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Visual soil examination and evaluation in the sub-humid and semi-arid regions of Kenya

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ABSTRACT

Soil quality is indicated by the interaction of physical, chemical and biological soil properties. The importance of physical properties, for example soil structure, lies in the fact that they enhance chemical and biological soil functions. Consequently, periodic assessment of structural quality is an important aspect of soil quality management. Quantitative soil properties can be used as indirect indicator parameters for soil structural changes. However, measuring these properties is not applicable, especially for smallholder farmers who cannot afford to pay for laboratory tests. This study contributes to the validation of visual field assessments by comparing the performance of such methods on 'tropical' soils. The study was conducted across two regions with contrasting soil types and land use, in the sub-humid with clay Nitiosl and semi-arid with sandy loam Cambisol locations of Kenya. At both locations, visual methods were tested on soils under cropland and under natural forests (NF). Under the cropland, evaluation sites were selected from researcher and farmer managed sites. Visual scores from visual soil assessment (VSA), visual evaluation of soil structure (VESS) and visual evaluation of soil structure using the core (coreVESS) were correlated with soil physical and chemical properties measured in the laboratory. Under the clay Nitisol, absolute values of Pearson r between VSA scores and laboratory measured soil properties ranged from 0.84 to 0.54, for VESS, they varied between 0.75 and 0.37 while for coreVESS, they ranged from 0.84 to 0.60. For the sandy loam Cambisol, absolute Pearson r values between laboratory measured soil properties and VSA scores ranged from 0.83 to 0.29, the r values were between 0.88 and 0.45 for VESS and between 0.81 and 0.40 for coreVESS. From the obtained correlations, we concluded that the visual methods tested are capable of distinguishing structural quality due to different land use and are therefore suitable for assessing soil structural quality of tropical soils in Africa. Management thresholds were determined using bulk density (BD). The target value for good soil quality ($Sq<2$) for the Kibugu Nitisol was $BD = 0.0012*SOC+0.6476$ ($r = 0.71$; SOC is soil organic carbon), while the trigger and remediation values were 0.93 Mg m^{-3} ($Sq = 2$) and 0.99 Mg m^{-3} ($Sq = 3$), respectively. In the absence of SOC data, the target mean BD for $Sq<2$ is 0.79 Mg m^{-3}. For Machang'a Cambisol, the target, trigger and remediation values were 1.48 Mg m^{-3} ($Sq = 2$), 1.56 Mg m^{-3} ($Sq = 3$) and 1.64 Mg m^{-3} ($Sq = 4$), respectively.

1. Introduction

In Kenya, crop production systems are characterised by continuous soil tillage, low use of fertilizer inputs and consequently low soil quality. This process, over time, has led to physicochemical soil quality degradation, giving low crop yields. Strategies aimed at soil quality improvement are therefore needed. Optimal soil quality is indicated by the interaction of physical, chemical and biological soil properties (Knight et al., 2013; Reynolds et al., 2009). For example, soil structure, a major physical property, controls many chemical and biological functions of the soil (Guimarães et al., 2017; Reynolds et al., 2009; Dexter, 2004). A good soil structure improves soil fertility and hence increases crop yields (Pulido Moncada et al., 2017). According to Kay and Angers (2001), soil structure can be described in terms of: (i) structural form,

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the heterogeneous arrangement of pores and solids at any given time; (ii) structural stability, the ability of soil to retain its structural form after exposure to stress; and (iii) structural resilience: the ability of soil to recover its structural form through natural processes. Consequently, periodic assessment of the three structural parameters is important as it offers a means of establishing the state of soil aggregation, allowing for soil quality improvement interventions where necessary.

Quantitative soil properties like bulk density, air permeability, penetration resistance, infiltration rate, soil water retention curve and related soil physical quality indicators can be used as indirect indicator parameters for soil structural changes (Cherubin et al., 2017; Reynolds et al., 2009; Lal and Shukla, 2004). However, measuring these properties is not applicable in all circumstances and especially not for smallholder farmers who cannot afford to pay for laboratory tests (Newell-Price et al., 2013). For this reason, Visual Soil Examination and Evaluation (VSEE) methods have been developed for use in circumstances where laboratory tests are not possible (Newell-Price et al., 2013).

VSEE methods allow for soil structure assessment directly in the field, require little equipment, are inexpensive and give immediate results (Ball et al., 2017; Guimarães et al., 2017). Additionally, these methods can be easily used by non-soil experts like extension officers and farmers, helping them make soil management decisions on the spot (Ball et al., 2007) by comparing soil quality (Sq) scores with threshold values. On the other hand, disadvantages of these 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 soil block extraction results in the destruction of significant area on the farm (Balarezo Giarola et al., 2013; Kerebel and Holden, 2013).

VSEE techniques are classified into 'spade' and 'profile' methods (Mueller et al., 2009). Spade methods are based on the extraction of a soil block using a spade allowing structural evaluation up to 0.5 m. On the other hand, profile methods require mechanical excavation of soil profiles allowing structural evaluation up to 1.5 m depth. As such, the spade tests are quicker and can be done in the field more often to assess a greater number of blocks, whereas, profile tests are more time consuming and a more limited number of point assessments can be done (Emmet-Booth et al., 2016). As such, the profile methods evaluate different soil profiles. These methods provide detailed lateral and vertical information about specific sample points. On the other hand, spade methods evaluate up to 50 cm deep, require a spade for soil exposure and indicate structural quality more quickly over wide spatial area (Emmet-Booth et al., 2019). Widely used examples of spade methods are VSA (Visual Soil Assessment) (Mueller et al., 2013; Shepherd, 2009) and VESS (Visual Evaluation of Soil Structure) (Ball et al., 2007). The coreVESS method (Visual Evaluation of Soil Structure on intact soil cores) is adopted from the field VESS method (Johannes et al., 2017). Under coreVESS, the same soil sample in a core is used for laboratory measurements as well as for visual evaluation. The advantage of the coreVESS method compared to spade methods is that samples are visually evaluated at standardized moisture conditions, which is nearly impossible to achieve in the field. As such, the influence of soil moisture on structure scores is minimized. The CoreVESS method enables the evaluation of soil at depths deeper than with the spade method. VSEE examination procedures differ in the way the soil is handled prior to assessment, the assessment depth and scoring criteria. Nevertheless, they all evaluate anthropogenic effects on soil structure (Franco et al., 2019) by focusing on Kay & Angers' (2001) first property, structural form, which describes the size, shape, breaking strength and visible porosity of aggregates (Ball et al., 2007; Mueller et al., 2009).

In the tropical region, VSEE methods have been evaluated under Ferrasols (Cornelis et al., 2019; Cherubin et al., 2017; Guimarães et al., 2017, 2011; Giarola et al., 2010), Acrisol (Guimarães et al., 2011; Pulido Moncada et al., 2014a), Luvisol and Lixisol (Pulido Moncada et al., 2014a), and Ultisols (Cherubin et al., 2017). In the temperate regions, evaluation of VSEE methods on Cambisol has been reported (Johannes et al., 2017; Pulido Moncada et al., 2014b; Guimarães et al., 2013). It has been concluded that VSEE methods are of sufficient sensitivity to detect changes in structural quality of soil resulting from differences in land use. This demonstrates their potential for direct on-farm assessment. Given that the correlation between visual observations and field or laboratory measurements are often soil type dependent (van Leeuwen et al., 2018), there is still need to validate the VSEE methods for other tropical soil types. This study therefore focused on evaluating the applicability of these methods on tropical Nitosols and Cambisols.

Even though the relationship between cropping practices and yield is complex and yield reduction can result from limitations other than soil structural quality, studies from temperate Luvisols (Mueller et al., 2009; Munkholm et al., 2013), temperate Vertisol (Çelik et al., 2019) and tropical Oxisols (Giarola et al., 2013) have reported correlations between visual methods and crop yields. Focusing on tropical Nitisols and Cambisols, this study aims to i) investigate the applicability of VSEE methods (VSA, VESS and coreVESS) in evaluating and detecting changes in soil structure differences resulting from different land use (natural forest and cropland) and management (Conservation Agriculture, CA and Integrated Soil Fertility Management, ISFM based practices), ii) evaluate if VSEE scores are correlated with individual quantitative soil quality parameters and which parameter best explains the scores, iii) determine whether VSEE scores are correlated with maize grain yield and iv) explore possibilities for maintaining good soil quality and improving moderate to poor soil quality. With good correlations, the authors could be able to give concrete recommendations to those interested in using VSEE methods in tropical Africa. It is hypothesized that i) the VSEE methods will be able to detect changes in soil structure resulting from different land and management ii) the VSEE scores will correlate strongly with quantitative soil parameters and iii) VSEE scores will correlate with maize grain yield.

2. Materials and methods

2.1. Study area and experimental design

This study was conducted in Embu county of Kenya which has contrasting agro-ecologies. More specifically we selected a sub-humid (Kibugu, 0°26′S and 37°26′E) and semi-arid (Machang'a, 0°46′S and 37°39′E) location. Rainfall in both areas is bimodal with two distinct seasons: long rains lasting from March to June and short rains lasting from October to December. Kibugu is located at an altitude of 1543 m above sea level. Long-term mean rainfall is 521 and 354 mm for the long and short rains, respectively. Machang'a is at 1106 m above sea level with a long-term mean rainfall of 333 and 302 mm for the long and short rains, respectively. The soil type was Nitisol with clay texture and Cambisol with sandy loam texture, in Kibugu and Machang'a, respectively (WRB, 2006). The characteristics of the soils under study is given in Table 1.

At both locations, VSEE methods were tested on cropland and natural forest. Under the cropland, evaluation sites were selected from researcher and farmer managed sites. The researcher managed sites (r) had maize monocrop trials established under four treatments, (i) conventional farming with no inputs, rCT, (ii) no tillage with mulch and use of fertilizer, rNTF, (iii) conventional farming with use of fertilizer and manure, rCTFM and (iv) no tillage with mulch and use of fertilizer and manure, rNTFM. The treatments were randomly laid down following a one farm one replicate design. At the start of the experiment, seedbeds for plots under tillage (rCT and rCTFM) were prepared by hand hoeing up to 15 cm, while plots under no tillage (rNTF and rNTFM) were sprayed with a non-selective herbicide (Wipeout, Juanco SPS limited), at an application rate of 1.0 L ha^{-1} to clear all weeds. Maize was planted in plots of size 0.75 × 0.25 m in sub-humid Kibugu and 0.90 × 0.30 m in semi-arid Machang'a (Mucheru-Muna et al., 2010). Plots under rNTF,

Table 1
Mean values of basic soil properties with standard deviations in parentheses of the two soils under study. pH (H_2O), soil pH in water (1:5); soil organic carbon (SOC); total nitrogen (TN), Resin-P, available phosphorus; exchangeable potassium (Exch K); bulk density (BD) texture and texture (clay, silt and sand).

Soil property	Clayey Nitisol	Sandy loam Cambisol
pH-H_2O	5.7 (0.2)[b]	6.9 (0.6)[a]
SOC (g kg^{-1})	19.2 (4.3)[a]	6.2 (3.8)[b]
TN (g kg^{-1})	2.2 (1.2)[a]	0.7 (0.4)[b]
TP (g kg^{-1})	1.3 (0.2)[a]	0.1 (0.0)[b]
Resin-P (mg kg^{-1})	16.5 (21.4)[a]	7.5 (9.6)[a]
Exch. K (mg kg^{-1})	0.4 (0.2)[a]	0.7 (0.4)[a]
BD (Mg m^{-3})	0.9 (0.0)[b]	1.5 (0.0)[a]
Clay (g kg-1)	747 (6.0)[a]	134 (5.5)[b]
Silt (g kg-1)	158 (4.5)[a]	125 (2.6)[b]
Sand (g kg-1)	88 (2.7)[b]	747 (5.9)[a]

Values indicated with the same letter are not significantly different between the Nitisol and Cambisol.
Upper case A and B are used to show significant differences in properties between treatments while lower case a and b show significant differeces in properties between top and sub layers.

rCTFM and rNTFM were fertilized with 80 kg N ha^{-1} (Urea), 30 kg P ha^{-1} (Triple Super Phosphate) and 40 kg K ha^{-1} (Muriate of Potash) every growing season. Split applications were used for N: 40 kg N ha^{-1} at planting and top dressed at the same rate 6 weeks after planting. Fully decomposed cow manure containing 2.1 % N was applied at 2 t ha^{-1} on plots under rCTFM and rNTFM on a furrow during planting. Two weeks after germination, maize stover mulch was applied on the plots under rNTF and rNTFM to achieve ~30 % soil cover. Weeding was performed twice per season using a hand hoe for plots under tillage and a selective herbicide (Tingatinga, Geneva agrochemical limited) at an application rate of 1.5 L ha^{-1} for plots under no tillage. Army worms were controlled by preventive and curative spraying two to three times per season using Volium Targo pesticides, Syngenta, at an application rate of 0.5 L ha^{-1}.

The farmer managed sites (f) involved maize mono-cropping with ox plough and hand hoe to a depth of 30 cm in Machang'a and 15 cm in Kibugu, hereby termed as (fCT). In addition, farmer managed perennial cash crops (fP), *Cathe edulis* commonly known as 'miraa', under hand hoeing up to 30 cm in Machang'a was investigated. In Kibugu, on the other hand, perennial cash crop included *Coffea arabica* commonly known as 'kahawa' under hand hoeing up to 30 cm.

While the farmer managed sites have been in existence for more than ten years, the researcher managed sites were established in 2017 and had been, at the time of this study running for four consecutive seasons. Farmer managed maize monocrops mostly received no inputs while the perennial cash crops received calcium ammonium nitrate and manure at irregular intervals and irregular rates. Table 2 shows a summary of management systems involved. Natural forests, NF, in the sub-humid Kibugu were mainly primary forest classified as indigenous forests. They consisted of native species with no human intervention such that their ecological processes were intact and not significantly disturbed. The semi-arid Machanga on the other hand was characterized by shrubs. The forests were not protected, they were open and used for free-range livestock rearing.

2.2. Soil sampling

From each location, Kibugu and Machang'a, soil samples were collected from 31 sites making a total of 62 sampling points (Table 2). In each site, next to the visually evaluated pit, one undisturbed sample per depth and a composite disturbed soil samples were collected in December 2018 from 0 to 15 cm and 15–30 cm, representing top layer and sub layer, respectively. The disturbed samples were taken with a soil auger in three positions around the pit. These depths were chosen based on the observation that in our study regions, maize crop had most of the roots concentrated in the top 15 cm and few roots below this depth. The undisturbed soil samples were collected using Kopecky rings of 5 cm inner diameter and 5.1 cm height with a volume of 100 cm^3 following the method described by Dirksen (1999). The disturbed samples were placed in sealed plastic bags while the undisturbed samples were placed in special metallic cases with shock absorbing foam to keep them intact. The samples were transported to Ghent University, Belgium for subsequent analysis.

2.3. Visual soil evaluation and examination

Soil blocks were used to evaluate soil structure in the field using VSA (Shepherd, 2009) and VESS (Ball et al., 2007; Guimarães et al., 2011) methods. In the laboratory, undisturbed soil cores of 100 cm^3 were used to evaluate soil structure using coreVESS as stipulated by Johannes et al. (2017). All visual soil evaluation was done on a top layer (0−15 cm) and sub layer (15−30 cm). Ball et al. (2007) suggested that layered evaluation of soil structure is important in making soil management decisions. As such, a layer with a score higher than Sq 4 is limiting for growth and requires management attention. Soil blocks extraction and evaluation as well as soil sampling was done when soil was near field capacity. All scoring in the field was done by two experienced persons. During the scoring process, agreement in scores given by the two people occurred in approximately 70 % of the times. In the 30 % where given scores was different between the two people, an average of the two scores was assigned.

2.3.1. Visual soil assessment (VSA)

One soil block per layer, 15 cm deep, 20 cm thick and 20 cm wide was extracted and put on a plastic bag. As suggested by Shepherd (2009), clayey soils from Kibugu were dropped a maximum of three times from 1 m height in a plastic basin while clods from the sandy loam in Machang'a were dropped once from a height of 0.5 m height. VSA indicators assessed were; soil texture, soil structure, soil porosity, number and colour of soil mottles, soil colour, earthworms and soil

Table 2
Involved land use and management systems.

Site type	Management system	Tillage system	Inorganic fertilizer	Organic inputs	Soil cover	Sampled sites	
						Kibugu	Machang'a
Researcher managed	rCT	Conventional	0	0	0	5	5
	rNTF	No tillage	$N_{80}P_{30}K_{40}$	0	Maize stover (30 %)	5	5
	rCTFM	Conventional	$N_{80}P_{30}K_{40}$	Manure (2 t ha^{-1})	0	5	5
	rNTFM	No tillage	$N_{80}P_{30}K_{40}$	Manure (2 t ha^{-1})	Maize stover (30 %)	5	5
Farmer managed	fCT	Conventional	0	$Manure_{Irre}$	0	5	5
	fP	Conventional	CAN_{Irre}	$Manure_{Irre}$	0	3	3
Forest	NF					3	3

CT is conventional tillage, NTF is no tillage with use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with use of fertilizer and manure, P is perennial crop, NF is natural forest, r and f represent researcher and farmer managed sites, respectively, $N_{80}P_{30}K_{40}$ is 80 kg nitrogen ha^{-1}, 30 kg phosphorus ha^{-1} and 40 kg potassium ha^{-1}, respectively, CAN_{Irre} and $manure_{Irre}$ is calcium ammonium nitrate and manure at irregular interval and irregular rates, respectively.

smell. Potential rooting depth was not evaluated to avoid destruction of area in the experimental plots given that the evalaution was done during the crop growing period. Scores for each individual indicator were given by comparing the soil with reference photographs as described in the VSA manual (Shepherd, 2009). Each indicator was scored as VS of 0 (poor), 1 (moderate), 2 (good), or in-between (0.5 = moderately poor and 1.5 = moderately good) in respect to reference photos. The scores for each attribute were then weighted and summed up to derive a final overall score for soil structural quality following Shepherd (2009). VSA scores were assigned per layer and the overall block layer score was taken as the arithmetic mean of the two layers since we evaluated two layers of same depth (15 cm). Soils with a sum of visual scores ranking <20 have a poor soil quality, and soils with values >37 have a good soil quality. Values between these ranges are considered to be of a moderate soil quality. In our study as potential rooting depth was eliminated from the scoring, the threshold between moderate and good structural score dropped from 37 to 33.

2.3.2. Visual evaluation of soil structure (VESS)

VESS block extraction also involved two consecutive soil blocks, which allowed a deeper evaluation of contrasting layers than by using the standard VESS (Cornelis et al., 2019). The assessment of the soil blocks included manual break down of aggregates by hand and assessing the individual criteria, i.e. ease of breaking aggregates, size and appearance of aggregates and visible porosity. One overall score per block was then assigned based on an integrated appreciation of the individual criteria as suggested in the standard VESS (Ball et al., 2007). The blocks of soil were scored 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 overall score of the 30 cm soil block was determined by multiplying the score of each layer by its thickness and dividing the product by the overall depth (Ball et al., 2007). As we evaluated two layers of same depth (15 cm), the overall block layer score was taken as the arithmetic mean of the two layers. Under VESS-based methods, soils with scores below Sq 2 are of good structural quality, Sq 2–3 indicates moderate structural quality while Sq 4 and above indicates poor structural quality.

2.3.3. Visual Evaluation of Soil Structure on undisturbed soil samples (coreVESS)

The 100 cm^3 undisturbed soil samples were equilibrated at −100 hPa and used to perform the coreVESS according to Johannes et al. (2017). Similar to field VESS, soil assessment included manual break down of aggregates by hand and assessing the individual criteria, i.e. breaking difficulty, aggregate shape and visible porosity. For these three criteria, coreVESS scores from 1 to 5 were given as described in the score card by Johannes et al. (2017), where a score of 1 shows the best soil structure. Visual evaluation and examination was done on the same intact cores that were used for the analysis of quantitative soil properties (Johannes et al., 2017).

2.4. Soil shear strength

Top layer and sub layer shear strength was measured in the field using a pocket vane tester (Eijkelkamp Soil & Water, the Netherlands), with a measuring range of 0–250 kPa. To take measurements, the vane was placed on the pit wall. The meter was then turned by hand at a constant speed from zero in the direction of one until the head slipped back, leaving the arrow at the highest shear strength. To ensure constant meter turning speed, the measurements were done by the same person. Measurements were done concurrently with the visual soil evaluation when soil was near field capacity.

2.5. Laboratory analysis

For each site, one intact 100 cm^3 core per depth was used for several soil physical parameters analyses. First, the soil cores were gradually saturated in a tray. They were then transferred to a permeameter (Eijkelkamp Soil & Water, type 09.02.01.05) for measuring hydraulic conductivity (K_s) using the constant head method. The water discharge was measured until a constant flux enabling calculation of K_s (m d^{-1}) using Darcy's equation:

$$K_s = \frac{Q_w\, L}{A\ \Delta H} \tag{1}$$

where Q_w is the outflow of water through the soil core (m d^{-1}), L is the length of the soil core (m), A is the surface area of the soil core (m^2) and ΔH is hydraulic head difference (m H_2O).

After the K_s measurement, the samples were transferred to a sand box for measuring soil water retention curve as stipulated by Cornelis et al. (2005). Measurements at higher matric potential −10 hPa, −30 hPa, −50 hPa, −70 hPa and −100 hPa were made using the sand box apparatus (Eijkelkamp Soil & Water). The soil cores were then used for measuring air permeability (K_a) at −100 hPa using a steady-state in-house made air permeameter proposed by Grover (1955). Air permeability K_a (μm^2) was calculated as:

$$K_a = \frac{Q_a\, \eta_{a\,L}}{A\ \Delta\ P} \tag{2}$$

where Q_a is the outflow of air through the soil core (m s^{-1}), η_a is the air viscosity (Pa s or kg m^{-1} s^{-1}), L is the length of the soil core (m), and ΔP is the pressure head difference across the sample (m)

After measuring K_a, the samples were used for coreVESS analysis (as described in 2.3.3) and subdivided into three sub-samples for soil water content measurements at lower potentials of −330 hPa, −1000 hPa and −15000 hPa using pressure chambers (Soilmoisture Equipment, Santa Barbara CA, USA). As stipulated by Reynolds et al. (2007), water content at field capacity (FC) was taken at −100 hPa, matric porosity (MatPor) at −10 hPa and permanent wilting point (PWP) at −15000 hPa, while soil dry BD was determined as the mass of dry soil divided by the soil volume. Other soil properties used as soil quality indicators were derived from the soil water retention curve (Reynolds et al., 2009).

$$AC = \theta_s - \theta_{FC} \tag{3}$$

$$MacPor = \theta_s - MatPor \tag{4}$$

$$PAWC = \theta_{FC} - \theta_{PWP} \tag{5}$$

$$RWC = 1 - \frac{AC}{\theta_s} \tag{6}$$

where AC is air capacity, θ_s, θ_{FC}, and θ_{PWP} is the volumetric water content at saturation, field capacity and permanent wilting point, respectively, MacPor is macro porosity, MatPor is matric porosity, PAWC is plant available water content and RWC is relative water capacity.

From the collected disturbed samples, aggregate stability was measured by the fast wetting procedure outlined by Le Bissonnais (1996). Fast wetting was chosen based on its ability to evaluate a large range of soils as affected by rapid wetting, appropriate for tropical areas that experience heavy rainstorms (Le Bissonnais, 1996). Moreover, the fast wetting procedure has been shown to differentiate tropical soils under different management practices (Cornelis et al., 2019). Five grams of aggregates measuring 3−5 mm were put in an oven at 40 °C for 24 h to bring aggregates to the same wetness. They were then immersed in a 250 cm^3 beaker filled with 50 cm^3 of deionized water for 10 min. The soil materials were transferred into a 50 μm sieve previously immersed in ethanol. The soil materials from the 50 μm sieve were oven dried for 10 min to evaporate the ethanol and gently sieved on a column of sieves: 2000, 1000, 500, 200, 100 and 50 μm to determine the fragment size distribution. The aggregate stability was expressed by mean weight diameter (MWD), which is the sum of the mass fraction of soil remaining on each sieve after sieving multiplied by the mean aperture of the adjacent mesh. Soil organic carbon was determined using an elemental analyzer (ANCA-SL, PDZ Europa, UK) coupled to an IRMS (20−20, SerCon, UK).

2.6. Maize grain yield

Maize grain yield was determined when 75 % of plants in a trial had dried up. Total fresh weights were measured in the field and sub-samples (six maize cobs of different sizes) taken to the lab for oven drying. Grain productivity was calculated by multiplying the total fresh weight of cobs in a net plot with the proportion of dry kernels obtained from the sub-sampled cobs to the total fresh weight of the sub-sampled cobs.

2.7. Soil Quality Index (SQI) and management thresholds

Soil quality index was calculated using the individual soil quality indicators (SQi's) following the approach of Cornelis et al. (2019) as;

$$SQi' = \frac{SQi - SQi_{\min}}{SQi_{\max} - SQi_{\min}} \tag{7}$$

and consequently,

$$SQI = \sum_{i=1}^{n} \frac{SQi'}{n} \tag{8}$$

where the subscripts 'min' and 'max' refer to the minimum and maximum value for the specific SQi in our dataset, the prime ′ denotes the normalisation to a unit-less value, and n is the number of SQi's to calculate SQI. The SQI is an integrated score calculated from individual soil quality parameters. It is an aspect of soil structural quality that has been shown to be highly captured by visual evaluation and examination of soil structure (Cornelis et al., 2019). Soil structure degradation diagnosis requires a few, inexpensive and easy-to-perform analyses. As BD is one of the easily measurable parameters in most laboratories it was used to set target, trigger and remediation values to be used as management thresholds. In addition, the importance of BD parameter as an indirect indicator of aeration, strength, and ability to store and transmit water has been documented (Reynolds et al., 2009). As the correlations between coreVESS scores and SOC were both highly significant for the two soils types, i.e. r = 0.74 and r = 0.80 for Nitisol and Cambisol, respectively, BD was correlated with SOC. The management thresholds were calculated following the approach of Johannes et al. (2019).

2.8. Statistical analysis

All statistical computing and graphic design was carried out in the R environment (version 3.4.2.). A Shapiro-Wilk and Levene test was applied to test the normality and equality of variance, respectively. Differences between land use and management scores were evaluated through Anova and whenever significant differences occurred, their separation was done using Tukey's honest significance of difference. To enable detection of soil structural quality degradation occurring as a result of land use change, NF data was included in this analysis. The Pearson statistic was used to test the relationship between VSEE method scores as well as their relationship with measured and calculated soil physical parameters. For the latter, data from the cropland was used excluding NF whose values were treated as outliers for such an analysis. In addition, excluding NF from this analysis makes it possible for the researchers to determine the applicability of these methods only for cropland, which is important for the smallholder farmers. Relationship of VSEE scores with measured soil properties were evaluated by means of conditional inference tree (CTREE) analysis. One of the strengths of CTREE analysis is that the dependent variable is recursively partitioned following permutation and significance testing of splitting variables, which avoids bias in covariate selection (Hothorn et al., 2006). The covariates included in the CTREE analysis were: K_a, K_s, porosity, AC, shear strength and SOC under the two soil types. MWD was included under all the CTREEs except under VESS and coreVESS in the sandy loam Cambisol because it was not significantly correlated with those Sq scores. In the CTREE analysis, porosity was used in place of BD to use 'more is better' scoring criteria. All statistical differences were tested at $p < 0.05$.

3. Results

3.1. Soil structural quality under different land use and management

For cropland, both soil types gave Sq scores in the top and sub layer that were mostly significantly different under all VSEE methods, in contrast with NF where Sq at both depths was not different (Tables 3 and 4). In both soil types, the top layer showed a better soil quality compared to the sub layer. This was confirmed by measured soil parameters (Table 5), with most of the parameters being significantly different between top and sub layer. In both the top and sub soil, Sq values indicated that the soil structural quality ranged from moderate to good soil quality. None of the management practice resulted in Sq values of <20 under VSA, meaning the soils are not structurally poor. This was also the case under VESS-based methods with Sq values indicating good to moderate structural quality, with no poor structural quality category.

Under the Nitisol, NF had significantly better scores under VSA compared to the researcher managed improved systems (rNTF, rCTFM and rNTFM) both in the top layer ($p = 0.0001$) and sub layer ($p < 0.0001$). The improved management practices did not show significant difference in VSEE scores, which was reflected by the soil physical

Table 3
Mean top (0-15 cm) and sub (15-30 cm) layer structural quality (Sq) scores and standard error in parentheses for the clayey Nitisol under Visual Soil Assessment without considering rooting depth (Sq-r VSA), Visual Evaluation of Soil Structure (Sq VESS) and Visual Evaluation of Soil Structure using cores (Sq coreVESS) for different land use and management systems.

Method	Sq-r VSA		Sq VESS		Sq coreVESS	
Man / Depth	0−15 cm	15−30 cm	0−15 cm	15−30 cm	0−15 cm	15−30 cm
NF	38 (0)^{Aa}	35.3 (1.3)^{Aa}	1.2 (0.3)^{Ba}	1.7 (0.3)^{Ba}	1.0 (0)^{Ba}	1.5 (0)^{Ba}
rCT	**31.7 (1.2)^{BCa}**	**27.9 (0.8)^{BCb}**	1.9 (0.2)^{Ab}	2.7 (0.6)^{ABa}	2.0 (0)^{Ab}	2.8 (0.8)^{Aa}
rNTF	34.5 (2.1)^{Ba}	**29.6 (1.4)^{Bb}**	1.9 (0.2)^{Ab}	2.4 (0.4)^{ABa}	1.8 (0.3)^{Ab}	2.5 (0.5)^{ABa}
rCTFM	33.4 (2.9)^{Ba}	**28.9 (0.5)^{Bb}**	2.0 (0)^{Ab}	2.6 (0.4)^{ABa}	1.9 (0.2)^{Ab}	2.5 (0.5)^{ABa}
rNTFM	34.4 (1.4)^{Ba}	**29.9 (1.9)^{Bb}**	2.0 (0)^{Ab}	2.8 (0.6)^{ABa}	1.8 (0.3)^{Aa}	2.5 (0.6)^{ABa}
fCT	**29.8 (1.0)^{Ca}**	**26.6 (0.7)^{Cb}**	2.0 (0)^{Ab}	**3.1 (0.6)^{Aa}**	2.0 (0)^{Ab}	2.6 (0.5)^{ABa}
fP	**32.5 (0)^{BCa}**	**29.0 (0.9)^{Bb}**	1.8 (0.3)^{Ab}	3.0 (0)^{Aa}	1.8 (0.3)^{Ab}	3.0 (0)^{Aa}

NF is natural forest, CT is conventional tillage, NTF is no tillage with mulch and use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with mulch and use of fertilizer and manure, P is perennial crop, r and f represent researcher and farmers managed sites, respectively. Values in a column followed by the same uppercase letters indicate no significant differences between land uses. Under the same evaluation method, values indicated with similar lower case letters are not significantly different between top (0−15 cm) and sub (15−30 cm) layer for each land use and management system (Man). Values in bold show scores that are below or above the set threshold for good structural quality (33 and 3 for VSA and VESS- based methods, respectively). As such, values < 33 and >3 represent moderate structural quality for VSA and VESS-based methods, respectively.
Upper case A and B are used to show significant differences in properties between treatments while lower case a and b show significant differeces in properties between top and sub layers.

Table 4
Mean top (0-10 cm) and sub (15-30 cm) layer structural quality (Sq) scores and standard error in parentheses for the sandy loam Cambisol under Visual Soil Assessment without considering rooting depth (Sq-r VSA), Visual Evaluation of Soil Structure (Sq VESS) and Visual Evaluation of Soil Structure using the core (Sq coreVESS) for different land use and management systems.

Method	Sq-r VSA		Sq VESS		Sq coreVESS	
Man / Depth	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
NF	35.0 (0) A^{a}	**31.3 (2.0)^{Aa}**	1.7 (0.3)^{Ba}	2.0 (0)^{Ba}	1.7 (0.2)^{Ba}	2.0 (0)^{Ba}
rCT	**27.6 (0.8)^{BCa}**	**24.9 (0.5)^{Cb}**	2.0 (0)^{ABb}	**3.4 (0.4)^{Aa}**	2.1 (0.2)^{Ab}	**3.4 (0.5)^{Aa}**
rNTF	**30.6 (1.3)^{Ba}**	**26.6 (1.3)^{Bb}**	2.2 (0.3)^{ABb}	**3.3 (0.3)^{Aa}**	2.1 (0.2)^{Ab}	**3.5 (0.5)^{Aa}**
rCTFM	**28.8 (0.7)^{BCa}**	**24.5 (0)^{Cb}**	2.1 (0.2)^{ABb}	**3.4 (0.2)^{Aa}**	2.2 (0.4)^{Ab}	**3.6 (0.5)^{Aa}**
rNTFM	**30.2 (0.4)^{Ba}**	**26.5 (1.1)^{Bb}**	2.2 (0.3)^{ABb}	**3.3 (0.3)^{Aa}**	2.2 (0.4)^{Ab}	**3.2 (0.4)^{Aa}**
fCT	**29.6 (1.4)^{BCa}**	**24.7 (0.8)^{Cb}**	2.3 (0.3)^{Ab}	**3.2 (0.3)^{Aa}**	2.4 (0.4)^{Aa}	2.8 (0.4)^{ABa}
fP	**26.7 (1.6)^{Ca}**	**24.5 (0)^{Ca}**	2.0 (0)^{ABb}	**3.2 (0.3)^{Aa}**	2.0 (0)^{Ab}	**3.0 (0)^{ABa}**

NF is natural forest, CT is conventional tillage, NTF is no tillage with mulch and use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with mulch and use of fertilizer and manure, P is perennial crop, r and f represent researcher and farmers managed sites, respectively. Values in a column followed by the same uppercase letters indicate no significant differences between land uses. Under the same evaluation method, values indicated with similar letters are not significantly different between top (0–15 cm) and sub (15–30 cm) layer for each land use and management system (Man). Values in bold show scores that are below or above the set threshold for good structural quality (33 and 3 for VSA and VESS- based methods, respectively). As such, values < 33 and >3 represent moderate structural quality for VSA and VESS-based methods, respectively.
Upper case A and B are used to show significant differences in properties between treatments while lower case a and b show significant differeces in properties between top and sub layers.

properties. Under the field VESS-based methods, structural quality was significantly different between the cropland and the NF in the top layer ($p < 0.0001$) and in the sub layer ($p = 0.03$). Better scores in the NF compared to the cropland was reflected by the measured soil physical properties, which were significantly different between the NF and the cropland both in the top and sub layer (Table 5).

Under the Cambisol, like the Nitisol, NF had significantly better VSA scores ($p < 0.0001$) compared to cropland (Table 4). The sub layer had moderate structural quality under all the methods for the Cambisol (bold values in Table 4). Under field VESS method, there were no significant differences between the researcher managed sites (rCT, rNTF, rCTFM and rNTFM) with significant differences occurring between NF and the cropland in the top ($p = 0.02$) and sub layers ($p < 0.0001$). Measured physical properties were likewise significantly better under the NF compared to the cropland (Table 5). According to the category of obtained Sq values, if soil structural quality is good, it should be maintained while moderate to poor soil structural quality requires interventions to bring the quality to acceptable levels (see section 4.6).

3.2. Relationship between VSEE methods, scores and measured individual soil physical properties

Under both soil types, comparing between methods, the highest correlations (r of 0.94 and 0.97) were found between VESS-based methods (Fig. 1a, d), followed by correlations (r of 0.88 and 0.82) between VSA and VESS method (Fig. 2b, e) and correlations (r of 0.93 and 0.78) between VSA and coreVESS method (Fig. 1c, f) and (e) under the clay Nitisol and sandy loam Cambisol, respectively. Correlations between VSA and VESS-based methods were lower for the sandy loam Cambisol in comparison with the Nitisol.

Under the clay Nitisol, absolute values of Pearson r between VSA scores and laboratory measured soil physical properties ranged from 0.84 to 0.54 (Figs. 2 and 3). For VESS, absolute values of r varied between 0.75 and 0.37 (Fig. 2 and Table 6), while for coreVESS, they ranged from 0.84 to 0.60 (Figs. 2 and 5). For the sandy loam Cambisol, absolute Pearson r values between laboratory measured soil properties and VSA scores ranged from 0.83 to 0.29 (Figs. 2 and 4). The absolute r values were between 0.88 and 0.45 for VESS (Fig. 2 and Table 6) and

Table 5
Mean top (0-10 cm) and sub (15-30 cm) layer soil physical properties with standard deviations in parentheses under different land use and management practice (Man) for the different soil types.

Soil type		Depth/Man	NF	rCT	rNTF	rCTFM	rNTFM	fCT	fP
Nitisol	BD (Mg m^{-3})	0–15	0.67 (0.1)^{Ba}	0.96 (0)^{Aa}	0.91 (0)^{Aa}	0.92 (0.1)^{Aa}	0.89 (0.1)^{Aa}	0.9 (0.1)^{Aa}	0.9 (0A)^{a}
		15–30	0.77 (0)^{Ba}	0.98 (0.1)^{Aa}	1.02 (0)^{Aa}	0.99 (0.1)^{Aa}	0.97 (0.1)^{Aa}	0.9 (0)^{Aa}	1.0 (0)^{Aa}
	K_s (m d^{-1})	0–15	15.4 (1.1)^{Aa}	3.3 (3.6)^{Ba}	4.8 (2.6)^{ABa}	2.7 (2.5)^{Ba}	5.1 (3.3)^{ABa}	12.1 (11.8)^{ABa}	4.05 (0.9)^{ABa}
		15–30	8.9 (0.8)^{Ab}	0.7 (0.6)^{Bb}	3.8 (5.1)^{Bb}	0.8 (1.1)^{Bb}	2.0 (2.9)^{Bb}	1.7 (1.7)^{Bb}	1.7 (0.1)^{Bb}
	K_a (μm^2)	0–15	46.3 (11)^{Aa}	9.7 (4.1)^{Ba}	13.6 (11)^{Ba}	11.5 (7.9)^{Ba}	17.4 (3.3)^{Ba}	11.6 (11.9)^{Ba}	12.5 (4.2)^{Ba}
		15–30	46.7 (6.5)^{Aa}	3.8 (2.6)^{Bb}	7.2 (5.6)^{Bb}	7.4 (11.5)^{Ba}	4.2 (4.9)^{Bb}	13.8 (9.3)^{Ba}	10.3 (8.5)^{Ba}
	MWD (mm)	0–15	2.9 (0.1)^{Aa}	0.8 (0.2)^{Ba}	1.2 (0.3)^{ABa}	1.1 (0.3)^{ABa}	1.1 (0.3)^{ABa}	1.0 (0.2)^{ABa}	1.0 (0)^{ABa}
		15–30	2.0 (0.2)^{Aa}	0.67 (0.30)^{Ba}	0.78 (0.20)^{Bb}	0.80 (0.15)^{Bb}	0.68 (0.25)^{Bb}	0.9 (0.2)^{Ba}	0.7 (0.1)^{Ba}
	Soil shear strength (kPa)	0–15	60(0.7)^{Ab}	80 (22)^{Ab}	84 (21)^{Ab}	65 (4)^{Ab}	87 (29)^{Ab}	101 (27)^{Ab}	75 (21)^{Aa}
		15–30	124(11)^{ABa}	135 (22)^{ABa}	120 (21)^{ABa}	114 (14)^{ABa}	112 (30)^{Aa}	141 (12)^{Aa}	83 (14)^{ABa}
Cambisol	BD (Mg m^{-3})	0–15	1.4 (0)^{Ba}	1.49 (0)^{ABb}	1.34 (0.1)^{ABb}	1.53 (0.1)^{Aa}	1.48 (0.1)^{Aa}	1.5 (0)^{ABa}	1.4 (0.1)^{ABa}
		15–30	1.5 (0)^{Aa}	1.72 (0.2)^{Aa}	1.58 (0.1)^{Aa}	1.52 (0)^{Aa}	1.52 (0)^{Aa}	1.6 (0.1)^{Aa}	1.6 (0.1)^{Aa}
	K_s (m d^{-1})	0–15	3.4 (0.9)^{Aa}	0.5 (0.5)^{Ba}	0.9 (0.8)^{Ba}	1.1 (0.6)^{Ba}	1.1 (0.6)^{Ba}	0.4 (0.1)^{Ba}	0.8 (0.1)^{Ba}
		15–30	2.0 (0.7)^{Aa}	0.3 (0.4)^{Ba}	0.6 (0.9)^{Ba}	0.3 (0.3)^{Ba}	0.1 (0.1)^{Bb}	0.3 (0.4)^{Ba}	0.2 (0.1)^{Bb}
	K_a (μm^2)	0–15	11.3 (2.2)^{Aa}	2.7 (1.1)^{Ba}	2.8 (1.3)^{Ba}	3.6 (1.9)^{Ba}	3.3 (1.2)^{Ba}	1.9 (0.6)^{Ba}	1.8 (0.5)^{Ba}
		15–30	7.65 (1.8)^{Ab}	0.7 (0.7)^{Bb}	1.1 (0.9)^{Bb}	0.7 (0.5)^{Bb}	0.5 (0.6)^{Ba}	0.4 (0.3)^{Bb}	1.1 (0.4)^{Bb}
	MWD (mm)	0–15	1.1 (0.3)^{Aa}	0.29 (0.06)^{Ba}	0.36 (0.06)^{Ba}	0.31 (0.04)^{Ba}	0.38 (0.18)^{Aa}	0.3 (0) ^{Ba}	0.4 (0)^{Ba}
		15–30	1.1 (0.4)^{Aa}	0.42 (0.14)^{Ba}	0.39 (0.11)^{Ba}	0.36 (0.09)^{Ba}	0.45 (0.14)^{Ba}	0.4 (0)^{Ba}	0.3 (0)^{Ba}
	Soil shear strength (kPa)	0–15	108 (12)^{ABb}	80 (2)^{Bb}	90 (13)^{ABb}	76 (10)^{Bb}	93 (21)^{ABb}	85 (20)^{ABb}	114 (7)^{Ab}
		15–30	129(12)^{Aa}	108 (31)^{Aa}	135 (16)^{Aa}	129 (13)^{Aa}	132 (18)^{Aa}	123 (7)^{Aa}	129 (1)^{Aa}

NF is natural forest, CT is conventional tillage, NTF is no tillage with mulch and use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with mulch and use of fertilizer and manure, P is perennial crop, r and f represent researcher and farmers managed sites, respectively. Under the same soil type and for each property, values in a row indicated with similar capital letters are not significantly different between land use and management practice for each soil depth. Under each management practice, values indicated with similar lower case letters are not significantly different between top and sub layer for each soil property. Upper case A and B are used to show significant differences in properties between treatments while lower case a and b show significant differeces in properties between top and sub layers.

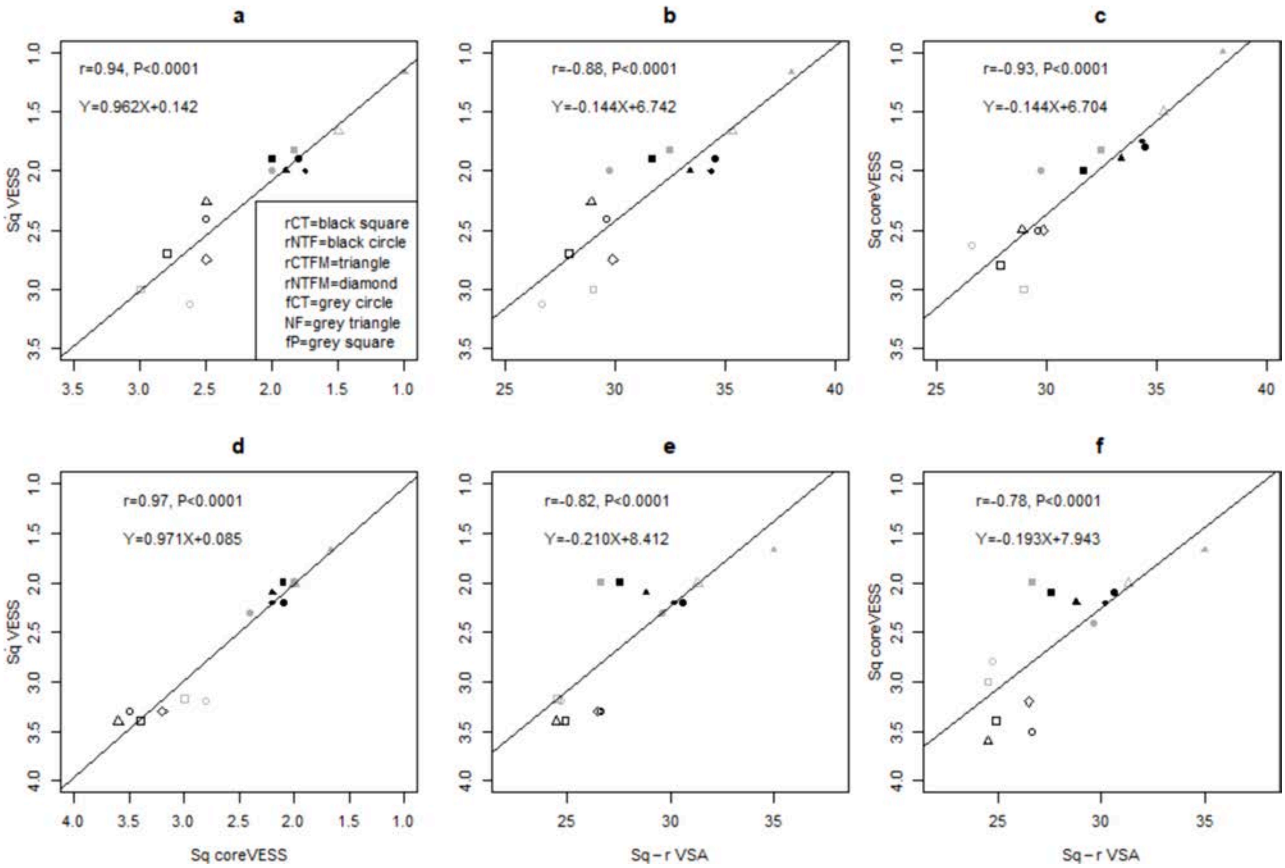

Fig. 1. Relationship between structural quality (Sq) scores for the clayey Nitisol (a-c) and sandy loam Cambisol (d-f) under the three used VSEE methods, i.e., Visual Soil Assessment without considering rooting depth (Sq-r VSA), Visual Evaluation of Soil Structure (Sq VESS) and Visual Evaluation of Soil Structure using cores (Sq coreVESS) for different land use and management systems. Sq is structural quality, NF is natural forest, CT is conventional tillage, NTF is no tillage with mulch and use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with mulch and use of fertilizer and manure, P is perennial crop, r and f represent researcher and farmer managed sites, respectively. Closed and open symbols presents top and sub soil layers, respectively. Full lines show correlation lines while r shows the Pearson correlation coefficient.

between 0.81 and 0.40 for coreVESS (Figs. 2 and 6). Overall, under the clay Nitisol highest correlations were found with K_s, MWD and shear strength. SOC, BD and AC took intermediate positions, while K_a showed the lowest correlation. In the sandy loam Cambisol, K_a had the highest correlation for all the methods with K_s shear strength and SOC undertaking intermediate positions. Correlations with MWD remained relatively low.

Under the Nitisol, relationship between VSA scores and soil quality indicators derived from soil water retention curves were mostly significantly correlated (Table 7). Levels of significance are indicated per parameter in Table 7. The scores had no significant relationship with VESS-based methods. Under the Cambisol, the relationships were mostly significant with strong relationships with VESS-based methods. PAWC was not significantly related with the VSEE scores from all methods and in the two soil types. It is important to note that, even though the data sometimes seem to suggest non-linear relations, which would have resulted in higher correlation coefficients, we kept all relations linear for the sake of simplicity.

3.3. Overall assessment of relationship between soil properties and VSEE scores

While the previous relationships were based on correlations between individual soil properties and the VSEE scores, this section presents an overall relationship between the VSEE scores and all the properties. Recursive partitioning under CTREE allows for an integrated assessment of the relations and identifies the soil property that better explains the variability of scores under each method. Most of the variability for VSA Sq scores under the Nitisol was explained by MWD and shear strength (Fig. 7a). Best VSA Sq scores were obtained for MWD > 1.17 mm. In sites with MWD < 1.17 mm, better VSA Sq scores were obtained on soils with shear strength < 118 kPa. Under a Cambisol, VSA Sq scores variability resulted from K_a and shear strength (Fig. 7e). The scores were better in sites with $K_a > 2.39$ μm^2. In sites where K_a was lower than this value, the lowest scores were obtained when shear strength exceeded 98 kPa.

On the other hand, variability of VESS Sq scores was best explained by MWD under Nitisol (Fig. 7b) with best VESS Sq scores occurring when MWD > 1.53 mm. The scores were significantly related to K_a and porosity under Cambisol (Fig. 7d). When $K_a > 1.08$ μm^2, VESS Sq scores were determined by the soil's porosity with better VESS Sq scores occurring when porosity > 0.45 m^3 m^{-3}. Consequently, low K_a values showed worse VESS Sq scores. Similar to VSA and VESS Sq scores, MWD was a key soil property in defining coreVESS Sq scores variability under the Nitisol (Fig. 7c). Better coreVESS Sq scores were obtained when MWD > 1.18 mm. Lastly, under the sandy loam Cambisol, worst scores occurred when $K_a < 1.27$ μm^2 (Fig.7f). When K_a values were higher than this value, better scores were given when $K_s > 0.53$ (m d^{-1}).

3.4. Structural quality improvement

In this analysis, the role of SOC in improving soil structure under cropland is presented. Improved soil structure will in return result in better VSEE scores. Under the Nitisol, VSA scores increased by 0.64 when SOC content increased by 1 g kg^{-1} (Fig. 2). VESS and coreVESS

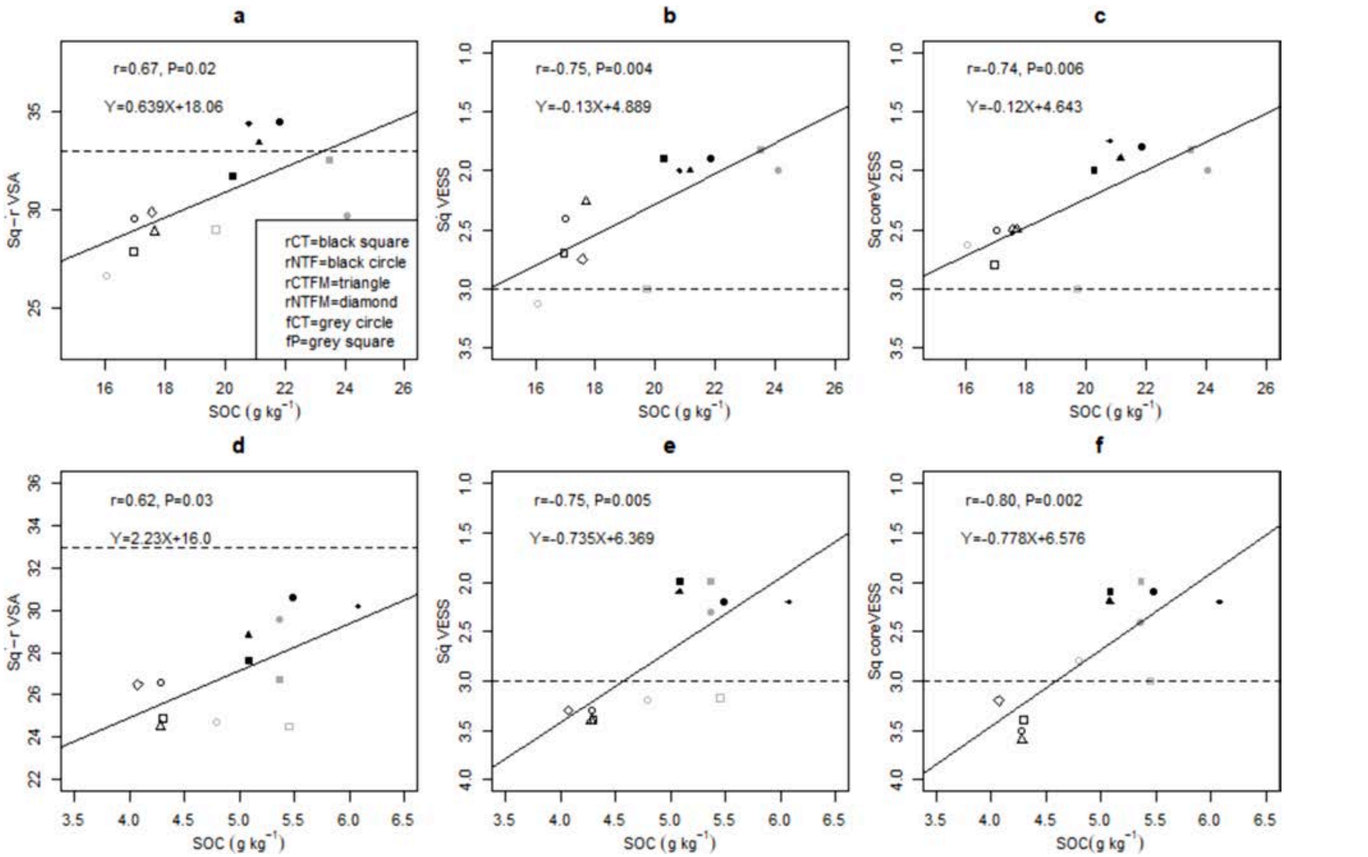

Fig. 2. Relationship between Visual Soil Assesment without considering rooting depth (sq-r VSA), Visual Evaluation of Soil Structure (sq VESS), Visual Evaluation of Soil Structure using the core (Sq coreVESS) scores and soil organic carbon (SOC) under clayey Nitisol (a-c) and sandy loam Cambisol (d-f). Sq is structural quality, CT is conventional tillage, NTF is no tillage with mulch and use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with mulch and use of fertilizer and manure, P is perennial crop, r and f represent researcher and farmer managed sites, respectively. Closed and open symbols presents top and sub soil layers, respectively. Full lines shows correlation lines while r shows the Pearson correlation coefficient.

scores reduced by 0.13 and 0.12, respectively, when SOC content increased by 1 g kg^{-1}. On the other hand, under the Cambisol, VSA, VESS and coreVESS scores increased by 2.2, reduced by 0.7, and reduced by 0.8, respectively, when SOC content increased by 1 g kg^{-1}.

3.5. Relationship between VSEE scores and maize grain yield

Maize grain yield from the 20 researcher managed sites per location was used for this analysis. We did not manage to get maize yield data from farmer managed sites. Under the Nitisol, absolute values of Pearson r between maize grain yield and VSEE Sq scores ranged from 0.61 to 0.36 (Fig. 8). Under the sandy loam Cambisol, they varied from 0.38 to 0.11. Correlations were significant under the Nitisol while using VSA and coreVESS.

3.6. Visual scores, Soil Quality Index (SQI) and management thresholds

To determine how well VSEE scores correlate with overall soil quality index, the scores were compared with an integrated SQI which was calculated from quantitative soil physical properties used as SQi's (Fig. 9). It should be noted that our SQI used those SQi's that represent soil structural quality only as per our objective and thereby excludes a wide range SQi's that characterizes physical, chemical and biological soil properties. SQi that showed a significant correlation with Sq scores were used. Under the Nitisol, absolute values of Pearson r between SQI and VSEE Sq scores ranged from 0.59 to 0.66. They ranged between 0.64 and 0.78 under the Cambisol. All the correlations highly significant for all the methods and under the two soil types (Fig. 9). For management thresholds, the regression describing the target value (Sq<2) for the Kibugu Nitisol was BD = 0.0012*SOC+0.6476 (r = 0.71) with significant intercept and slope (Table 8). In the absence of SOC data, the target mean BD for Sq<2 is 0.79 Mg m^{-3}. For Sq = 2 and Sq = 3, the slopes of the regression lines were not significant. Therefore, the trigger and remediation values were the mean values of Sq = 2 and Sq = 3, namely 0.93 Mg m^{-3} and 0.99 Mg m^{-3}, respectively. For the Machang'a Cambisol, the slopes of the regression lines were not significant for Sq = 2, Sq = 3 and Sq = 4. Therefore, the target, trigger and remediation values were the mean values of Sq = 2, Sq = 3 and Sq = 4, namely 1.48 Mg m^{-3}, 1.56 Mg m^{-3} and 1.64 Mg m^{-3}, respectively (Table 8).

4. Discussion

4.1. Can visual soil evaluation detect structural differences between land use and short-term soil management practices?

Significant differences in VSEE scores between top and sub layer under the NF were not anticipated as differences under NF are expected to occur at deeper depths. This is because the top and sub layers of the NF are not altered by human activities like in the croplands. As such, the NF acted as a reference to the cropland. The significant differences in VESS scores between top and sub layer under the cropland could be related to the creation of a more dense layer in the sub layer due to repeated turning of the top layer during land operations. In addition, the more dense sub layer had low SOC, high BD and low $K_{s\ as}$ compared to the top layer. While this difference was not reflected by the quantitative approach e.g. BD, they were detected under VSEE (semi-quantitative

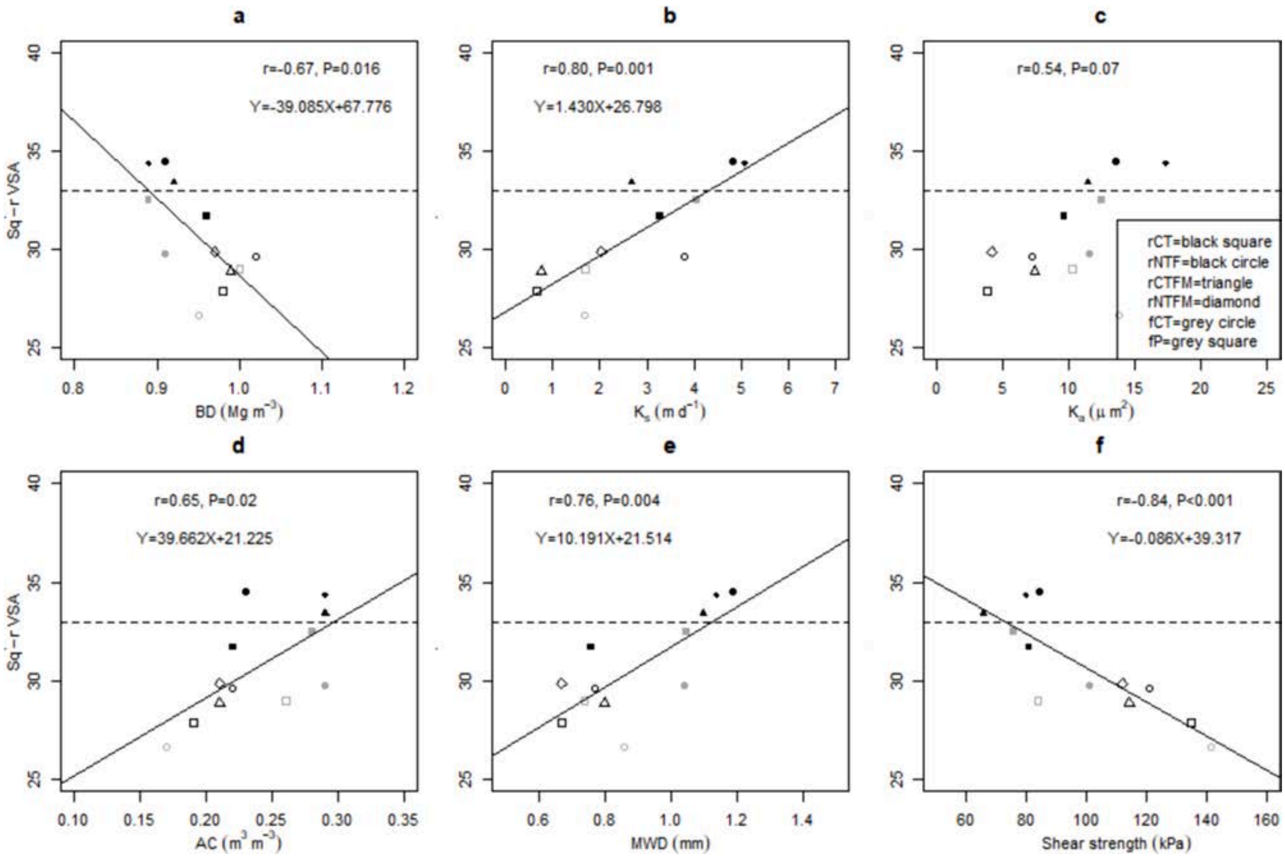

Fig. 3. Relationship between Visual Soil Assesment without considering rooting depth (Sq-r VSA) scores and physical soil quality properties under different land use and management sysytems under clayey Nitisol. BD is bulk density, K_s is saturated hydraulic conductivity, K_a is air permeability, AC is air capacity, MWD is mean weight diameter, Sq is structural quality, CT is conventional tillage, NTF is no tillage with mulch and use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with mulch and use of fertilizer and manure, P is perennial crop, r and f represent researcher and farmer managed sites, respectively. Closed and open symbols presents top and sub soil layers, respectively. Full lines shows correlation lines while r shows the Pearson correlation coefficient.

Table 6
Relationship between Visual Evaluation of Soil Structure (VESS) scores and physical soil quality properties for the Nitisol and Cambisol.

Soil type	BD (Mg m^{-3})	K_s (m d^{-1})	K_a (μm^2)	AC (m^3 m^{-3})	MWD (mm)	Shear strength (kPa)
Clayey Nitisol	0.62*	−0.68*	−0.37	−0.60*	−0.67*	0.68*
Sandy loam Cambisol	0.73**	−0.71**	−0.88***	−0.78**	−0.45	0.82***

BD is bulk density, K_s is saturated hydraulic conductivity, K_a is air permeability, AC is air capacity and MWD is mean weight diameter. Correlations significant at $P < 0.001$ are indicated by ***, $P < 0.01$ by **, $P < 0.05$ by *.

approach) showing the ability of the semi-quantitative approach to detect (small) changes in structural quality. This ability of VSEE to detect small changes in structural quality could be because VSEE is an integrated examination of soil structural quality while the quantitative approach refers to one aspect of soil structural quality, for example BD. In other studies, the dense sub layers showed an increase in BD and reduced K_s due to decreased continuity of pores (Pulido Moncada et al., 2014a; Guimarães et al., 2013). This was the case in the current soil layers with the sub layer showing moderate soil structural quality under VSA method. The denser sub layer in cropland showed increasing BD, and decreasing K_a and K_s from top to sub layer. Physical soil properties (BD, K_s, K_a, MWD) were also better in NF for both soil types which explains the higher scores. It is therefore important to emphasize the ability of VSEE scores to distinguish between NF and cropland, and better VSEE scores in the top layer compared to the sub layer. High top layer Sq compared to the sub layer Sq has been reported by other authors (Guimarães et al., 2013, 2011; Giarola et al., 2010; Cornelis et al., 2019). Assigning of scores per layer allows for appreciation of better soil quality near the soil surface and is useful in making future management plans to improve the sub layer (Guimarães et al., 2013).

The VESS scores were significantly different between NF and the cropland with the NF showing better structural quality. This indicates that all tested VSEE methods were able to assess differences in soil quality resulting from different land use. These results are in agreement with other studies in tropical environments that found good soil structural quality under natural forests using VSEE methods (Cornelis et al., 2019; Cherubin et al., 2017; Guimarães et al., 2013). VESS scores of the NF was slightly lower under the Cambisol compared to the Nitisols. This could be explained by the nature of forests. NF under the Cambisol is in a semi-arid region where livestock grazing is a free range system. Livestock trampling in this kind of forests could reduce the structural quality. Overall, compared to the Nitisols, most sites under the Cambisol showed moderate soil structural quality. This could be because the Nitisols under study have inherently better soil quality compared to the Cambisol (Mutuku et al., 2021).

The researcher managed trials, which included no tillage and

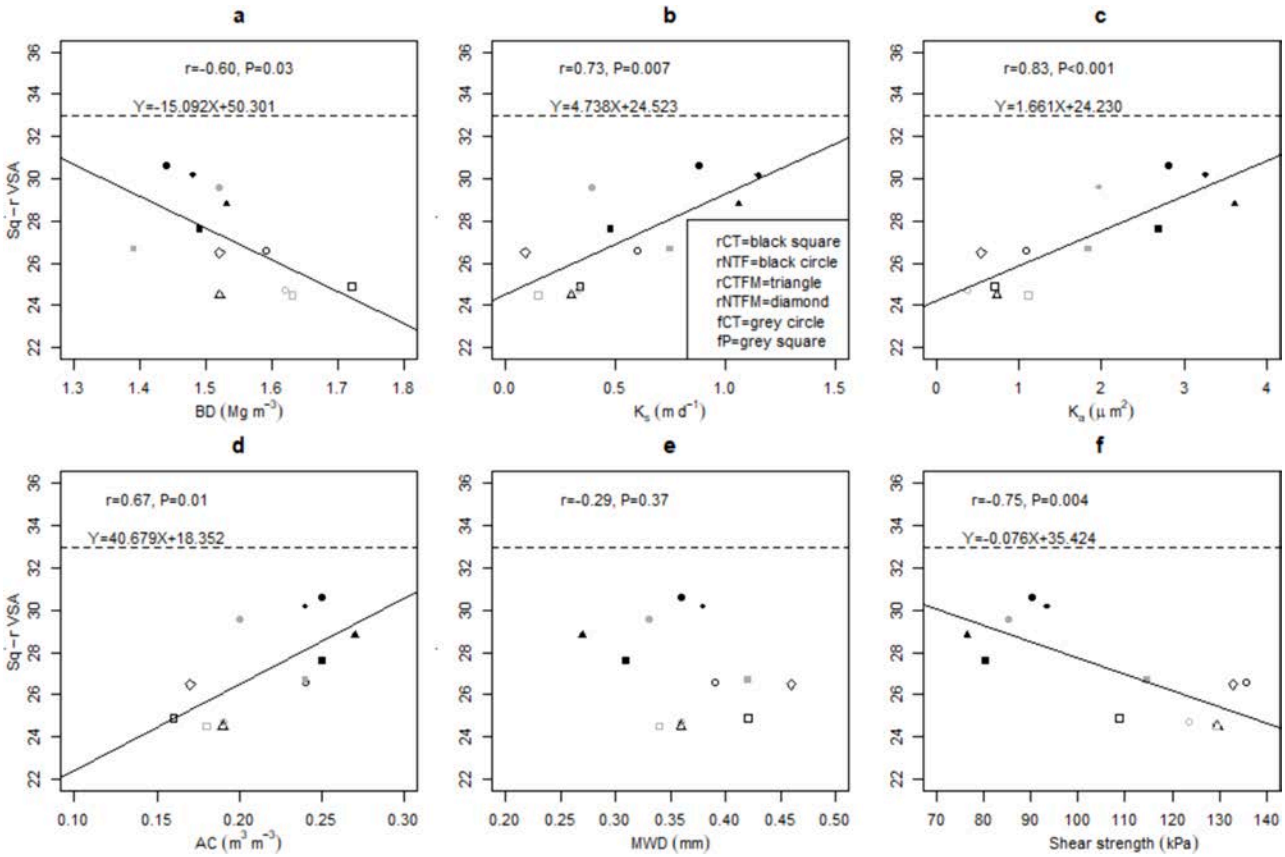

Fig. 4. Relationship between Visual Soil Assessment without considering rooting depth (Sq-r VSA) scores and physical soil quality properties under different land use and management systems under sandy loam Cambisol. BD is bulk density, K_s is saturated hydraulic conductivity, K_a is air permeability, AC is air capacity, MWD is mean weight diameter, Sq is structural quality, CT is conventional tillage, NTF is no tillage with mulch and use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with mulch and use of fertilizer and manure, P is perennial crop, r and f represent researcher and farmer managed sites, respectively. Closed and open symbols presents top and sub soil layers, respectively. Full lines shows correlation lines while r shows the Pearson correlation coefficient.

conventional tillage systems, were established to help improve soil quality and hence crop yields. However, VESS-based methods did not show significant differences in soil structural quality between the improved management systems (rNTF, rCTFM and rNTFM). While it was expected that NT improved structural quality, the improvement in soil structural quality under minimum or no tillage systems is time dependent (Araya et al., 2016; Madarász et al., 2016; Micheni et al., 2016; Sithole et al., 2016; Thierfelder et al., 2015). Our researcher managed trials were run for two years which could be the reason for lack of significant differences in Sq scores between treatments. Likewise, Giarola et al. (2010) reported no significant difference in scores between no tillage and mechanical subsoiling under Ferrasols in Brazil. The lack of significant difference in scores between treatments was reflected by the soil physical properties which showed no significant differences. Other authors have also reported lack of significant differences in scores between management practices. For example, after three years of conservation tillage practices on tropical Ferrasols in Uganda, Cornelis et al. (2019) did not observe significant differences in VSEE-based Sq scores between the practices. This indicates that VSEE methods are most likely not able to detect structural changes occurring due to crop management practices in the short term (two years). However, in a long-term trial, these differences might be evident. On the other hand, under all the VSEE methods, farmer managed perennial crop (fP), though in existence for over ten years did not show a lower structural quality in the top layer as would have been expected. Since the crops grown under fP are cash crops, farmers are keen to maintain the soil quality (through addition of organic and inorganic fertilizer, though at irregular basis, and also deep digging to break hard pans) for improved production and higher incomes, which might explain its relative good quality. In addition, due to the nature of the perennial crops, soils under them are mostly covered, which favors microbial activity

4.2. Which visual method to use

The higher mutual correlation between VESS-based methods in comparison with VSA could be due to the scoring criteria used. In our study, VESS scoring in the field was given one overall score after considering all the suggested criteria. In the laboratory, even though scores under coreVESS were given per the three set criteria (see 2.3.3), many times the criteria received the same scores, thereby making the scoring similar to one overall score. In general, good correlations were obtained under the Nitisol irrespective of the VSEE method used. These gave a strong correlation between VSA and either VESS or coreVESS methods and indicates less dependency of the evaluation criteria and soil moisture status on Sq scores of the Nitisol, even though field tests were done near FC. Under the Cambisol, the correlation between VSA and VESS indicates the influence of scoring criteria (Fig. 1e) and more importantly, the influence of both scoring criteria and moisture content (Fig. 1f) on the Sq of these soils. Under the Cambisol, all the methods, show a clear distinction between the top and sub layer scores with top layer having better scores compared to the sub layer. Our results are in agreement with Pulido-Moncada et al. (2014a) who reported a Pearson correlation of 0.78 between VSA and VESS while evaluating tropical sandy loam to silt loam soils. Similar correlations have been reported by Cornelis et al. (2019) under tropical sandy clay loam soils. As such, for our clay Nitisol and sandy loam Cambisol, with the highly significant

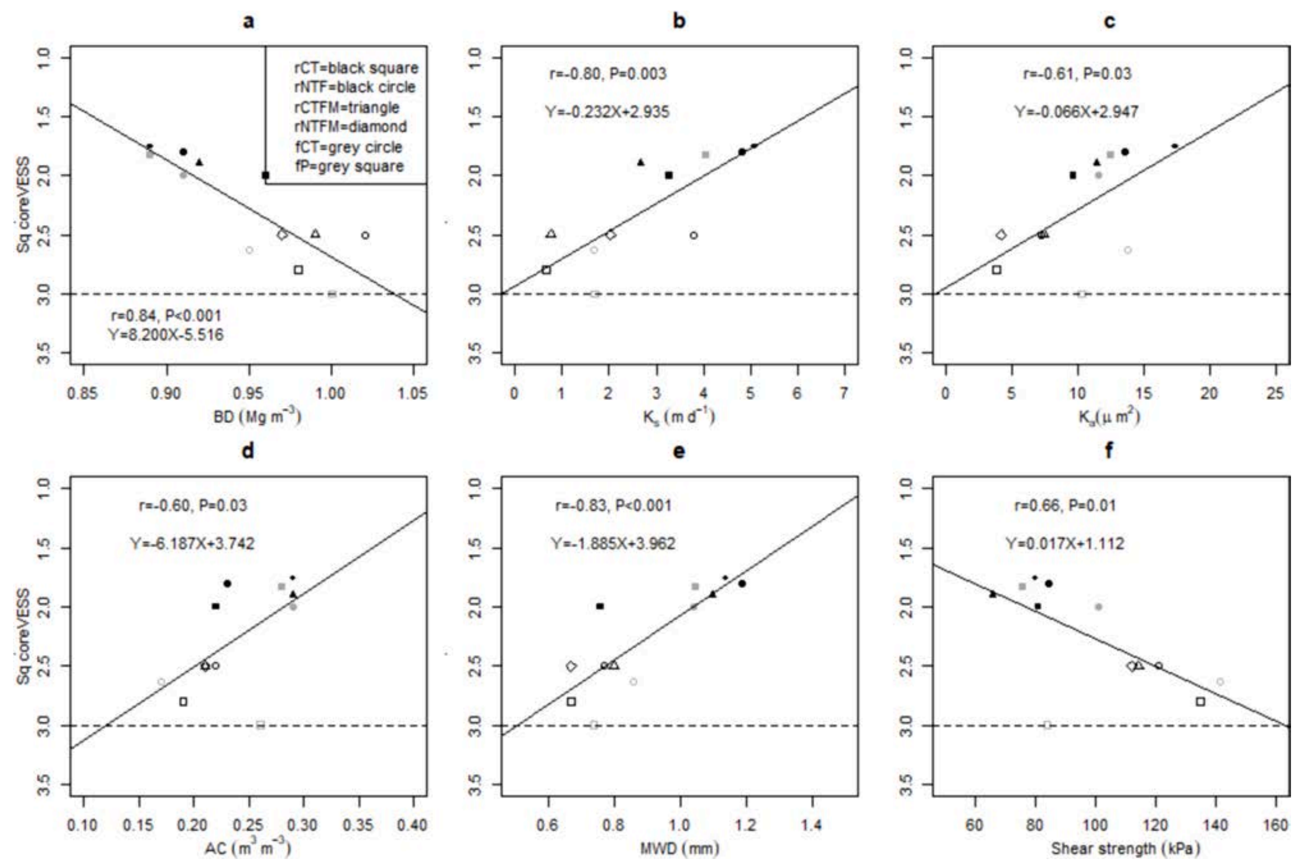

Fig. 5. Relationship between Visual Evaluation of Soil Structure using the core (Sq coreVESS) scores and physical soil quality properties under different land use and management systems under clay Nitisol. BD is bulk density, K_s is saturated hydraulic conductivity, K_a is air permeability, AC is air capacity, MWD is mean weight diameter, Sq is structural quality, CT is conventional tillage, NTF is no tillage with mulch and use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with mulch and use of fertilizer and manure, P is perennial crop, r and f represent researcher and farmer managed sites, respectively. Closed and open symbols presents top and sub soil layers, respectively. Full lines shows correlation lines while r shows the Pearson correlation coefficient.

correlation between the three VSEE method scores, the use of any of the three VSEE methods would depend on user preference and practicability.

4.3. Measured soil physical properties supporting the use of visual methods

From CTREE analysis, the correlations between VSEE scores and measured soil physical properties indicate that VSEE scores under Nitisols are more related to aggregate stability ($p = 0.0001$). Nitisols are known for their good aggregation and good drainage capacity (WRB, 2006). This might explain why scores are related with K_s and MWD, however, the scores under the Cambisol are related mainly to air and water movement parameters, K_a ($p = 0.001$), porosity ($p = 0.01$) and K_s ($p = 0.02$). Compared to the Nitisol, these soils have a high BD and low porosity and also sub angular blocky aggregates. As such, fields with relatively high BD and low porosity received lower scores which is an indication of resistant to transmission of water and air (Pulido Moncada et al., 2014a, b). Overall, correlations between Sq scores and a range of soil properties was highly significant. While correlating VSEE scores with individual soil properties, several authors have reported similar results. For example, Mueller et al. (2009) reported correlations between VSEE methods and soil strength and dry bulk density in loam to silt loam soils of humid region. VSEE scores were related to BD, porosity, SOC and K_s in tropical soils ranging from sandy clay loam to clay loam (Pulido Moncada et al., 2014a). In temperate silt loam soils, VSEE scores were related to SOC, plant available water capacity, aggregate stability and porosity while in sandy loam soils, they were related to water flow properties (Pulido Moncada et al., 2014b). The obtained correlations indicate the relationship between soil properties. As such, fields with lower scores have low SOC, high BD and consequently decreased continuity of soil pores and reduced permeability (K_a and K_s). In their study under tropical sandy, medium and clay textured soils, Cherubin et al. (2017) reported correlations between VESS scores and BD as well as with soil resistance to penetration. Reported also is that BD, resistance to penetration and K_a were related to VESS scores under temperate clay and sandy loam soils (Guimarães et al., 2013). Under temperate sandy loam soils, Tuchtenhagen et al. (2018) reported good relationships between VESS scores and BD, porosity, aggregation, and SOC. Correlations between SOC, BD, AC, K_a, K_s, and MWD with VSEE scores have also been reported by Cornelis et al. (2019) under tropical sandy clay loam to sandy loam soils. As such, a soil with high SOC will have high aggregate stability, better structural quality and consequently better VSEE scores. On the other hand, soil with continuous pores and presence of large pores have high K_s and K_a. It is also a clear indication that ‘we can see what we measure’ (Shepherd and Park, 2003). As in the latter study, we obtained poor relations between PAWC and VSEE scores which could be explained by the fact that PAWC depends on factors other than soil structure, such as soil texture and SOC. This result is in line with Botula et al. (2012) who found no difference in water content at field capacity when using repacked or intact cores taken from tropical soils, which demonstrates that structure does not affect the water content at field capacity of these soils.

The most significant physical soil property in explaining variation of Sq scores under all the VSEE methods for the Nitisol was MWD. MWD, which defines the different sizes of soil aggregates is an important

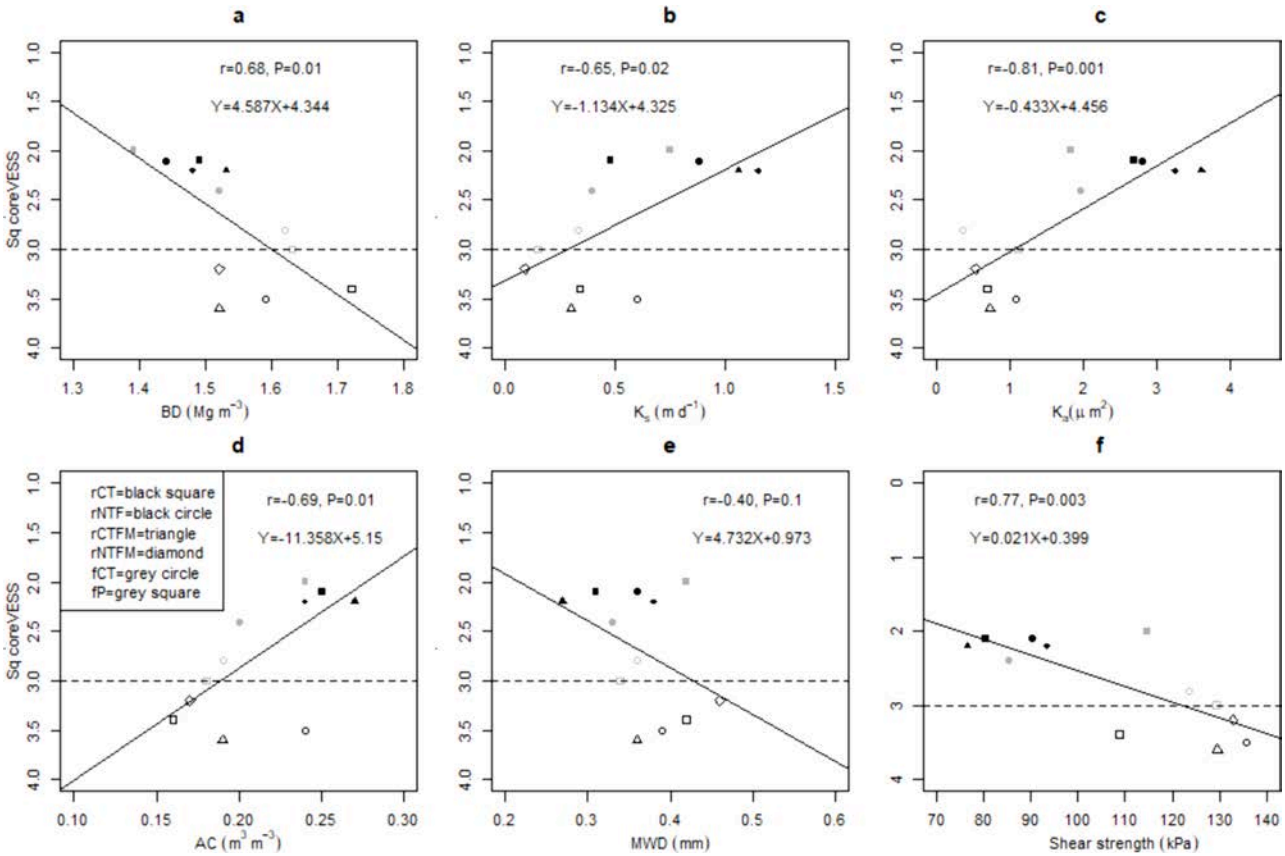

Fig. 6. Relationship between Visual Evaluation of Soil Structure using the core (Sq coreVESS) scores and physical soil quality properties under different land use and management systems under sandy loam Cambisol. BD is bulk density, K_s is saturated hydraulic conductivity, K_a is air permeability, AC is air capacity, MWD is mean weight diameter, Sq is structural quality, CT is conventional tillage, NTF is no tillage with mulch and use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with mulch and use of fertilizer and manure, P is perennial crop, r and f represent researcher and farmer managed sites, respectively. Closed and open symbols presents top and sub soil layers, respectively. Full lines shows correlation lines while r shows the Pearson correlation coefficient.

Table 7
Relationship between Visual Soil Assessment without considering rooting depth (sq-r VSA), Visual Evaluation of Soil Structure (VESS), Visual Evaluation of Soil Structure using core (coreVESS) scores and soil physical properties for the Nitisol and Cambisol.

Soil type		FC $m^3\ m^{-3}$	PWP $m^3\ m^{-3}$	MatPor $m^3\ m^{-3}$	MacPor $m^3\ m^{-3}$	PAWC $m^3\ m^{-3}$	RWC
	Sq-r VSA	−0.38**	−0.24*	−0.28*	0.33*	−0.06	−0.36**
Nitisol	Sq VESS	0.19	0.14	0.26	−0.27*	0.01	0.21
	Sq coreVESS	0.25	0.14	0.30	−0.27*	0.06	0.22
	Sq-r VSA	−0.40**	−0.41**	−0.28*	0.31*	−0.09	−0.41**
Cambisol	Sq VESS	0.50***	0.53***	0.38**	−0.43***	0.09	0.52***
	Sq coreVESS	0.40**	0.45***	0.27	−0.38*	0.02	0.45***

FC is water content at field capacity, PWP is permanent wilting point, MatPor is matric porosity, MacPor is macro porosity, PAWC is plant available water content and RWC is relative water capacity. Correlations significant at $P < 0.001$ are indicated by ***, $P < 0.01$ by **, $P < 0.05$ by *.

indicator of soil structure. Aggregate's stability and the pores between them influence water movement and storage, aeration, erosion, biological activity and the crop growth (Amézketa, 1999). MWD is influenced by soil organic matter among other factors and therefore best placed to explain structural quality (Abiven et al., 2009). It was as such chosen as an explanatory variable by the CTREES. Aggregate stability is also directly related to shear strength of a soil and it is therefore not surprising that the model picked shear strength as a second separator of the Sq scores. While using a hand vane, shear strength values in the range of 51–107 kPa at 15 cm depth and on clay loam temperate soils, depending on traffic-induced soil compaction have been reported (Emmet-Booth et al., 2020). Under the sandy loam Cambisol, next to K_a, which was also among the highly correlated individual parameter is shear strength, porosity and K_s, which confirms dependency of VSEE scores to air and water movement parameters. While a K_a value of 2.39 μm^2 was used to distinguish better structural quality under the Cambisol, it is important to note that soils with K_a values < 20 μm^2 has been classified as soils having very slow K_a by Fish and Koppi (1994). As such, the Cambisol had very low K_a values which indicates impermeable soils according to Ball et al. (1988). On the other hand, K_s values of 0.1 m day^{-1} have been indicated as the critical limit below which crop production is frequently and substantially impaired by inadequate root zone aeration, reduced trafficability, and increased surface runoff and erosion (Reynolds et al., 2007).

However, care should also be taken while using the K_a thresholds given by Fish and Koppi (1994) because this classification was done based on soils from the temperate region and application in the tropics might need some adjustments. On the other hand, under the Nitisol and

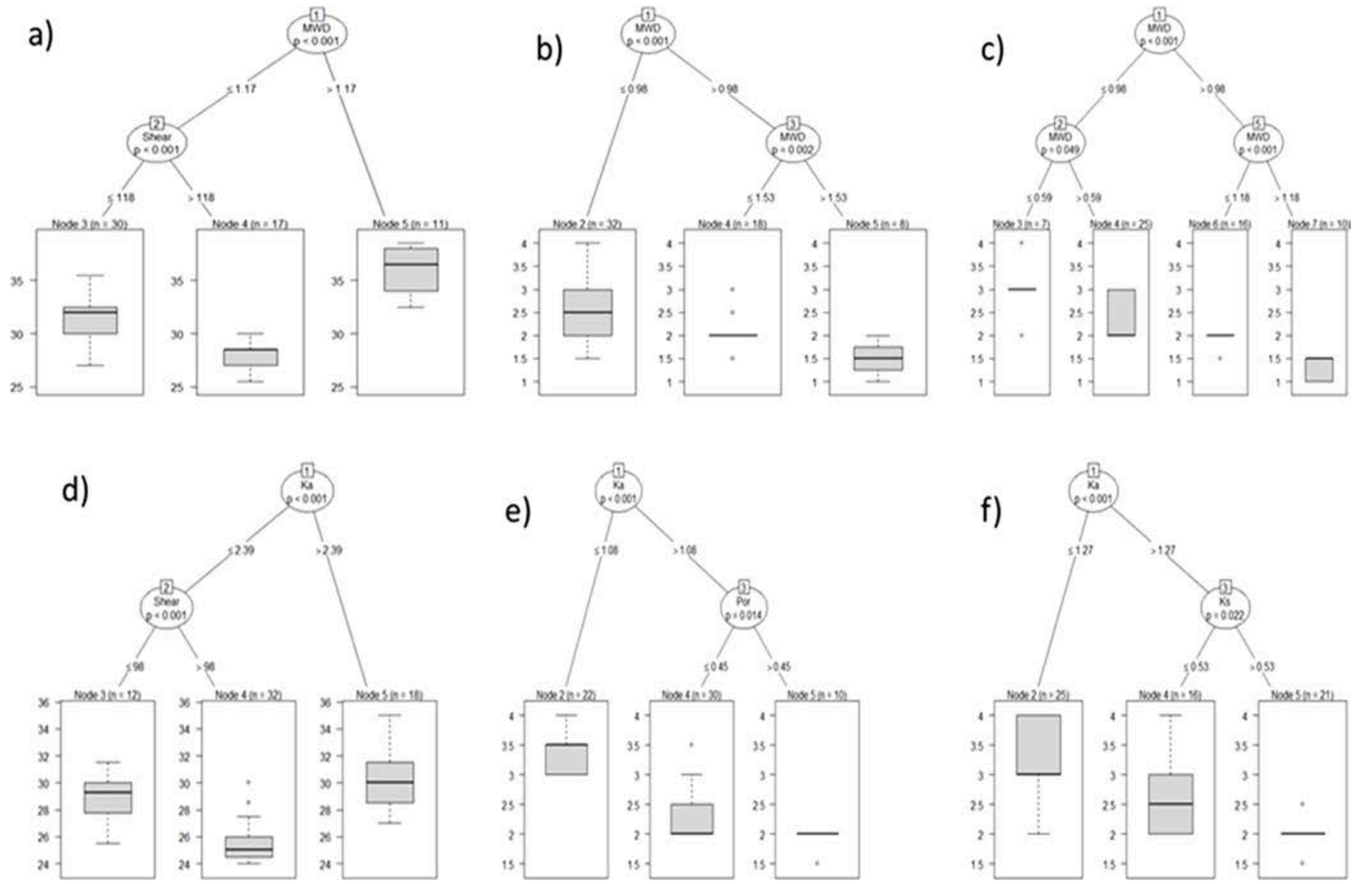

Fig. 7. Recursive partitioning of VSA Sq scores (a, d), VESS Sq scores (b, e) and coreVESS Sq scores (c, f) in relations to soil properties under the Nitisol (top panels) and the Cambisol (bottom panels). Horizontal solid line on the boxplots show the median soil quality scores, box outline shows the 50th percentile scores, upper and lower whiskers indicate maximum and minimum scores, respectively, and outliers (open circles). MWD is mean weight diameter (mm), Shear is shear strength (kPa) and Ka is air permeability (μm^2), Por is porosity (%) and Ks is saturated hydraulic conductivity ($m\ d^{-1}$).

Cambisol, obtained K_s values were above the given critical value of 0.1 m day^{-1} (Reynolds et al., 2007). Similar to K_a thresholds values, the K_s threshold value has been developed for temperate fine textured soil and therefore its applicability for tropical medium textured soil is still questionable.

4.4. The importance of soil organic carbon

Studies have consistently shown the benefit of manure and adequate fertilization in maintaining agronomic productivity by increasing C inputs into the soil (Reeves, 1997). SOC impacts on other physical, chemical and biological soil properties and its key role as an important indicator for physical soil quality has been reported (Shukla et al., 2006). Therefore, investing in management practices which improve SOC is expected to improve overall soil structural quality hence better VSEE scores. From the correlation equations in Fig. 2, an increase of SOC by 1 g kg^{-1} should improve VSEE scores more in the Cambisols than Nitisols. It is therefore apparent that the improvement of SOC is more profitable for the sandy loam as compared to the clay Nitisol. Given that the Nitisols under study have relatively high levels of clay with corresponding low quantities of SOC while the sandy loam Cambisols have relatively low clay levels and considerably low SOC content, organic matter improvement will not come without a huge investment in terms of addition of organic residues and especially under the Cambisol. To intensify agricultural production, it would be better if SOC was added to the Nitisols and the Cambisols converted to other land uses, for example agro-forestry, rangeland or natural vegetation. This way, the inherently low fertility Cambisols will benefit from these systems (Alao and Shuaibu, 2013).

4.5. Visual methods, maize grain yield and Soil Quality Index

The observed significant correlations under the Nitisol indicate that VSA and coreVESS scores can be applied as an input parameter in a statistical model, in the absence of measured laboratory parameters, to predict maize production suitability. This would be useful for policy makers in Sub-Saharan Africa as they would be able to assess the effect of soil structural quality improvement measures on maize grain yield. Mueller et al. (2009), while using the Peerlkamp test to evaluate temperate loam soils reported significant correlations between VSEE scores and crop yields. A correlation of 0.46 between VESS scores and soybean yield has been reported by Çelik et al. (2019). Correlations between VESS scores and crop yields have also been reported elsewhere (Tormena et al., 2016; Munkholm et al., 2013; Giarola et al., 2013). The rather low correlation obtained between VSEE scores and grain yield under the Cambisols could be related to crop yield dependency on spatial rainfall variability, in such semi-arid regions, other than on soil structural quality. The correlations could also be explained by the fact that maize yield under this soil was also not significantly related to any of the soil physical parameters (data not shown). On the other hand, maize yield under the Nitisol was marginally correlated to permeability ($p = 0.06$) (data not shown). Nevertheless, our correlations show that at least much of the variation in yield appears to be explained by soil structural quality in addition to nutrient balance which explains the majority of yield variations. The complexity of crop yield, to be explained by soil structure alone, is confirmed by the correlation

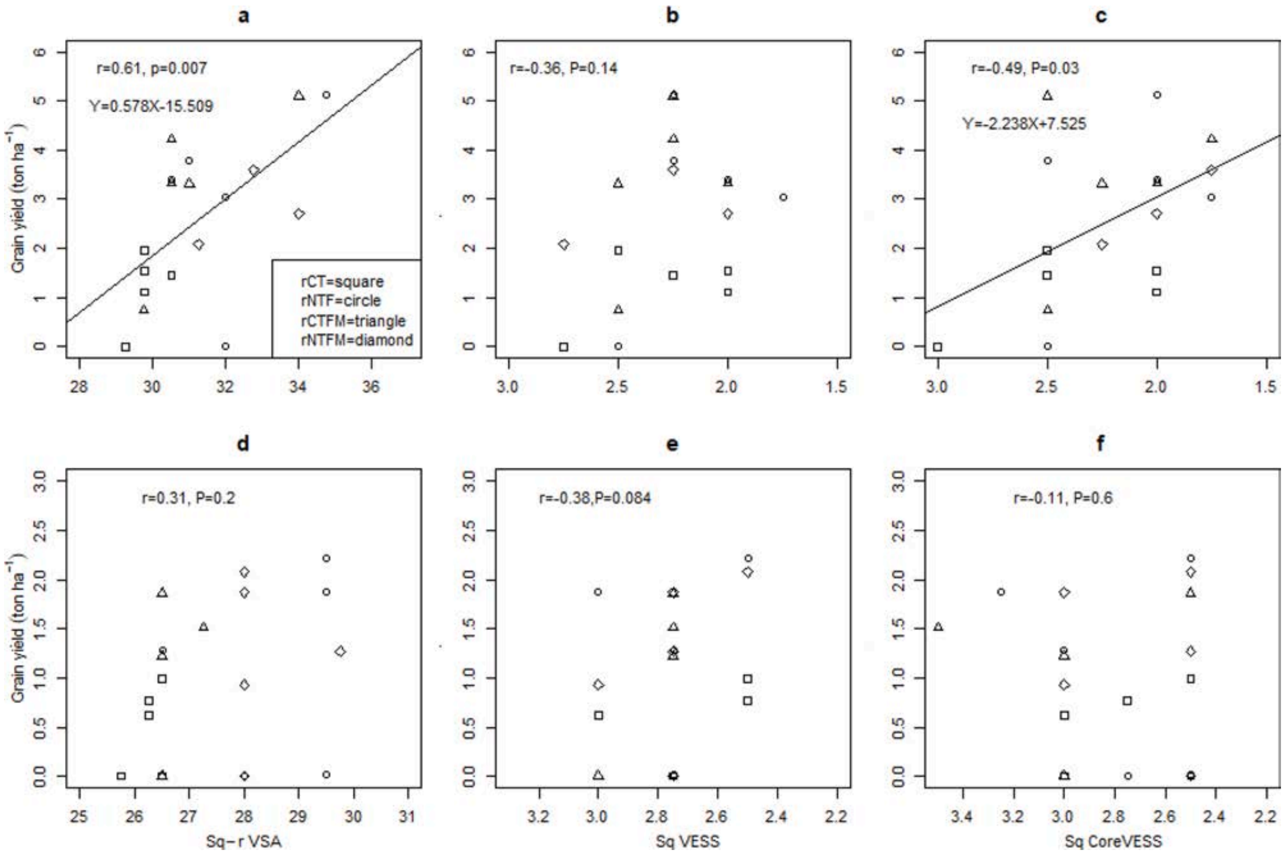

Fig. 8. Maize grain yield under different management systems in function of structural quality (Sq) scores for Nitisol (a-c) and Cambisol (d-f) under the three visual soil evaluation methods, i.e., Visual Soil Assessment without considering rooting depth (Sq-r VSA), Visual Evaluation of Soil Structure (Sq VESS) and Visual Evaluation of Soil Structure using cores (Sq coreVESS) for 0-30 cm block. CT is conventional tillage, NTF is no tillage with use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with use of fertilizer and manure, r placed in front of each system represents researcher managed sites. Full lines show correlation lines while r shows the Pearson correlation coefficient.

between VSEE Sq scores and SQI. These highly significant correlation suggest that visual evaluation and examination methods capture well the integrated aspects of soil structural quality. This observation again confirms the usefulness of the tested VSEE methods in evaluating soil structure under tropical Nitisol and Cambisol.

4.6. Maintaining and improving soil structural quality

With the obtained moderate scores for our Nitisol and Cambisol under cropland, it is advisable that reasons for the reduced soil structural quality, as compared to the forest soil, should be investigated and soil management adapted to improve the structural quality. As such, if soils are of good quality, it is important to monitor changes in soil conditions and adopting appropriate good soil management practices while when soils are of intermediate and poor quality, interventions for improvement are necessary. There exist several interventions to help maintain or improve soil structure (Ball et al., 2000). For African tropical soils, these interventions are and not limited to, firstly, the use of no tillage or reduced tillage to improve soil aeration, improve infiltration and drainage, conserve soil moisture, and maintain soil organic matter and biological activity (Shepherd et al., 2000). Secondly, cultivation should be done when soils are not too wet nor too dry. Cultivating too wet soils restricts soil fracturing, causes smearing and the formation of thin plough pans that reduce infiltration of water, while too dry soils will not break down with further cultivation to give a fine seedbed because they are hard to till. Cultivation at the right soil water content maximizes breakdown of clods and allows finer seedbed preparation. Thirdly, whenever hard pans occur and especially below the plough layer, subsoiling will be beneficial. This practice loosens the soil, allowing better air and water movement, and making it easy for plants to establish extensive root systems (Shepherd et al., 2000). Fourthly, crop rotations especially with crops that have vigorous root systems that act as biological repairers (Pulido Moncada et al., 2020a) can be a good alternative to alleviate soil compaction.

The simplified management thresholds used BD and SOC as indicators. BD is one of the parameters that is easily determined in most laboratories and has been used as a physical soil quality indicator (e.g., Reynolds et al., 2007). Due to its simplicity in measurements, researchers and agronomists can use BD to make management decisions following the given thresholds. In addition, also SOC can be readily determined. To improve and maintain SOC, farmers are encouraged to use no tillage systems, retain crop residues rather than removing them from the field and incorporate other organic materials to the soil such as, farm compost and animal manure (Shepherd et al., 2000).

4.7. The usability of VSEE methods

While there exists highly significant correlations between VSEE scores and soil physical properties, the use of these VSEE methods requires further actions. A major precondition for the use of visual evaluation methods is training. The training is important for all the involved parties and especially the extension officers and research institute personnel who can then train the farmers. An important aspect could also be to research on existing traditional methods of soil quality evaluation so that they can be merged with the VSEE methods. For easy use, VSEE manuals should be translated from English to languages that farmers can easily understand, e.g., Swahili for East Africa. After trainings, farmers can easily use the VSEE methods in the farms. A common

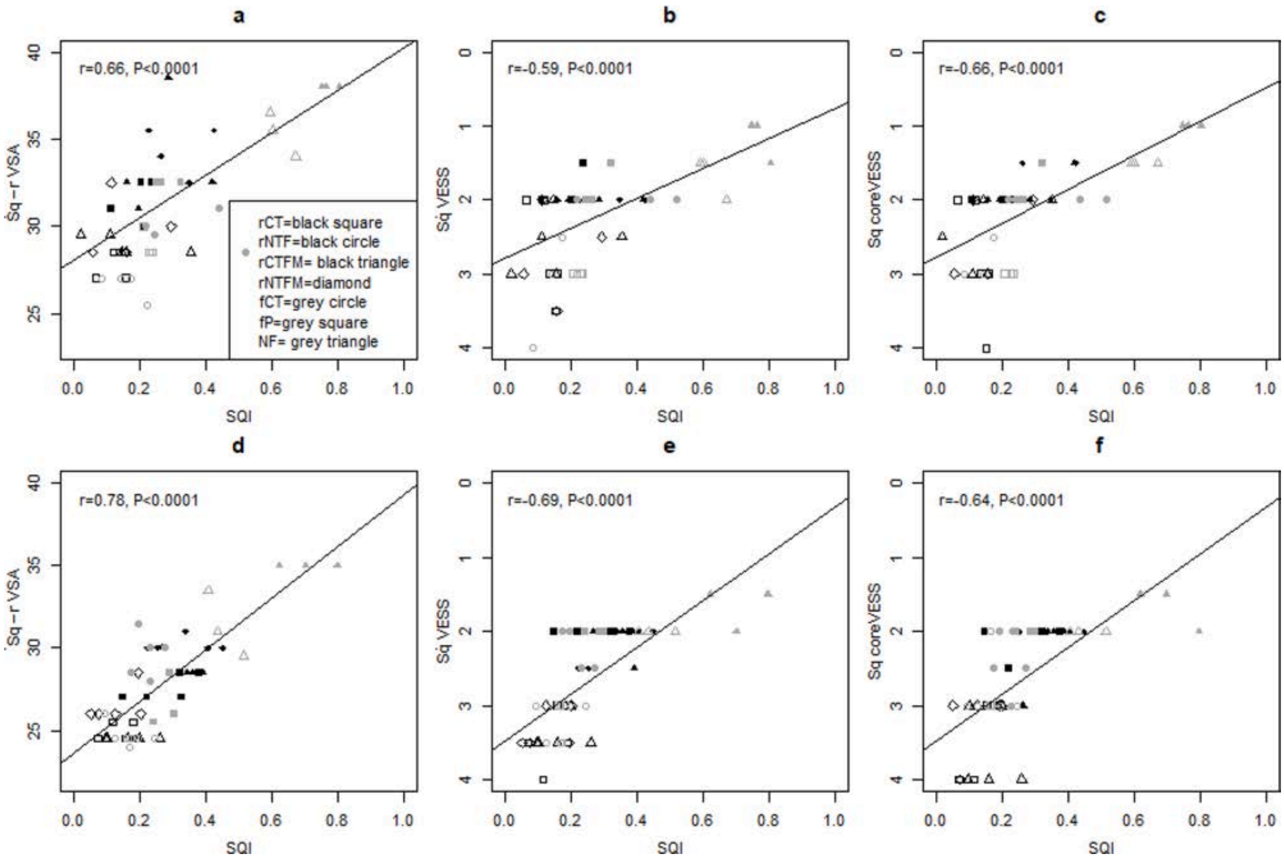

Fig. 9. Relationship between Visual Soil Assesment without considering rooting depth (sq-r VSA), Visual Evaluation of Soil Structure (Sq VESS), Visual Evaluation of Soil Structure using the core (Sq coreVESS) scores and Soil Quality Index (SQI) under clayey Nitisol (a-c) and sandy loam Cambisol (d-f). Sq is structural quality, CT is conventional tillage, NTF is no tillage with mulch and use of fertilizer, CTFM is conventional tillage with use of fertilizer and manure, NTFM is no tillage with mulch and use of fertilizer and manure, P is perennial crop, NF is natural forest, r and f represent researcher and farmer managed sites, respectively. Closed and open symbols presents top and sub soil layers, respectively. Full lines shows correlation lines while r shows the Pearson correlation coefficient.

Table 8
Bulky density (BD) values and their interpretation.

Limit value	BD (Mg m^{-3})		Corresponding coreVESS value		Interpretation
	Nitisol	Cambisol	Nitisol	Cambisol	
Target	0.0012*SOC+0.6476	1.48	Sq<2	Sq = 2	A guide value for soil management. Healthy soils should be below this value.
Trigger	0.93	1.56	Sq = 2	Sq = 3	Value above which the reasons for the poor soil structure quality should be investigated and soil management must be adapted to improve structure quality.
Remediation	0.99	1.64	Sq = 3	Sq = 4	Short term improvements of soil structure quality are needed.

SOC is soil organic carbon.

Swahili proverb says, "*mambo ya shamba uishia shambani*" translated as "farm matters are better discussed on the farm" (Pulido Moncada et al., 2020b).

5. Conclusion

This study demonstrated the ability of visual examination methods (VSA, VESS and coreVESS) to detect changes in soil structure resulting from different land use and management under both Nitisol and Cambisol. Derived correlations indicate that semi-quantitative VSEE methods are useful and reliable to inform farmers on soil properties related to aggregation, water movement, aeration and hence suitability of the soil for optimal root growth. These methods have an advantage in that it is possible to summarize in a simple score the overall structural quality of the soil which is easy to interpret by farmers with prior training. These methods can however not be used entirely as a replacement to laboratory measurement of soil properties. As the VSEE methods have been found to be useful diagnostic tools for evaluation and controlling soil structural quality, they could be used as an alternative procedure by resource constrained farmers or complimentary methods for periodic assessment of soil quality by researchers. As such, these methods have also been recommended for monitoring programmes by non-governmental organizations (Pulido Moncada et al., 2020b). Maize grain yield and the visual scores showed useful relationships, especially under the Nitisol. From the significant correlations obtained between VSEE scores and soil physical properties in the visual field assessments on Kenyan soils with contrasting soil type and land use and management, we suggest the methods as alternative complementary rapid field methods for assessing structural quality of tropical African soils. Based on the significant correlation between the three methods, either can be used in soil evaluation depending on the user and practicability. The determined management thresholds apply to Nitisols and Cambisols. Applicability to other soil types requires further investigation.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

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