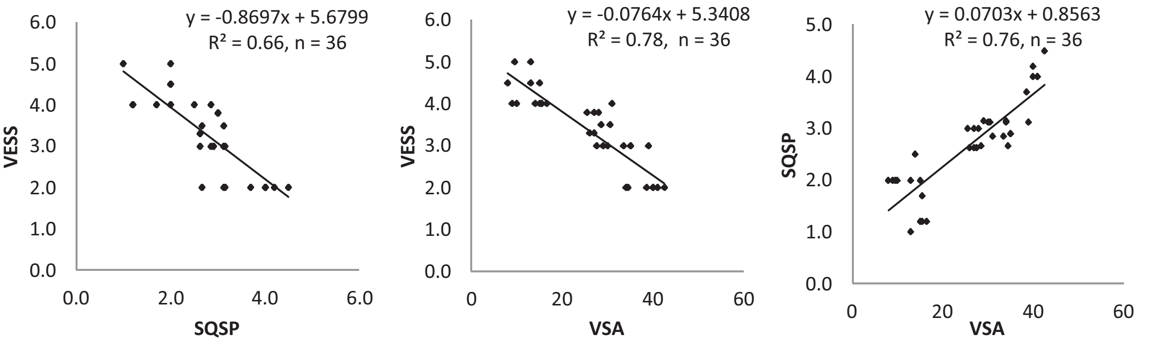

Fig. 2. Relationship between scores of the visual field assessments from collected data in 'tropical' Venezuelan soils (V1–V6). SQSP, soil quality scoring procedure; VESS, visual evaluation of soil structure; VSA, visual soil assessment.

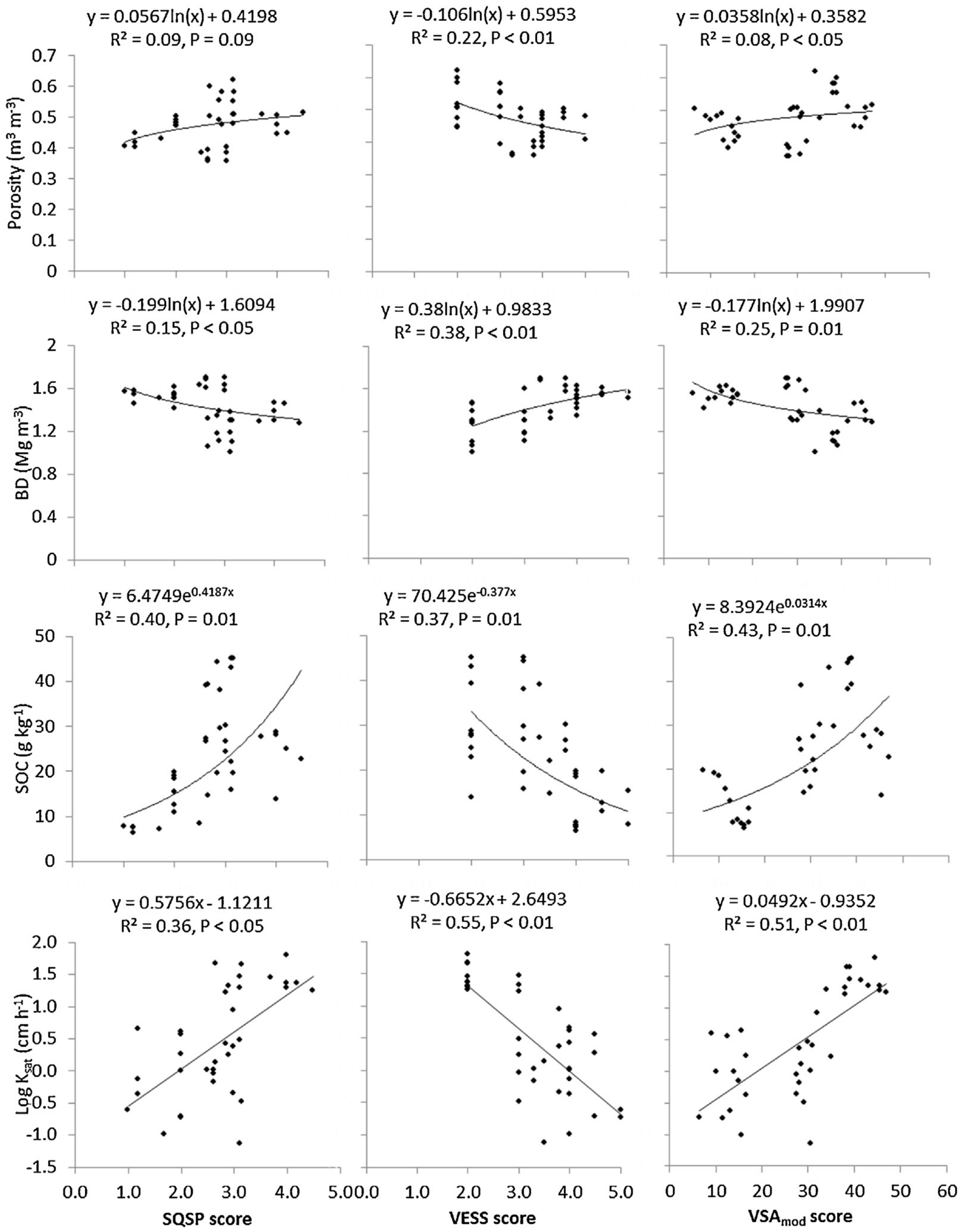

Fig. 3. Relationships between the visual field assessment scores (SQSP, VESS and VSA_{mod}) and the soil physical properties measured in the laboratory: porosity, bulk density (BD), soil organic carbon (SOC), and saturated hydraulic conductivity (Ksat). Threshold values of soil physical properties such as BD $>$ 1.4 Mg m^{-3}, SOC $<$ 25 g kg^{-1} and log Ksat $<$ 0.5 cm h^{-1} correspond to a deterioration of the soil structural quality (SQSP $<$ 3, VESS $>$ 3 and VSA_{mod} $<$ 30) of the Venezuelan 'tropical' soils under study.

by Mueller et al. (2013). Who found the worst structure status on soils characterized by imperfect land drainage, continuous cereal growth, high intensity of tillage and traffic. Best scores of the visual structure were given for properly managed soils with reduced tillage, crop rotation, and low traffic intensity.

In this study it was confirmed that simple indicators allow the evaluation of the compaction status of soils. These indicators were the presence of clods, high rupture resistance, lower porosity into aggregate's faces, limitation of root growth, change in aggregate shape as well as the difficulty to extract the soil block and to break down the soil block into aggregates. The three visual field assessments were capable to distinguish between compacted soils and well-structured soils (Table 3). This supports that the identification of soil compaction can be conducted directly in the field as was mentioned by Batey and McKenzie (2006).

In general, the VESS and VSA scores indicated that the samples of soils under no tillage had a 'good' soil structural quality (Tables 2 and 3). On the other hand, soils under conventional tillage or trampling showed a detrimental impact on soil structure. In all cases, VESS scores indicated a better soil structural quality in the upper layer (0–50 or 100 mm). This is consistent with a general understanding of the influence of the agricultural activities on soil structural quality. Differences in structural quality of layers and under different soil tillage have been mentioned by other authors (Shukla et al., 2003; Askari et al., 2013).

Conclusions about the effects of land use, vegetation type, root growth stage and soil management cannot be drawn from our data

Table 7
Relationships between field assessment scores and the *S* index and the structural stability index (StI), which have been used as soil quality indicators.

Relationship	Equation	R^2	Significance	*n*
S index vs. SQSP score	S index = 0.002SQSP + 0.0394	0.05	NS	36
S index vs. VESS score	S index = −0.0015VESS + 0.0499	0.03	NS	36
S index vs. VSA_{mod} score	S index = 0.0002VSA + 0.0406	0.06	NS	36
StI vs. SQSP score	$\text{StI} = 1.5082e^{0.4621\text{SQSP}}$	0.40	$P < 0.01$	36
StI vs. VESS score	$\text{StI} = 28.476e^{-0.507\text{VESS}}$	0.55	$P < 0.01$	36
StI vs. VSA_{mod} score	$\text{StI} = 1.7081e^{0.0404\text{VSA}}$	0.59	$P < 0.01$	36

SQSP, soil quality scoring procedure method; VESS, visual evaluation of soil structure method; VSA_{mod}, visual soil assessment method modified; NS, not significant.

set because of differences in other factors that affect soil structural quality such as drainage, climate, pedogenesis, as well as the possible interaction between them. However, the study demonstrates the utility of field assessment for visually identifying soil structural quality.

4.2. Validity of the methods based on their relationships with soil physical properties of soil structure

Results confirm the hypothesis that in these 'tropical' Venezuelan soils, there are also associations between the visual scores and soil physical properties as have been reported for 'temperate' soils (Mueller et al., 2009, 2013; Guimaraes et al., 2011; Murphy et al., 2013). In this study, significant relations between porosity, BD, SOC, and Ksat with SQSP, VESS and VSA were found. However, it should be emphasized that these relationships were stronger ($P < 0.01$, $r > 0.4$, $R^2 > 0.4$) with the VESS and VSA (Table 6 and Fig. 3) than with the SQSP method.

These relationships indicate that the visual field assessments can evaluate soil structure degradation by compaction, which is related to a decrease in SOC, an increase in BD and consequently decreasing in continuity of soil pores and reduction in permeability (Ksat). It can be postulated that from comparing the different graphs of Fig. 3, the evaluated soils presented deterioration of the soil structure when the BD is higher than 1.4 Mg m^{-3}, SOC is lower than 25 g kg^{-1}, and log Ksat is lower than 0.5 cm h^{-1}.

In temperate conditions, Mueller et al. (2009) also found similarity between soil physical properties (SOC, BD, AC and penetration resistance) with soil scores of visual field assessments based on the Peerlkamp method (Ball and Douglas, 2003), VSA and FAO description (FAO, 2006). Shepherd and Park (2003) found close correlations between the VSA score of soil structure and soil properties such as dry aggregate size distribution, Ksat, air permeability, macropores, BD and aggregate stability, which made them to conclude that 'we can see what we measure'. Apparently, in both 'tropical' and 'temperate' soils visual field assessments are similar to measured BD, SOC and Ksat.

According to Newell-Price et al. (2013), the advantage of visual field assessments is that it is possible to summarize in a simple score the overall soil structure condition of a block of soil, as well as to rapidly identify restrictive layers. Visual field assessments provide more information than quantitative methods such as BD, porosity and air permeability. On the other hand, measuring these soil physical properties have the advantage of providing quantitative data at specific depths, which would be difficult to obtain using visual evaluation alone.

Visual scores were well associated with the relation SOC-texture present in the soils (StI). Evidence of this is the significant exponential relations (Table 7) and strong correlations (Table 6) between the visual scores and the StI. However, no-relations were found when visual scores and indicators calculated from SWRC, such as *S* index, AC, RWC, and PAWC, were compared. Our results suggest that the visual soil quality of the soils under study is more related to water movement than water retention parameters. Mueller et al. (2009) mentioned that characterization of physical soil quality by a single indicator like the *S* index of Dexter (2004) is an extreme simplification of soil physical processes and the results can be biased.

For revealing the pore network in its entirety, Boizard et al. (2013) stated that a micro-morphological assessment (analysis of images) enables to obtain detailed information about characterization of cracks and the macropore network for a more effective description of the functioning of soil and root growth.

4.3. Adjustment of the visual assessments for tropical soils

In each soil of this study the visual field assessment was conducted when the soils were close to FC, moist or suitable for grazing or cultivation, and when the temperature was low compared to the maximum peak at noon time. Such conditions are necessary to obtain a good evaluation of number of earthworms (NE) according to Araujo and López-Hernández (1999). When VSA was used for assessing the soil structural quality of the Venezuelan 'tropical' soils, constraints were found when using the rating of NE of the method. The 'poor' visual scores (Table 4) given to the NE found in the Venezuelan 'tropical' soils, and the no significant correlation between the NE scores with all the overall scores of visual assessments as well as with the soil physical properties (Table 5), suggest that the scores given by Shepherd (2009) based on conditions in New Zealand, are not necessarily generally valid, and do at least not apply for the tropical conditions in the Venezuelan study area.

According to the values reported for savannah (30 individual m^{-2}) and agricultural organic systems in savannah (145 individual m^{-2}) in Venezuela (Araujo and López-Hernández, 1999), V1 and V2 present a large NE. Table 8 shows a modified ranking of NE proposed from the Venezuelan study area, based on the density of earthworms found in the studied soils, which provides a significant correlation of the modified visual score of NE with other indicators (Table 5). However, there is no a noticeable increase in the relationship of the soil physical properties and the recalculated overall score of the VSA (VSA_{mod} in Table 5).

The results in terms of soil quality from the SQSP method were not generally supported by the other visual methods and measured soil physical properties (Tables 3, 5 and 6). This method required modification for evaluating structural condition of soils under fallow or natural vegetation because of the difficulty in evaluating the root system. Regarding the VSA, this comprises the evaluation of the potential rooting depth in spite of the root system condition (distribution, quantity, bending and thickening), which on the one hand is an advantage, compared to the SQSP, when the field assessment is conducted at an early crop stage or in soils without crop production where the evaluation of the rooting system is not possible. But on the other hand, the evaluation of the potential rooting depth in the VSA needs more effort and time, especially in heavy soils. Therefore, the use of other well-known indicators for root growth evaluation such as the root length density (Tennant, 1975) or the root distribution (profile wall method by Böhm, 1979) is recommended for visual examination in heavy soils.

Table 8
Earthworm numbers and species present in the soil blocks evaluated for Venezuelan 'tropical' soils.

Soils	Density of earthworms (individual m^{-2})				Number of species[b]	Visual score of VSA	Modify visual score of VSA[c]
	Mean	Standard deviation	Max[a]	Min[a]			
V1	196	196	525	0	1	0	1.0
V2	196	58	250	125	1	0	1.3
V3	8	13	25	0	1	0	0
V4	13	14	25	0	1	0	0
V5	117	133	375	0	1	0	0.8
V6	0	0	0	0	0	0	0

VSA, visual soil assessment.

[a] Max and min = the largest and the smallest values of the number of earthworms in the first 20 cm of soil.

[b] Only one specie was present in each soil or at least earthworms with the same colour and appearance.

[c] Visual scores given by using ranking of earthworm numbers per block of soil based on the density of earthworms present in the evaluated soils. Visual scores: 2 = >10, 1.5 = 8–10, 1 = 5–7, 0.5 = 4–2, 0 = <2.

Finally, from the practical point of view, the time to perform each method is variable. This depends on the difficulty in extracting and breaking up the soil block as well as the identification of the features. The quickest method was VESS, followed by SQSP and VSA. The lower the number of features present in the soil, the less the time needed.

5. Conclusions

The SQSP, VESS and VSA were suitable for differentiating the soil structural quality of different agricultural tropical soils. For some soil conditions, the SQSP tends to overestimate the soil structural quality, and it is not sensitive enough when limitations in the evaluation of rooting system are present. In order to improve the accuracy of the VSA under tropical conditions, the rating of biological parameters such as earthworm number has to be adapted to the local condition. The scores obtained by the visual methods showed relationships with physical properties or indicators of soil quality measured in the laboratory such as bulk density, soil organic carbon and saturated hydraulic conductivity. This provided evidence of 'poor' or 'good' condition of soil structure to soil functioning from simple visual observations. In conclusion, the acceptable performance of these visual field assessments on 'tropical' Venezuelan soils with contrasting soil type and land use allows suggesting them as alternative complementary rapid field methods for assessing structural quality of 'tropical' soils.

Acknowledgements

This research was supported in part by the Consejo de Desarrollo Científico y Humanístico (CDCH) of the UCV and with the cooperation of the laboratory of the Department of Soil Management, Ghent University, Belgium. The support of Gustavo Rodriguez, Jacqueline Saddy and Egli Castillo from the Agronomy Faculty of the Universidad Central de Venezuela (UCV) in the field work is gratefully acknowledged. The authors are also grateful to the anonymous referees for their helpful comments and suggestions.

References

Araujo, Y., López-Hernández, D., 1999. Caracterización de las poblaciones de lombrices de tierra en un sistema de agricultura orgánica ubicado en una sabana en el Amazonas venezolano. Ecotropicos 12 (1) 49–55.

Askari, M.S., Cui, J., Holden, N.M., 2013. The visual evaluation of soil structure under arable management. Soil & Tillage Research 134, 1–10.

Balarezo Giarola, N.F., da Silva, A.P., Tormena, C.A., Guimaraes, L.R.M., Ball, B.C., 2013. On the visual evaluation of soil structure: the Brazilian experience in oxisols under no-tillage. Soil & Tillage Research 127, 60–64.

Ball, B.C., Batey, T., Munkholm, L.J., 2007. Field assessment of soil structural quality – a development of the Peerlkamp test. Soil Use and Management 23, 329–337.

Ball, B.C., Douglas, J.T., 2003. A simple procedure for assessing soil structural, rooting and surface conditions. Soil Use and Management 19, 50–56.

Batey, T., 2000. Soil profile description and evaluation. In: Smith, K.A., Mullins, C.E. (Eds.), Soil and Environmental Analysis: Physical Methods. 2nd ed. Marcel Dekker, Inc., New York, pp. 595–628.

Batey, T., McKenzie, D.C., 2006. Soil compaction: identification directly in the field. Soil Use and Management 22, 414.

Böhm, W., 1979. Methods of Studying Root Systems. Ecological Studies, vol. 33. Springer, Berlin, Heidelberg/New York.

Boizard, H., Yoon, S.W., Leonard, J., Lheureux, S., Cousin, I., Roger-Estrade, J., Richard, G., 2013. Using a morphological approach to evaluate the effect of traffic and weather conditions on the structure of a loamy soil in reduced tillage. Soil & Tillage Research 127, 34–44.

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3–22.

Cornelis, W.M., Khlosi, M., Hartmann, R., Van Meirvenne, M., De Vos, B., 2005. Comparison of unimodal analytical expressions for the soil–water retention curve. Soil Science Society of America Journal 69, 1902–1911.

Dexter, A.R., 2004. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120, 201–214.

FAO, 2006. Guidelines for Soil Description. Available at: ftp://ftp.fao.org/agl/agll/docs/guidel_soil_descr.pdf (accessed 12.2012).

Guimaraes, L.R.M., Ball, B.C., Tormena, C.A., Balarezo Giarola, N.F., da Silva, A.P., 2013. Relating visual evaluation of soil structure to other physical properties in soils of contrasting texture and management. Soil & Tillage Research 127, 92–99.

Guimaraes, R.M.L., Ball, B.C., Tormena, C.A., 2011. Improvements in the visual evaluation of soil structure. Soil Use and Management 27, 395–403.

Kerebel, A., Holden, N.M., 2013. Allocation of grass fields to Hybrid Soil Moisture Deficit model drainage classes using visual indicators. Soil & Tillage Research 127, 45–59.

Kodesova, R., Jirku, V., Kodes, V., Muehlhanselova, M., Nikodem, A., Zigova, A., 2011. Soil structure and soil hydraulic properties of Haplic Luvisol used as arable land and grassland. Soil & Tillage Research 111, 154–161.

Lal, R., Shukla, M.K., 2004. Principles of Soil Physics. Marcel Dekker, New York, ISBN: 0-8247-5324-0, pp. 716.

McGarry, D., 2006. A Methodology of a Visual Soil Field Assessment Tool to Support, Enhances, and Contributes to the LADA Program. 50 pp.FAO, Roma. , In: ftp://ftp.fao.org/agl/agll/lada/vsfast_methodology.pdf (accessed 19.05.11).

McKeague, J.A., Wang, C., Coen, G.M., 1986. Describing and interpreting the macrostructure of mineral soils – a preliminary report. Technical Bulletin, 47 pp. 1986-2E. LRRI contribution 84-50.

McKenzie, D.C., 2001. Rapid assessment of soil compaction damage – I. The SOILpak score, a semi-quantitative measure of soil structural form. Australian Journal of Soil Research 39, 117–125.

McKenzie, D.C., 2013. Visual soil examination techniques as part of a soil appraisal framework for farm evaluation in Australia. Soil & Tillage Research 127, 26–33.

Mueller, L., Kay, B.D., Hu, C., Li, Y., Schindler, U., Behrendt, A., Shepherd, T.G., Ball, B.C., 2009. Visual assessment of soil structure: evaluation of methodologies on sites in Canada, China and Germany. Part I: Comparing visual methods and linking them with soil physical data and grain yield of cereals. Soil & Tillage Research 103, 178–187.

Mueller, L., Shepherd, G., Schindler, U., Ball, B.C., Munkholm, L.J., Hennings, V., Smolentseva, E., Rukhovic, O., Lukin, S., Hu, C., 2013. Evaluation of soil structure in the framework of an overall soil quality rating. Soil & Tillage Research 127, 74–84.

Munkholm, L.J., 2000. The spade analysis – a modification of the qualitative spade diagnosis for scientific use. DIAS-report No. 28. Plant Production, Danish Institute of Agricultural Sciences.

Munkholm, L.J., Heck, R.J., Deen, B., 2013. Long-term rotation and tillage effects on soil structure and crop yield. Soil & Tillage Research 127, 85–91.

Murphy, B.W., Crawford, M.H., Duncan, D.A., McKenzie, D.C., Koen, T.B., 2013. The use of visual soil assessment schemes to evaluate surface structure in a soil monitoring program. Soil & Tillage Research 127, 3–12.

Newell-Price, J.P., Whittingham, M.J., Chambers, B.J., Peel, S., 2013. Visual soil evaluation in relation to measured soil physical properties in a survey of grassland soil compaction in England and Wales. Soil & Tillage Research 127, 65–73.

Pagliai, M., Vignozzi, N., Pellegrini, S., 2004. Soil structure and the effect of management practices. Soil & Tillage Research 79, 131–143.

Peerlkamp, P.K., 1959. A visual method of soil structure evaluation. Meded. v.d. Landbouwhogeschool en Opzoekingsstations van de Staat te Gent XXIV (24) 216–221.

Pieri, C.J.M.G., 1992. Fertility of Soils: A Future for Farming in the West African Savannah. Springer-Verlag, Berlin, Germany.

RETC (RETention Curve), 2008. RETC Model. USDA-ARS U.S. Salinity Laboratory, Riverside, CA. , In: http://ars.usda.gov/Services/docs.htm?docid=8952.

Roger-Estrade, J., Richard, G., Caneill, J., Boizard, H., Coquet, Y., Defossez, P., Manichon, H., 2004. Morphological characterisation of soil structure in tilled fields: from a diagnosis method to the modelling of structural changes over time. Soil & Tillage Research 79, 33–49.

Scholefield, D., Patto, P.M., Hall, D.M., 1985. Laboratory research on the compressibility of 4 topsoils from grassland. Soil & Tillage Research 6, 1–16.

Shepherd, T.G., 2009. Visual Soil Assessment. Volume 1. Field Guide for Pastoral Grazing and Cropping on Flat to Rolling Country, 2nd ed. Horizons Regional Council, Palmerston North 119 pp.

Shepherd, T.G., Park, S.C., 2003. Visual soil assessment: a management tool for dairy farmers. In: Brookes, I.M. (Ed.), Proceedings of the 1st Dairy 3 Conference. Continuing Massey University Dairy farming Annual (Volume 55) Dexcel's Ruakura Dairyfarmers' Conference, April 7–9, Rotorua, pp. 111–123.

Shukla, M.K., Lal, R., Ebinger, M., 2003. Tillage effects on physical and hydrological properties of a typic argiaquoll in Central Ohio. Soil Science 168, 802–811.

Soil Survey Staff., 2010. Keys to Soil Taxonomy, 11th ed. USDA-Natural Resources Conservation Service, Washington, DC.

SPSS Inc., Chicago, USA.

Tavares, J.F., Ralisch, R., Guimaraes, M.F., Medina, C.C., Balbino, L.C., Neves, C.S.V.J., 1999. Método do perfil cultural para avaliação do estado físico de solos em condições tropicais. Revista Brasileira de Ciencia do Solo 23, 393–399., In: http://sbcs.solos.ufv.br/solos/revistas/v23n2a22.pdf.

Tennant, D., 1975. A test of a modified line intersect method of estimating root length. Journal of Ecology 63, 955–1001.

van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892–898.