Visual soil evaluation: a summary of some applications and potential developments for agriculture

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Abstract: Visual soil evaluation techniques have gained popularity and are increasingly used in agriculture and soil science for research, consultancy and teaching purposes. We describe recent applications, developments, opportunities and limitations, mainly of the Visual Evaluation of Soil Structure (for topsoil (VESS) and for subsoil (SubVESS)), and of the Visual Soil Assessment (VSA). Data are taken from experiments on compaction and from assessments made in farmer's fields in the UK, Brazil and New Zealand. The methods are widely used to detect compaction and are well-suited for monitoring changes in compaction status, particularly in relation to weather extremes. VESS proved useful in distinguishing grazing vs wheel compaction in the UK and Brazil by permitting detection of layers at different depths within the topsoil zone. The depths of compact layers are important for scoring management decisions for soil improvement. However the use of scores as limiting thresholds in different soil types needs the back up of further soil measurements and/or additional visual assessments of soil and crop. VSA and VESS were also used to estimate the risk of significant soil emissions of nitrous oxide where compaction damage was present and rates of mineral N fertiliser were high. Visual assessments also have the potential to assess the risk of surface water runoff and nutrient loss. The potential role of soil colour was shown for the further development of visual evaluation techniques for a soil carbon storage index. Visual soil evaluation techniques also provide a useful visual aid for improving soil awareness in groups of stakeholders, helping the exchange of knowledge and ideas for innovation in agriculture.

Editors of Special Issue of Soil & Tillage Research

Our Ref: BB/STR1

15 June 2016

Dear Thomas, Rachel, Lars and Mathieu

Manuscript: Visual soil evaluation: a summary of some applications and potential developments for agriculture

I enclose a revised version of the above paper on behalf of myself and colleagues for the special issue of 'Soil & Tillage Research' on Visual Soil Evaluation and Compaction Research. This is based on the two talks that I gave at the meeting in Brazil in May 2014.

Yours sincerely

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Shahid Hussain and Dr Lars Munkholm,
Journal Manager
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18th May 2016

Dear Shahid Hussain and Lars,

Ref.: Ms. No. STILL-16-214
Title: Visual soil evaluation: a summary of some applications and potential developments for agriculture Soil & Tillage Research: Revision notes and responses

You suggested that we revise our paper according to the comments of Reviewer 2. We could not find any comments by Reviewer 2. I checked with Lars and the Editor and they confirmed that we are to revise it according to the comments of Reviewer 3.

The comments of the reviewer are shown in italics below with our responses in plain type. In the paper, new text is shown in red.

A valuable paper summarising the possible methodologies and applications of visual soil evaluation. However, in its present form, the paper seems to be either incomplete or has confused aims. In its content the paper concentrates on the several specific examples of the application of visual soil assessment (VSA), but in its conclusions tends to imply very broad applications for VSA.

We have re-worded the last sentence of the Conclusions to align with the aims of the paper as stated in the Introduction. We have removed the suggestion that it provides an appreciation of the importance of soil for humankind and moderated our claim that it raises general soil awareness. We have adjusted the last sentence in the Abstract and the final Highlight to fit in with this.

The discussion and descriptions in the paper also tend to be somewhat data free in several critical instances. This may be forced on the authors because of the limitations of space, but it is noticeable. In several instances, the text is unclear and needs clarification, but these should be easily fixed.

The referee has made suggestions in his specific comments on where more data are required and our responses to these should have improved this along with clarification of areas of the text.

A reader approaching this paper with a broader view of soil science may be looking for more from this paper, especially about where VSA fits into the general field of soil and land evaluation. The suggestion is that the authors may benefit from considering the papers by Sanchez et al. (2003) and Palm et al. (2007) which discus some of the broader aspects of soil and land evaluation. Of course much depends on the objective of the paper. It would be possible to define exactly what aspects of environmental services and soil condition can be evaluated by VSA.

We have added three paragraphs to the beginning of the paper which explain the relevance of the application of visual evaluation techniques. In the first paragraph the idea of a fertility capability classification or soil productivity function (for cropping) in relation to land evaluation is introduced. The second paragraph shows the contribution of visual soil evaluation and soil structural quality to the specification of this productivity function. The third paragraph introduces the idea of visual evaluation for estimating environmental services and for guiding soil management decisions. In the second and third paragraph we state the main soil and environment properties that can be evaluated by use of visual soil evaluation.

A further potential lack of precision in the paper is the use of the terms soil health, soil quality and soil condition. All of which are used in the paper. This is a perennial and common problem because of the general lack of clear definitions and clear guidelines for the accepted use of these terms, but the authors may need to define on of these terms in the paper and settle a single use. The problem is more acute because VSA is a method to detect the effects of land management on soils, and the use of the terms soil health and soil quality has become confused between the inherent properties of the soil and those soil properties that are result of the effects of land management.

We have settled on the term soil quality for all references to scores from Visual Soil Evaluation. Soil quality is now defined in the second last sentence of the Introduction. We have also made clear that although, strictly speaking, the numbers given to soil quality refer to 'soil structural quality', this may be generalised to 'soil quality' as structure is such an important component of our definition of soil quality. This is now stated in Section 2.1.1. We have removed all references to soil structural quality, health and – where is refers to a measure of quality - condition.

Overall the paper is a useful contribution and needs to be published, but some revision is required.
Sanchez P.A., Palm C.A., Buol S.W. (2003). Fertility capability classification: a tool to help assess soil quality in the tropics. Geoderma 114: 157 – 185.
Palm C., Sanchez P., Ahamed C., Awiti A. (2007). Soils: A Contemporary Perspective. Annual. Review of Environmental Resources 32: 99–129.

Specific Comments
Section 1
The introduction lacks a description of the general context for the application of VSA. For example how does the application of VSA vary between soil types (Nitosols, Solonetz, Vertosols, Luvisols etc), and with the effects of different forms of land degradation (compaction, sodicity, salinity, acidification etc). This would provide readers with the background of when and how to apply VSA methodologies. The Special issue of Soil and Tillage can be used to summarise this?

We have added three sentences to the second last paragraph of the Introduction to state that soil structure is a generic indicator of soil quality and that although soil type may influence the actual estimate of quality, the application of the estimate (for example in highly degraded soils) in terms of soil function is largely independent of soil type. Specific aspects of different degradation processes are dealt with elsewhere in the paper.

Line 64
Soil quality needs to be defined or a reference given.

See our response to the general comment on soil quality above

Lines 74 to 86
Soil texture, sodicity and the presence of highly stable aggregates formed by sesquioxides can influence the interpretation of these scores.

This comment is similar to that made for lines 134-136. For texture, please see our response to that comment below. We have included statements on the influence of aggregation and factors that affect it such as sodicity related to soil types in a new second paragraph in Section 2.1.1. This includes a reference by Oades and Waters on aggregation.

Line 91
Greater contribution from biotic activity in subsoils? Presumably this refers to the activity of roots forming biopores?

To overcome the impression that biotic activity is greater in subsoils than in topsoils, we have made it clear that, in the absence of tillage, the relative contribution of the structure forming processes including biotic activity is greater in the subsoil. We have also replaced 'biotic activity' with 'biopore creation'.

Line 95
Explain what the "anthropic transition layer" is.

We have explained that this is layer or pan just below the topsoil that was compacted or smeared during tillage or harvesting.

Lines 87 to 115
A large block of text. Break up into paragraphs?
Or suggest
At line 74 have subsection 2.1.1 – The Method
At line 116 have subsection 2.1.2 – Scoring
At line 127 have subsection 2.1.3 – Applying the Method in the Field
At line 155 have subsection 2.1.4 – Interpretation of the Results

This is helpful and we have adopted the scheme. We have re-ordered the material slightly in section 2.1.3 to start with a more general statement 'The recommendation for the test is..' that was at original line 131. We have also brought up some of the material on moisture content at sampling from lines 151 – 154.

Line 127
Suggest "….In dry and hard soils…." – delete "However"!

Done

Line 127

Give World Reference Base equivalents for Oxisols and Alfisols

Done. We have moved these definitions up to the location where these names are first given, the second paragraph of Section 2.1.1

Line 132
Explain what is the friable range of water contents based on field capacity, plastic limits or both.

We have defined the friable range in terms of plasticity limits and given a reference to a soil physics text in a new second sentence to Section 2.1.3

Line 136
Use words instead of acronym "..longest dimension about 7 – 10 cm".

Done

Lines 134 – 146
This method does seem to assume soils in the loam and clay loam texture groups based on the description of the behaviour. Perhaps a few comments on how soil texture and sodicity might affect the observed behaviour are appropriate.

The influence of texture on cohesion is discussed in the fourth and sixth sentences of new Section 2.1.1.

Line 150
Is there a simple field test to determine if the moisture content is suitable for making a valid VSA? For example the rolling of a rod of soil or change of colour on wetting?

We have added a statement that in soils that are too wet for visual evaluation and that are finer than sandy loam in texture will readily roll into a thread. This statement has been moved up to be close to the statement that was originally at line 132. It forms the third sentence of Section 2.1.3.

Lines 151 – 154
This does not completely appear consistent as Oxisols by definition should drain very quickly. Do you mean Vertosols?

We agree.

Line 156
Use of the term soil quality v soil condition. Need to distinguish between inherent soil properties and those that are a result of the effects of land management.

This relates to the earlier discussion on soil quality where we decided to focus on the term quality. We have re-worded this statement to make it clear that consultants' usage is to monitor quality as affected by land management and to inform future management decisions.

Line 178

An overall "block" score or "profile" score? Profile score is clearer?

This paragraph refers to the topsoil VESS and we are referring here specifically to the score of the extracted block. Further, since the term profile has meaning in soil science relating to the full depth of soil we prefer to use block. To make our meaning clear we have stated 'topsoil block'

Line 218 – 229
The potential problem with such comparisons is that it is often not practically possible for soils under agricultural production to be rehabilitated to the condition that they had under native forest.

To make it clearer that we are not necessarily suggesting that the target is to get back to the structural condition of a native forest, we have used the term 'indicator' rather than 'reference' for the soil quality. We have also make it clearer that such a comparison is not always possible by making an insertion at the beginning of the sentence. In the following sentence we have also stated that use of this indicator can show whether there has been a decline in quality as well as the extent of any decline.

Section 2.3
An important Section but lacking in any data or examples. A few good examples of published relationships between VSA and observed soil properties would add substantially to the credibility and perceived usefulness of VSA methodology. It is essential for the usefulness of this paper that examples of these relationships be demonstrated here, not just referenced. The recommendation is that a table showing some of the key relationships along with the statistical significance of the relationships be included.

We have now included a new Table 2 that summarises some of the relationships of VESS scores with other soil properties as regressions or correlations.

Lines 251 – 256
The timing of the VSA assessments is critical. The period in the cropping or pasture cycle needs to be standardised, especially if year to year comparisons are to be made and long term trends identified.

Yes, we agree. We have inserted two sentences after the current second sentence that explain that the frequency of measurement may reveal information about different processes with annual appraisal on a fixed date may revealing longer term impacts of the rotation while within year assessment may provide short-term detail on individual agricultural operations.

Line 270
Suggest "....can damage soil structure..."

Done

Lines 272 – 274

Because VSA largely assesses soil structure. Many of the effects on yield detected by VSA are likely to be event driven and vary from year to year depending on rainfall and moisture conditions (runoff, poor germination, poor drainage etc).

Agree. We have stated that any damage to soil structure resulting from the effects of routine crop management due to compaction or tillage events will be reflected in changes in VESS scores and included a statement at the end of the paragraph that soil quality whether measured by visual assessment or other means is not the only driver of crop or pasture production.

.

Lines 278 – 279
Suggest " .....were established (24 x 20 m) which included trampling....."

Done

Lines 287 – 291
A bit confusing. A lower score means a better structure in VESS yet some of these comments do not seem consistent with this??? Please check.

Yes, we needed to change 'poorer' to 'improved' at original line 288 (line 359 in the revised version).

Line 306
Waterlogging in combination with sodicity can especially degrade soil structure. What is the mechanism of soil structure degradation from water logging in non-sodic soils?

We have explained the mechanisms in an insertion extending the first sentence and adding a new second sentence to the last paragraph of Section 3.1.

Lines 324 – 328
Support with the few numbers and facts.

We have added some facts and numbers from measurements of how increases in structural score were accompanied by increases in moisture content and nitrous oxide flux and decreases in carbon dioxide flux. These appear in the second half of the first paragraph of Section 4.1.

Lines 328 – 362
The explanation and the accompanying Figure (4) are confusing and unclear. Something appears to be missing in Figure 4 as the Figure is almost incomprehensible as it stands. Perhaps when the Figure is resolved, the rest of the explanation will become clearer, but understanding the explanation at the moment requires a high level of intuition.

We apologise that an incompletely labelled version of Figure 4 was submitted. A complete version is now submitted. We have also extended our explanation to make the relationships between water content, WFPS and nitrous oxide emission clearer. We have also added information on carbon dioxide and methane emissions.

Line 369
Rather an obtuse explanation requiring to many jumps from the reader. What exactly is meant by "poor quality soils"???

We have extended this sentence to make it clear that poor quality soils resulted from pugging or poaching and that the damage extended throughout the topsoil.

Line 375
Again more explanation required.

We have inserted a statement that the churning of the soil surface due to poaching increased the soil surface area.

Line 396
Suggest "The compaction of grassland soils…….."

Done

Lines 400 – 403
Unclear what is meant by "positive raltionship"??? Explain more clearly.

We have re-worded this to make it clear that SOM content and percentage sand content were both positively correlated with the VSA score

Line 418
No such texture group as "coarse loamy". Please give proper soil texture classes included in the is study. Also "soil structure damage" is a very general term. Did this involve loss of SOM, compaction, surface crusting.

We agree but this is as the soil description is written in the original reference. Similarly "soil structural damage" is as used in the reference but we agree that the statement is not clear and have changed the text to reflect what they were referring to i.e. surface slaking and loss of aggregation.

Lines 428 – 429
Expand on link between
nutrient leaching and soil hydraulic properties.

We have added a sentence that explains the potential use of visual techniques in this area because of the good associations found by Moncada et al. (2014a) between the results of visual examination and water flow properties, some of which are shown in Table 2.

Lines 443 – 448
Strange place to introduce this. Suggest adding to Section 4 as Section 4.4 Use of Image Analysis in VSA .

We do not agree with the reviewer that this para is better in section 4. It is here because we have just had a paragraph explaining the use of photographs and computers. Also Section 4 is specifically about the application of VSE for greenhouse gas emissions, carbon sequestration and leaching. We would prefer to leave this paragraph where it is.

Line 456
Not really scientific to describe the soil as "a living organism". Rather emphasise the importance of living organisms in soils.

We have re-worded this to emphasise the importance of living organisms within the soil to functions such as chemical changes and gas emissions.

Lines 466 – 517
More emphaisis on the depth where VSA assessed an its implications for basic functions such as germination, emergence, aeration, infiltration etc. Might also mention that VSA cannot necessarily assess for factors such as acidification, nutrients and general environmental services etc.

This section focuses on the use of VSE to allow soil management decisions aimed at improving or maintaining quality. We have made this clearer by re-wording the first sentence. We do agree that use should be made of the depth discrimination made possible by using VESS to relate near surface soil quality to germination and emergence or to determine the suitability of soils for no-till or minimum tillage or susceptibility to run-off. We have added two sentences to this effect to the end of the second paragraph. We have also stated that zones of Sq 4 close to the soil surface are likely to be more of an agronomic limitation as they will tend to limit early growth. We have added a sentence about this to the end of the third paragraph. In the next paragraph, where we discuss limitations to no-till in Brazil, we have included a statement that clods were found throughout the topsoil. We added two sentences at the end of this section making it clear that VSE is not a universal management tool. It needs to be accompanied by other relevant soil measurements such as pH, organic matter and chemical analysis in order to assess the status of aspects such as soil nutrients, chemical degradation and ecosystem services.

Line 539
Use of term soil condition!!!

We replaced this with the term soil quality as explained in our response to the General Comment on this aspect.

Lines 553 – 556
Evidence that a more general aim is intended for this paper?????

The title of this section 5.3 has been expanded to include the term 'knowledge exchange' so that the section more closely reflects the objectives as stated in the Introduction. We have deleted the second sentence which perhaps strays outside the general scope of this paper.

Table 3
Should be some explanation of what the Soil C Index is???

We have included a brief explanation in the caption to Table 3.

Figure 4
Something missing in the explanation of this figure??????
Yes, as explained above, a revised, complete version has now been submitted.

Highlights:

- Recent improvements and integration of VESS for topsoil and subsoil are described
- VESS detects compaction well and discriminated between damage by tractors and livestock
- Visual soil evaluation can estimate the risk of loss of N_2O, soil carbon and nutrients
- Visual soil evaluation can bring an awareness of soil quality to a range of users

Visual soil evaluation: a summary of some applications and potential developments for agriculture

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ABSTRACT

Visual soil evaluation techniques have gained popularity and are increasingly used in agriculture and soil science for research, consultancy and teaching purposes. We describe recent applications, developments, opportunities and limitations, mainly of the Visual Evaluation of Soil Structure (for topsoil (VESS) and for subsoil (SubVESS)), and of the Visual Soil Assessment (VSA). Data are taken from experiments on compaction and from assessments made in farmer's fields in the UK, Brazil and New Zealand. The methods are widely used to detect compaction and are well-suited for monitoring changes in compaction status, particularly in relation to weather extremes. VESS proved useful in distinguishing grazing vs wheel compaction in the UK and Brazil by permitting detection of layers at different depths within the topsoil zone. The depths of compact layers are important for scoring management decisions for soil improvement. However the use of scores as limiting thresholds in different soil types needs the back up of further soil measurements and/or additional visual assessments of soil and crop. VSA and VESS were also used to estimate the risk of significant soil emissions of nitrous oxide where compaction damage was present and rates of mineral N fertiliser were high. Visual assessments also have the potential to assess the risk of surface water runoff and nutrient loss. The potential role of soil colour was shown for the further development of visual evaluation techniques for a soil carbon storage index. Visual soil evaluation techniques also provide a useful visual aid for improving soil awareness in groups of stakeholders, helping the exchange of knowledge and ideas for innovation in agriculture.

Keywords: soil management; compaction; VESS

1. Introduction

Land evaluation methods require approaches that improve our understanding of the links between specific soil properties, soil processes, ecosystem services and soil degradation (Palm et al., 2007). A particular need was identified in the Tropics for scientifically rigorous, quantitative classification of soil fertility capability based on soil quality (Sanchez et al., 2003). Assessment of fertility capability, also known as the productivity function of soils, needs to be capable of integration within land evaluation frameworks and to be able to operate anywhere at a range of spatial scales (Mueller et al., 2012).

A key component of any such productivity function is the description and quantification of soil quality (Mueller et al., 2012). Visual soil evaluation is an important component of the assessment of agricultural soil quality (Mueller et al., 2013). Soil structure is a key aspect of soil quality that is sensitive to soil degradation (Mueller et al., 2012). Visual evaluation of soil provides important components of assessments of soil quality such as the Muencheberg Soil Quality Rating (Mueller et al., 2013) and the SoilPAK system for farm evaluation (McKenzie, 2013). Visual soil evaluation can specify ‘core’ soil indicators such as soil structure, rooting depth, wetness and slope and on specific hazard indicators such as high risk of flooding, drought or contamination which can be combined with climatic information to give a globally-applicable overall soil quality rating (Mueller et al., 2012).

The potential of visual evaluation of soil structure and related soil and land properties for specifying the environmental services of carbon storage, nutrient retention and reducing nitrous oxide (N_2O) emissions related to agriculture was recognised by Shepherd (2009). These use visually-assessed soil properties that include structure, rooting depth, texture, colour and mottling allied to visually assessed crop properties, location and farm management information. Visual soil evaluation techniques are applicable at the farm level and are important for guiding farmers in making soil management decisions (Shepherd, 2009; McKenzie, 2013; Guimarães et al., 2011).

A range of soil visual evaluation methods is available to assess fertility and soil structure (Boizard et al., 2007). The main methods of visual evaluation of soil structure focus on describing soil aggregates, porosity and rooting that relate to water storage and transport, root development and nutrient uptake. Soil structure is a generic indicator of soil quality and although soil type may influence the actual estimate of quality, the application of the estimate (for example in highly degraded soils) in terms of soil function is largely independent of soil type. The exceptions are peaty and sandy soils that have poorly developed structures and in paddies where aggregation is deliberately destroyed by tillage when very wet. Evaluation methods can be categorised into four types: (i) topsoil examination only such as the Visual Evaluation of Soil Structure (VESS) (Guimarães et al., 2011) and the Visual Soil Assessment (VSA) drop test (Shepherd, 2009); (ii) subsoil only e.g. SubVESS (Ball et al., 2015); (iii) topsoil and subsoil together such as SOILpak (McKenzie, 2013), ‘Profil Cultural’ (Peigné et al., 2013) and (iv) assessments that describe and measure more than soil structure such as the complete VSA analysis (Shepherd, 2009) and the Mueller Soil Quality Rating (M-SQR) (Mueller et al., 2013). A recent special issue of Soil & Tillage Research (Munkholm et al., 2013a) and book (Ball and Munkholm, 2015) summarised common methods of visual soil evaluation and their application to crop production, land appraisal, soil quality, soil compaction and the wider environment.

Here we focus mainly on the application of the topsoil and subsoil VESS in greater detail than in these recent publications. We summarise the VESS techniques and recent improvements in use and application, including the assessment of layering and the use of reference soils. We then show how VESS and VSA techniques can be applied for monitoring soil quality and fertility as influenced by soil management, for assessing the risk of greenhouse gas (GHG) emissions, carbon sequestration and leaching and for fostering stakeholder engagement in agricultural knowledge exchange and innovation. Here and throughout we follow the commonly accepted definition of soil quality as the capacity of a specific soil type to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation (Karlen et al., 1997). Data are from experiments on compaction and from use in farmer's fields in the UK, Brazil and New Zealand.

2. Summary of Visual Evaluation of Soil Structure (VESS)

2.1 General description of VESS and SubVESS

2.1.1. The method

The topsoil VESS (Ball et al., 2007; Guimarães et al., 2011) is a development of the Peerlkamp spade test (Peerlkamp, 1959) and retains emphasis on the evaluation of the sizes, shapes and visible porosity of broken soil fragments and aggregates. Root numbers within and between aggregates are also diagnostics. The method involves the removal and gentle breakup of a spadeful of topsoil by hand to reveal the main structural units and any layers of contrasting aggregation. The state of the spadeful of soil depends on texture as well as on the structure to be described. Comment on other factors such as water status is given below. While the cohesion of the spadeful of soil is less in very sandy soils, under the right conditions and with the appropriate care, soils from all other textures can be extracted. Each layer is compared to the photographs with identified dimensions and descriptions in a coloured chart and allocated to one of five soil quality (Sq) scoring categories. Strictly speaking, Sq scores are a measure of the quality of the soil structure. Structure is such an important contributor to the definition given by Karlen et al. (2007) at the end of the Introduction that we refer to scores throughout the text simply as 'soil quality'. Experienced users and those with knowledge of soil structure or soil physics can confidently assign scores in between categories. Inexperienced users only require 1-2 h of training to start meaningful scoring. Brief descriptions of the scoring categories from Sq 1=best to Sq 5=worst topsoil quality (VESS) and Ssq 1=best to Ssq 5=worst subsoil quality (SubVESS) are shown in Table 1.

The nature and behaviour of aggregates or their absence underpins many of the soil properties involved in visual evaluation. It follows that soil, environmental or management factors that favour aggregation (e.g. high cation exchange capacity, low exchangeable sodium percentage, and growing root systems) are associated with improved VESS scores, while those associated with a loss of aggregation (e.g. low cation exchange capacity, sodicity and waterlogging) are likely to be detrimental to VESS scores. Oades and Waters (1991) identified different aggregate stabilising mechanisms in different soil types with organic materials being dominant in Alfisols (Luvisols, WRB) and Mollisols (Chernozems, WRB) but oxides being the dominant agent for Oxisols (Ferralsols, WRB). They noted that Alfisols and Mollisols broke down sequentially in water indicating an aggregate hierarchy while the Oxisols were very stable in water but when breakdown did occur it was to clay sized particles. While aggregation mechanisms vary, the existence of these structural units across a wide range of soil types supports wide utility for visual classification schemes that include aggregate properties as a key measure.

A major feature of VESS is its ability to detect compaction damage. In extending this approach to the subsoil it was realised that a profile assessment was more suitable than a spade test. Subsoil aggregation and porosity differ from those in the topsoil because of the decreased role of organic matter and tillage and the greater relative contribution of swelling and shrinking, freezing and thawing and biopore creation to structure formation. Subsoil examination begins below spade depth (typically *c*. 25 cm), usually just beneath the topsoil and often below any Ap horizon where there may be a critical zone or pan that has been compacted or smeared by machinery during tillage, planting or harvest and termed the anthropic 'transition layer' by Peigné et al. (2013). As with topsoil VESS, subsoil layers are first identified (usually between 2 or 4) and each layer is scored. Physical differences are less visible in the subsoil than in the topsoil. Thus the subsoil version of VESS, SubVESS (Ball et al., 2015) involves a more comprehensive and progressive assessment of individual visual and tactile aspects. First mottling, then strength, porosity, roots (where present) and finally aggregates are assessed from which an overall SubVESS score is given. Scoring involves inspection of both the profile face after removal of soil that was structurally damaged during excavation – mainly for strength, rooting and macroporosity – and of fragments removed from the profile face. The descriptions of the subsoil quality (Ssq) scoring categories of SubVESS, given in Table 1, are mainly based on assessment of fragments to allow a succinct comparison with VESS. A more progressive assessment of individual visual and tactile aspects such as used in

SubVESS may be worthwhile for topsoil VESS, particularly when used for research purposes. A better description of porosity to reflect the importance of its contribution to drainage, aeration and root growth and of fragment stability to distinguish intensively tilled soils from stable aggregates would be useful to extend the role of VESS to better reflect agronomic limitations (Ball and Munkholm, 2015). For example, the human eye can usually see objects down to *c.* 20 μm diameter. This is just below the limit typically used to classify macropores i.e. pores that are drained of water at field capacity. Thus there is a link between pores seen by the human eye and those pores contributing to easy drainage of water.

2.1.2 Scoring

The VESS and SubVESS methods (Table 1) are suitable for use together. However SubVESS uses a separate and distinct scoring scale from VESS (Sq for topsoil and Ssq for subsoil) (Table 1) and the scores are not interchangeable. For example, in VESS scores Sq 1 and 2, comments on porosity relate to pores within aggregates (intra-aggregate porosity) but in SubVESS they relate to pores between aggregates (inter-aggregate porosity). Mottling is possible in Ssq 2−5 but only likely in Sq 4 and 5.

VESS is often sufficiently rapid to allow easy replication for statistical validation of the results. As a range of intermediates between scores are possible, they can be treated as continuous variables. Analysis of test samples revealed that distributions of scores were normal (Ball et al., 2007) so that robust mean scores are given.

2.1.3 Field application

The recommendation for the test is to avoid extreme wet or dry conditions and to sample preferably within the friable range of water contents *i.e.* when the soil crumbles under an applied load. This range will vary with soil texture but is between the shrinkage and plastic limits (Marshall et al., 1996). When the soil is too wet, *i.e.* beyond the plastic limit or field capacity, aggregates can be hard to discriminate and soils finer than sandy loam in texture will readily roll into a thread. In heavy textured soils with poor aggregation, such as in some Vertisols, the soil may need to drain for 3 days before sampling or longer in a post-harvest field under stubble or where covered with residues. In dry and hard soils, such as some Alfisols and Oxisols, the test can take much longer (Giarola et al., 2013). Although VESS works well in clayey tropical Oxisols, factors such as soil water content can influence the scores along with the presence of visible porosity even in compacted aggregates (Batey et al., 2015).

After breaking the block, break-up of the major aggregates with minimum subjectivity is particularly important to help ensure accurate scoring. We recommend the 'single-hand' method where a fragment of soil of longest dimension about 7−10 cm is placed in the palm, held in the fist position and progressively squeezed to break it. The force should be applied by closing the palm of the hand (like making a loose fist) in order to apply force evenly to the fragment rather than using the fingertips or thumb. If the fragment crumbles after applying force evenly, an Sq3 score is given, if it does not crumble an Sq 4 or 5 score is appropriate. Repeated application of this 'single hand' test to the same fragment will eventually result in break up, although it does not necessarily mean that the fragment score is Sq3. The appearance of macroporosity throughout is important for Sq 1−3 and only becomes diagnostic when porosity is limiting because the soil is compact. Thus in Sq 4 and 5 the large biopores

(> 1 mm diameter) become few, < 1 per 10 cm^3, and isolated so that they appear very distinct.

When the soil is too dry to be scored (less than the friable limit) with VESS, the aggregates become too hard to break up. Alternatively, in some soils, the aggregates become too fragile. When the soil is too wet (beyond the plastic limit), the fragment smears rather than breaking apart.

2.1.4 Interpretation of results

In our experience agricultural consultants and farmers tend to use VESS and SubVESS for rapid assessments of soil to monitor quality as affected by land management and to inform future management decisions. For topsoil assessments (e.g. suitability for use of no-till), a spade-hole is dug and a rapid overall assessment is made from the extracted sample. For subsoil assessments (e.g. to estimate the risk of waterlogging due to restricted water movement) then an intact sample may be extracted from below the spade depth with a smaller spade (~20 cm long) or with a large auger for application of SubVESS (Paul Hallett, personal communication, 2015). In this case SubVESS scores are based only on the condition of the fragments produced on breaking-up of the intact sample.

Scores (not necessarily an integer) are attributed as a weighted mean of layer scores across the sample from top to bottom. For subsequent data analysis it is important to record not only the score of the individual layers but the depth of any boundaries. In topsoil VESS, no more than three layers are possible within a spade depth of 25 cm. Any further division is impractical on the basis of insufficient sample to be rated. An exception to this may occur if the soil is slumped at the surface or if a thin platy pan is present. In practice, the depth range of the sampling layer is confined to > 5 cm and scoring to integer values.

2.2 Detection of layering, inversion and use of reference soils

The position and score of any compacted layer are very important and can provide more specific information for appropriate, targeted management than an overall topsoil block score. A field experiment in Paraná State, Brazil, where compaction by livestock appeared to be influencing crop productivity, illustrated the importance of identifying the location of the compacted layer within the profile. The treatments evaluated were two systems where no-tillage soybean was cropped in the summer and, in the winter, were under ryegrass (*Lolium multiflorum*) that was either a) grazed or b) cut for silage. Ten spadesful of soil were extracted from each area 45 days after the harvest of the summer soybean crop and scored with VESS.

Despite the different managements, both had a mean Sq of 3.7 (Fig. 1). However, scoring of the individual layers from 0–10 and 10–25 cm (Fig. 1) revealed differences in structural quality that were clearly visible during block inspection (Fig. 2). Both treatments contained a highly compacted layer with Sq 4 or higher, but at different depths. In the grazing plus cropping system the compacted layer was near the surface (occasionally extended to 14 cm depth) and with scores mostly of Sq 4 with one intermediate of Sq 4.5. In the conserved grass and cropping system the compacted layer was below 15 cm depth (most samples of Sq 4, with one at Sq 5). This treatment difference was likely to have resulted from the cattle hooves that, although applying more pressure than the tractor, compacted a smaller contact area under drier conditions than the tractor tyres. Silage operations require machinery typically with wheel loads greater than 7,000kg and 5 or 6 passes over the soil, during, mowing, turning and harvesting, often in wet conditions. The silage area at the time of sampling was under volunteer radish (*Raphanus sativus*) and rye grass that helped to improve soil quality due to vigorous root growth and stimulation of microbial activity. For example, Williams and Weil (2004) reported that the root channels created by forage radish alleviated the effect of compaction on soybean roots. The contrasting grass treatment produced different soil conditions for establishing the summer crop.

From our recommendations based on the VESS scores (Guimarães et al., 2011), the presence of a restricting layer near the surface in the grazed system was likely to require remediation by mechanical intervention whereas the same layer in the conservation system was of adequate soil quality and did not require short term remediation. Thus management decisions based on scores of the individual layers would differ from those made on the overall block scores as these would have been used to consider longer term changes in management to improve soil quality. The farmer in this area reported that during wet years there were no differences in soybean yield between the two areas, although in dry years the grazing plus cropping system produced 20% less than the silage plus cropping system. This is possibly because the presence of the compact surface layer restricted infiltration of water into the topsoil and root penetration to water at depth. Guimarães et al. (2011) also showed the importance of assessing the position of compacted layers using VESS for potential crop productivity in addition to soil management.

While not always possible, sampling soils in their original, native condition such as under native forest, or soils that have been less cultivated or disturbed such as permanent grass or a fence-line can provide an indicator of good quality. Comparison with agricultural soil provides information on whether and how far management has degraded the soil. The use of a reference soil is thus important to determine whether an area was subjected to compaction and/or loss of soil organic matter (SOM) as a result of management. Scores under native forests are typically between Sq 1 and 2 under Cambisols, with the better soil close to the surface (Guimarães et al., 2013). Poorer scores than this may occur in a secondary forest or in forest that has been disturbed as is common near urban areas. For example, in the above experiment the average structural quality under the forest was Sq 1.9. Although never cultivated, this forest had been subjected to a selective harvest 20 years ago.

2.3 Relating soil measurements to VESS scores

Several authors have shown correlations between VESS and other soil physical measurements, indicating that VESS, along with other visual assessment methods, can reveal differences between land use types and management options (Batey et al., 2015). VESS was related to a range of other soil quality indicators, some or which are summarised in Table 2, namely tensile strength (Guimarães et al., 2011), bulk density (Guimarães et al., 2013; da Silva et al., 2014; Moncada et al., 2014a), soil porosity (Munkholm et al., 2013b; Moncada et al., 2014ab), soil organic carbon (Moncada et al., 2014a), mean weight diameter of aggregates (Abdollahi and Munkholm, 2014; Moncada et al., 2014b), penetration resistance (Guimarães et al., 2013), least limiting water range (Guimarães et al., 2013), saturated hydraulic conductivity, unsaturated hydraulic conductivity and plant available water capacity (Moncada et al., 2014ab) and soil respiration (Cui and Holden, 2015). VESS has also been related directly to crop yield (Mueller et al., 2009; Munkholm et al., 2013b; Giarola et al., 2013). These relationships clearly show the relevance of soil quality derived from visual soil evaluation to other measurements of soil quality for a range of soil types.

3. Application of Visual Soil Evaluation for soil quality monitoring

Plant productivity can be directly influenced by the structural quality of the soil (Douglas, 1997; Botta et al., 2006; Koch et al., 2008). Visual soil evaluation is a useful estimate of soil quality at the time of measurement and, with repeated measurements, can quantify change. As with any measure of soil quality the frequency of measurement may reveal information about different processes. For example, for cropping an annual appraisal on a fixed date may reveal longer-term impacts of the rotation while within year assessment may provide detail on individual agricultural operations. Based on trends from such assessments, management decisions can be made to maintain, or to attempt to alter declining, status.

Digital photography to record the structure, colours and soil aggregate structure of the loosened samples can help record assessments, identify trends and compare soil quality between sampling points using photographs or on a computer. VESS assessments can assist in diagnosing soil problems that limit crop yield within a field. Scores under normal yielding areas can be used as a benchmark for comparison with low yielding areas and may enable identification of structural problems that need remediation.

3.1 Monitoring compaction and waterlogging effects

The VESS assessment has been used in conjunction with other physical measurements in a number of research projects that have addressed changes in soil structure and their effects on cropping (Ball et al., 2007; Guimarães et al., 2011). The compounding effects of routine crop management can damage soil structure over one or more compaction or tillage events and these changes will be reflected in VESS scores. The VESS assessments from a compaction experiment based on a grassland sward on an imperfectly drained silty clay loam (Gleyic Cambisol) in south-west Scotland (55°02'N, 3°W) (for further details see Ball et al. (2013)) showed a decrease in soil quality over time. Three main treatments areas were established (24 x 20m) which included trampling by dairy heifers, mechanical compaction from a tractor and a control of no compaction as three replicate blocks. The target ground pressure was 200−250 kPa, achieved by using heifers of average weight 532 kg and a loaded tractor of total weight 10.1 t. Compaction treatments were applied each autumn (October/November) from 2011 until October 2013 with three silage cuts taken in each subsequent year. VESS assessments were made throughout the experiment, after each application of the compaction treatment. The first application of the compaction treatments produced the most significant change in soil structure (Fig. 3). Of course, soil quality whether measured by visual assessment or other means is not the only driver of crop or pasture production.

The mean VESS scores for the no compaction treatment over the three years was 2.7 which was lower (improved structure) than the scores for both the tractor ($P<0.001$) and the trampling compaction ($P<0.01$). The VESS assessment showed the effects of the first and second compaction treatments on the soil structure from the trampling (2.7 to 2.8) from the compaction treatment in 2011 and 2.8 to 3.0 in 2012. The marked increase in VESS score in both compaction treatments over the winter of

2012–13 reflected the unusually wet conditions that made the soil susceptible to the compaction/deformation treatments. The tractor compaction gave an increase in VESS score from 2.7 to 3.4 after the first compaction treatment and from 3.6 to 4.2 after the second, made under unusually wet conditions (Fig. 3). The overall VESS score changed from a mean of 2.7 for the trampling compaction, which did not indicate any concern for soil structure or need to change management to a mean of 3.6 in 2014, indicating some change of management was needed to prevent the soil structure deteriorating further. The increased VESS score of 4.1 for the tractor compaction by October 2014 indicated more immediate and physical interventions would be needed (Fig. 3). The compaction extended below the topsoil so any improvement to the soil structure would be dependent on how deep the compaction layer was within the soil profile, which would have required further investigation using SubVESS, for example.

Waterlogging, especially of finer textured soils, can degrade soil structure, through the increase in bulk density of the lower horizons (Tishchenko et al., 2013; Thomasson, 1978). The lack of oxygen also creates chemically reducing conditions that can denature organic polymers involved in aggregation, cause precipitation of oxides that change soil colour, produce phytotoxic by-products that result in characteristic unpleasant odours and result in greenhouse gas emissions (section 4.1) (Weil and Brady, 2016). VESS was assessed in a silty loam soil in February 2010 on a grassland sward adjacent to the experiment described above. Soil that had been under standing water for 3 months gave scores of 3.5 and 4 that were greater than those in nearby non-waterlogged soil where the mean was 3.1 ± 0.1. These scores reflected how waterlogging had impaired the soil structure. The waterlogged soil was a dull grey colour with orange colours in the root and worm channels, all indicative of long-term chemical reduction.

4. Application of Visual Soil Evaluation for greenhouse gas emissions, carbon sequestration and N leaching

4.1 Greenhouse gas emissions

Although gas exchange is not related directly to the topsoil appearance, assessment of soil structure changes with depth using visual techniques is important in identifying layers active in the production and transmission of gases or layers that restrict gas exchange or are likely to be anaerobic (Ball, 2013a; Ball et al., 2013). These authors found that, in an arable soil in Scotland, as VESS score increased to Sq 4 or 5, the structure became more compact, causing greater soil wetness and N_2O emissions increased and carbon dioxide (CO_2) emissions decreased. For example, compaction during carrot production produced scores of Sq 5 to 30 cm depth. The large compact clods and minimal macroporosity reduced aeration in the succeeding forage crop. At 15-20 cm soil depth this resulted in increases in gravimetric moisture content of 7 g $100g^{-1}$ and in N_2O flux of 460 g N_2O-N ha^{-1} d^{-1} and a decrease in CO_2 flux of 17 kg CO_2-C ha^{-1} d^{-1} compared to less compacted areas of Sq 3. Structural damage is especially important within a few cm of the soil surface. For example, in a sandy loam under spring barley, at field capacity N_2O emission at 5 cm depth was ten times greater in soil of Sq 5 than in soil of Sq 2 (Ball et al., 2013)..

Quantitative indicators of flow and macroporosity relate to visual evaluation scores and clearly show the relevance of such scores to properties governing GHG emissions and nutrient leaching (Shepherd, 2003). As water-filled pore space (WFPS) - the proportion of pores filled with water - increases to saturation, CO_2 and N_2O, and finally CH_4 are emitted. The relationship between soil WFPS and the VSA assessment of soil porosity has been proposed as a ready guide to the susceptibility of a soil to emit GHGs (Shepherd, 2009).

The WFPS and water content at which GHGs are emitted in a Kairanga series soils, New Zealand, under pasture and at varying degrees of structural degradation under increasing periods of continuous cropping and conventional cultivation are shown in Fig. 4. Where the soil is moderately well-structured (VSA structure score of 1 and soil porosity score of 1.5), a water content of approximately 42 m^3 $100m^{-3}$ is required to ensure >70 m^3 $100m^{-3}$ WFPS and therefore able to generate significant emissions of N_2O. In contrast, a severely compacted soil after 11 years of poorly managed maize cropping with a VSA porosity score of 0 requires a water content of only 33 m^3 $100m^{-3}$ to reach the threshold 70 m^3 $100m^{-3}$ WFPS (Fig. 4). While the WFPS needs to reach 60-65 m^3 $100m^{-3}$ for substantial emissions of N_2O to occur (i.e. critical WFPS), the highest emissions occur by denitrification when the WFPS is between 70 and 90 m^3 $100m^{-3}$ with lowest emissions at WFPS < 50 m^3 $100m^{-3}$ (Fig. 4).

The critical WFPS is a major driver of GHG emissions and in finer textured soils is reduced as the degree of saturation required to generate GHGs decreases so that these soils tend to emit more GHGs than coarser textured soils. Soil CO_2 emissions increase linearly with increasing water content to a maximum of approximately 60 m^3 $100m^{-3}$ WFPS before decreasing and CH_4 emissions occur in very wet soils (WFPS > 95 m^3 $100m^{-3}$) with anaerobic conditions (Fig. 4). The severely compacted soil will therefore produce more GHGs than the well-structured soil because of the greater number of days during the year when the soil water content results in WFPS ≥ 70 m^3 $100m^{-3}$ WFPS (Shepherd, 2009). As macropores, mesopores and pore continuity decrease due to compaction, saturation is reached more quickly and lasts longer so that the risk of GHG emission is greater.

Soil structural damage from animal treading is expected not only to increase soil N_2O emissions but also to limit C storage, thereby impairing the C balance and long-term sustainability of pasture production. Interactions with N fertilizer application rate and type are likely so that N uptake can appear poor at high N application rates. To investigate this, we measured soil structural and pasture quality using visual techniques (VESS and VSA), alongside other key soil data, to identify N_2O emission potential in November 2010 on farms from an area of intensive dairy production near Palmerston North, New Zealand. Soil sampling and site details and results are listed in Table 3. Sites 1 to 6 were on Kairanga silty clay loam soils (Typic Endoaquepts; Soil Survey Staff, 2014), with two each receiving low, medium and high N applications. Sites 7 and 8 were on Manawatu fine sandy loam (Dystric Fluventic Eutrochrept, Soil Survey Staff, 2014), also a flood plain soil vulnerable to damage. The Kairanga soil is more susceptible to damage than the Manawatu partly because it is poorly drained. Farms were chosen according to three rates of N input. At each rate, fields containing soils of poor and moderately good quality were identified.

Shepherd (2009) used the VSA scores of four soil indicators, three pasture indicators, and the amount and form of N applied to estimate the likelihood and relative magnitude of N_2O flux at each site as a GHG emission index (Table 3). He has subsequently added stocking rate to the GHG emission index (T.G. Shepherd, personal communication, 2011). The likely magnitudes of N_2O fluxes were confirmed using a simple model of N_2O emissions based on measurements of soil mineral N, WFPS and soil temperature (Conen et al., 2000). Damage due to animal pugging or poaching that extended throughout the topsoil was more common at high N inputs (Table 3) than at low N inputs. At high N inputs, poorly structured soils were deemed most likely to emit high levels of N_2O due to their likely high WFPS even at relatively low soil water contents in combination with low porosity and air permeability (Table 3). The high soil temperatures further diminished the aeration status, especially near the soil surface, where the churning of the soil surface by poaching had increased the exposed soil surface area. At most sites, mineral N levels were unlikely to have limited microbial N transformations (Table 3).

Soil structural changes due to surface compaction can influence GHG emissions in arable systems. Under no-tillage in an Oxisol in Paraná State, Brazil, VESS scores and physical properties were more favourable in the crop rows than in the compacted interrows and these changes were found to affect soil CO_2 and N_2O emissions (da Silva et al., 2014).

4.2 Soil C storage

Soils will gain soil organic carbon (SOC) if the rate of carbon (C) addition exceeds the rate of C loss through decomposition and dissolved organic carbon (DOC) export. Crop and cropping system, type of tillage, extent of disruption of soil structures and the degree of soil cover by vegetation all influence soil decomposition and CO_2 emissions. Shepherd (2009) used nine VSA scores including soil texture, soil colour, rooting depth and extent, pasture growth and type and form of fertiliser N to develop a Soil C Index. Measured changes in C storage and the VSA Soil C Index of a soil under dairying in the Manawatu Region of New Zealand demonstrated a close relationship between measured and observed values (Table 4). Total SOC decreased initially over time reaching a steady state with a VSA Soil C Index of 21 (Cloy et al., 2015).

The compaction of grassland soils can weaken the ability of soil to store C and to allow water infiltration. Newell-Price et al. (2013) conducted a survey of grassland soil compaction in England and Wales using both the VSA technique and regular physical measurements of soil compaction (bulk density and penetration resistance) in 300 fields. They found that, alongside compaction status, the most important factors influencing VSA ranking scores, were SOM content and percentage sand content that were both positively correlated with the VSA score, indicating the potential for these visual techniques to estimate SOC content.

The visual property most indicative of C storage that the VSA and VESS techniques make use of is soil colour. SOM (and therefore SOC) contents can be roughly estimated using soil colour. Generally the darker brown the soil, the higher the SOM concentration but the role of soil texture, water status, carbonate and mineral contents on soil colour should be included (Escadafal et al., 1989). Colour chips in Munsell charts (Pantone, 2009) can be used to visually estimate a soil’s SOM content. For example, Wills et al. (2007) used Munsell colours to show that SOC could be predicted from field measurements and that separating samples by land use improved the predictions.

4.3 Nutrient leaching

Poor soil quality and fertility are associated with low nutrient retention and subsequent leaching into groundwater and waterways. The intensive use of well-drained, sandy and coarse loamy soils in the UK was found to produce surface slaking and a loss of aggregation resulting in increased surface-water runoff from fields that should naturally absorb winter rain (Palmer and Smith, 2013).

Shepherd (2009) used VSA scores of soil texture, structure, rooting depth and extent, pasture quality, pasture colour and growth compared with urine patches, and the type and form of fertiliser N to develop a nutrient loss index. Earthworm numbers were deleted and stocking rate and rainfall subsequently added (T.G. Shepherd personal communication, 2011). He used this to assess the potential for nutrient loss on a dairy farm in New Zealand and found good agreement with levels of N in streams running through the farm. Nevertheless, assessments of and the use of visual soil techniques to estimate nutrient leaching are not well documented. However soil visual techniques may prove useful in this area because Moncada et al. (2014ab) found good associations between the results of visual examination and water flow properties (Table 2).

5. Application of Visual Soil Evaluation to stakeholder engagement

5.1 Training and raising soil awareness

Training in visual evaluation of soils is a quick and efficient method of teaching researchers, advisors, students and land users about soil structure, porosity, roots and organic matter. Sampling different locations within a field or farm (including undisturbed soils under forest or long term grass) demonstrates soil variability. Taking photographs at different locations during assessments allows subsequent comparison on a computer screen that may reveal differences that were not initially apparent. If repeated over several seasons, data on long-term trends can be established.

The prospect of using or developing image analysis software to determine scores from images could ensure consistency of training and help minimise regional or operator differences. These could be developed into phone apps to reduce subjectivity in structure scoring. Automation may even be possible provided this does not reduce the value of understanding of the soil derived from feeling, examining and smelling it.

A major benefit of visual evaluation methods is that they raise awareness at all levels of soil experience. Although assessing structural scores is useful, a more important aspect is that users are simply becoming aware of the state of the primary resource and of its vulnerability. This is particularly useful in groups where members can discuss how the soil structure developed and, if necessary, how it can be improved. Another benefit is that, without time or effort constraints, the act of digging up a spadeful of soil and gently pulling it apart can be a positive and therapeutic experience. Smelling the soil reminds the assessor of the importance of living organisms within the soil to functions such as chemical changes and gas emissions. Such interactions connect the soil to the people who work it and increases motivation to care for and, if necessary, to restore the soil. It is easy to forget the obligations of stewardship (Lal, 2009). Thus farmers and stakeholders can share and develop further wisdom drawing on their affinity to the land and the need to use it with respect.

5.2 Scoring management decisions

The VESS and VSA methods provide an assessment of the current state of the soil and allow soil management decisions aimed at improving or maintaining quality. To link VESS to soil management, multiple samples are preferable especially where taken by more than one operator.

Soil with overall (whole block) scores Sq 1 to 2.9 do not require changes in management. From Sq 3 to 3.9 the soil structure shows less porosity and more smooth surfaces on aggregates that are larger (up to 10 cm) and are more subangular. Whether these scores are natural or the result of human impact may not be known but to maximise exploration of the soil by plant roots and to aid delivery of other soil functions, management should be to enhance function and to avoid risks of structural deterioration. Such changes in management may be long term and could include adoption of crop rotations with more abundant or deep penetrating root systems or practices that increase concentrations of SOM. Practices that avoid or minimise compaction will also tend to improve the Sq score. An opportunity exists to more directly link soil visual assessment to key areas of crop production (apart from root growth) such as germination and emergence by focusing on the scores at shallower depths and including surface soil conditions within any assessment. Such a focus may also help in describing the suitability of soils for no-till or minimum tillage (Ball and O'Sullivan, 1982) or susceptibility to run-off where near surface soil conditions are particularly important.

Whole samples or layers with structure scores of Sq 4 to 5 suggest, from correlations with soil properties (see 2.3), damage to soil function and are likely to have an impeded capacity to support plant production. While VESS alone should not guide soil management, scores of Sq ≥4 generally require direct intervention to improve soil quality. Note that a block or layer of Sq 3.5 will contain some soil of score Sq 4. If these are close to the soil surface then they are likely to be more of an agronomic limitation as they are likely to limit early plant growth.

Ideally we recommend that the validity of such thresholds to inform soil management is supported by other soil quality data such as bulk density, resistance to penetration, macroporosity or infiltration rates and by soil biological and yield data. Alternatively, other visible features could be used, such as evidence of waterlogging, decrease in yield or evidence of crop stress, rooting depth, surface relief (Shepherd, 2009; Ball et al., 2015). For example, in Brazil, in some areas under long-term no-tillage (> 10 yr), Sq 4 clods were found throughout the topsoil, based on resistance to break up, in heavy clay soils. Yet these soils appeared to have no restriction to production, possibly because the liberal application of mineral fertilisers compensated for any physical restraints to growth. Nevertheless, in such cases, it is common to observe a greater macro- and intra-aggregate porosity than expected due to crop rotation, mainly if radish and grasses such as rye grass are included. Williams & Weil (2004) and Abdollahi and Munkholm (2014) showed that continuous pores can be created by cover crops such as rye and radish. In such cases a field specific revised Sq threshold could be proposed.

Often the consideration of both topsoil and subsoil scores may suggest appropriate interventions. These could be mechanical such as restorative tillage or subsoiling if soil conditions are suitable. Also the application of gypsum or lime (calcium-based) to improve aggregation and internal drainage (Vance et al., 1998) or the use of transpiring vegetation to de-water the profile (Wheaton et al., 2008).

Nevertheless, it is important to consider the context of the measurements in terms of the success of the crop being grown, though Sq 4 soils are likely to be less resilient to factors such as extreme weather as shown by the results of the compaction experiment in Scotland (Fig. 3). The land user needs to make a management decision based on whether the limiting layer is allocated either in the first few cm of soil or deeper in the profile. The deeper the limiting layer is, depending on the crop, the less likely it is to fully restrict plant growth due to root densities decreasing with soil depth.

More comprehensive visual methods of crop and soil observation such as the VSA can form part of a management package that can be used to adjust a wider range of management variables (including fertiliser amendments) to maintain high soil and crop quality. This has been shown to work well with pastures where maintaining soil quality to maximise life in the soil can reduce mineral fertiliser inputs and associated losses. Nevertheless visual soil evaluation is not to be perceived as a universal management tool. It needs to be accompanied by other relevant soil measurements such as pH, organic matter and chemical analysis in order to assess the status of aspects such as soil nutrients, chemical degradation and ecosystem services.

5.3 Innovation and knowledge exchange in soil management and agronomy

Ideas that lead to better farming are often farmer centred and motivated by economics. The increase in tolerance and connection required for the success of such approaches can be achieved by development of a shared awareness of the land by all those associated with soil from farmer and advisor to research scientist (Ball, 2013b). Handling soil can release a flow of ideas and experiences that can be shared and developed. In addition, greater integration of the traditional knowledge and innovative thinking of farmers should help to improve food security (Venkateswarlu et al., 2013). Ball (2013b) also stressed the importance of integration of new agricultural methods with old, traditional methods and their development to adapt to local circumstances. Scientists and consultants can then expand and re-mould the knowledge that farmers already have (Shaxson, 2006), including where workers are poor, partially skilled or partially educated. Such approaches may be particularly important in small-scale agricultural systems such as urban agriculture that require research to improve understanding of local resources, their efficient use and climate–environment interactions in which visual soil evaluation has an important role in empowering local land users. Visual soil evaluation will also be clearly valuable for recording any improved soil quality.

6. Conclusions

Visual soil evaluation methods are particularly valuable for detecting compaction and can reveal changes in compaction, aeration and waterlogging status, including those related to weather extremes. The techniques reveal well the depths of compact or limiting layers within the topsoil and can be applied to provide management decisions for soil improvement. However the use of scores as limiting thresholds in different soil types needs the back up of further soil measurements and/or additional visual assessments. For scientific purposes, VESS is a useful initial test to provide information on the general quality of the soil and can then be used as a guide to the required scales for soil sampling and the types of samples required. VSA and VESS show useful potential for developing a GHG emission index, a soil carbon storage index and an index of nutrient leaching risk. Visual soil evaluation techniques can also prove useful in helping to raise stakeholder awareness of overall soil quality leading to the exchange of knowledge and ideas for innovation in agriculture.

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Table 1. Summary structural descriptions of VESS and SubVESS scoring categories for soil layers, based on inspection of aggregates or fragments. Sq refers to topsoil quality and Ssq refers to subsoil quality.

Structural quality		Topsoil		Subsoil
Good		**Sq1 Friable.** Rounded, porous aggregates <6mm. Easily crumbles		**Ssq1 Friable.** Rounded fragments, highly porous between aggregates, well-aerated (no mottling)
Good-moderate		**Sq2 Intact.** Rounded, porous aggregates 2mm-7cm.		**Ssq2 Firm.** Rounded and sub-angular fragments, moderate porosity, minor anaerobism (mottling) possible
Moderate		**Sq 3 Firm.** Porous rounded and sub-angular aggregates 2mm-10cm. Few non-porous large aggregates (clods).		**Ssq3 Some compaction.** Compact layers among angular structures. Fragments are angular and with low porosity, minor anaerobism (mottling) is possible

Moderate-poor		**Sq 4 Compact.** Mostly (up to 70%) large (>10cm), sub-angular clods. Large distinct macropores often containing roots		**Ssq4 Compact or large-scale structures.** Large angular structures, fragments are hard to extract and are angular wedges. Anaerobism is shown by grey colours and well defined mottles.
Poor		**Sq 5 Very compact.** Massive or composed of clods >10cm. Often anaerobic, few roots, pores and cracks.	 Photo by Anne Weill, Quebec	**Ssq5 Massive or structureless.** Very dense, tough fragments that are hard to extract and are angular wedges. Anaerobism is shown by grey colours and well defined mottles.

Table 2. Example relationships via linear regression or correlation between VESS scores (Sq) and soil properties

Soil property	Soil textures and/or management	Relationship (y = soil property, x = Sq score)	Significance (t-test for regression)	Source
Tensile strength	Clay	$y = 194.48x - 12.353; R^2=0.77$	* $P < 0.05$	Guimarães et al. (2011)
Tensile strength	Sandy	$y = 69.451x - 64.613; R^2 = 0.65$	* $P < 0.05$	Guimarães et al. (2011)
Bulk density	Clay	$y = 0.1209x + 0.8865; R^2 = 0.51$	* $P < 0.05$	Guimarães et al. (2013)
Bulk density	Sandy loam	$y = 0.189x + 0.7914; R^2 = 0.62$	* $P < 0.05$	Guimarães et al. (2013)
Bulk density	Tropical soils	$y=0.38\ln(x) + 0.9833; R^2 = 0.38$	** $P<0.01$	Moncada et al. (2014a)
Air Permeability	Clay	$y = -2.6078x + 12.655; R^2= 0.34$	** $P < 0.01$	Guimarães et al. (2013)
Air Permeability	Sandy loam	$y = -3.9507x + 19.168; R^2 = 0.24$	** $P < 0.01$	Guimarães et al. (2013)
Penetration resistance	Clay	$y = 0.6383x + 0.4446; R^2 = 0.65$	* $P < 0.05$	Guimarães et al. (2013)
Penetration resistance	Sandy loam	$y = 0.5187x + 0.0408; R^2 = 0.72$	* $P < 0.05$	Guimarães et al. (2013)
Least limiting water range	Tropical ferralsol	$y = - 0.0525x+ 0.1968; R^2 = 0.65$	*** $P < 0.001$	Guimarães et al. (2013)
Saturated hydraulic conductivity	Tropical soils	$y = -0.6652x + 2.6493; R^2 = 0.55$	**$P<0.01$	Moncada et al. (2014a)
Unsaturated hydraulic conductivity	Sandy loam	$y = -0.476x + 0.18; R^2 = 0.41$	* $\alpha = 0.02$	Moncada et al. (2014b)
Air-filled porosity	Silt loam	Correlation, $R^2=0.59$	*** $P < 0.001$	Munkholm et al. (2013b)
Porosity	Tropical soils	$y=-0.106\ln(x) + 0.5953; R^2=0.22$	**$P<0.01$	Moncada et al (2014a)
Mean weight diameter of aggregates	Typic Hapludalf	$y=3.82+1.8x; R^2 = 0.68$		Abdollahi and Munkholm (2014)
Mean weight diameter of aggregates	Silt loam	$MWD=0.422x + 0.572 \quad R^2 = 0.47$	** $\alpha = 0.01$	Moncada et al. (2014b)
Organic carbon	Tropical soils	$y = 70.425e^{-0.377x} \quad R^2 = 0.37$	** $P<0.01$	Moncada et al. (2014a)
Soil respiration	Loam	Correlation, $R^2 = -0.63$	** $P<0.01$	Cui and Holden (2015)

Table 3. Details of field sites, N application, structural quality, water-filled pore space (WFPS), air permeability, mineral nitrogen (N) contents, soil temperature and estimated greenhouse gas (GHG) index on two soil types under pasture. The GHG emission index was derived from visual assessment of texture, soil porosity, colour, mottling, pasture quality, pasture growth, pasture colour and growth relative to urine patches, and the amount and form of N applied (Shepherd, 2009). Standard error, n = 6 in most cases; air permeabilities are geometric means with standard errors back-transformed from logged data values.

Site[a]	N status[b] (kg/ha/yr)	Soil structure (VSA and VESS)	WFPS (%)	Air permeability (µm^2)	Soil NH_4^+-N content (mg/kg)	Soil NO_3^--N content (mg/kg)	Soil temperature at 5 cm depth (°C)	GHG emission index
1	Low – 45	Poor	67 ± 3.9	43 ± 16	4.0 ± 1.7	24 ± 2.6	20.3	Moderate – high
2	Low – 35	Moderately good	64 ± 2.3	137 ± 48	0.3 ± 0.1	25 ± 2.1	22.4	Moderate
3	Moderately high – 115	Poor	59 ± 2.5	52 ± 28	9.1 ± 2.9	11.4 ± 1.1	22.4	High
4	Moderately high – 250	Moderately good	54 ± 2.6	106 ± 21	2.6 ± 0.4	13.8 ± 1.7	22.4	Moderate
5	High – 435	Poor	56 ± 2.6	68 ± 11	6.4 ± 0.5	8.7 ± 1.8	23.4	High
6	High – 435	Moderately poor	54 ± 2.4	138 ± 52	5.9 ± 0.9	6.8 ± 1.5	23.4	High
7	High – 435	Moderately poor	47 ± 3.5	17 ± 6	20.1 ± 6.0	16.5 ± 4.0	23.4	Moderate - high
8	High – 435	Moderately good	38 ± 3.0	20 ± 4	12.5 ± 3.0	9.9 ± 4.6	22.5	Moderate

[a] Soils 1−6 are Kairanga silty clay loams and soils 7−8 are Manawatu fine sandy loams.

[b] N was applied as a foliar spray at sites 1 and 2, and as solid urea at remaining sit

Table 4. Changes in soil carbon (C) storage versus the VSA Soil C Index scores in the top 10 cm of a fine clayey soil[a] under dairying over time. The Soil C index is based on texture, clay mineralogy, soil colour, earthworm numbers, potential rooting depth and root length and density. Other indirect, non-soil visual indicators required include crop/pasture growth, the amount and form of fertilizer and N applied, and method of cultivation (for cropping) (Shepherd, 2009).

Year	Total organic C ($g\ kg^{-1}$)	Bulk density ($Mg\ m^{-3}$)	Total organic C (t/ha)	Soil C Index[b]
1982	56.0[c]	1.02	57.12	31.5
1985	55.0[d]	1.03	56.65	31.5
1989	52.4[d, e]	1.03	53.97	24.5
1992	51.0[f]	1.00 ± 0.03	51.00	21
1997	49.9 ± 0.32[g]	1.03	51.40 ± 0.33	21

[a] Kairanga silty clay loam soil (Eutric Gleysol, FAO classification; fine, mixed, mesic, Typic Endoaquept, Soil Survey Staff, 2014) formed from quartzo-feldspathic alluvium. [b] Shepherd (2009); [c] Shepherd (1992); [d] Sparling and Shepherd (1986); [e] Shepherd et al. (2001); [f] McQueen and Shepherd (2002), standard error n = 6; [g] Saggar et al. (2001), standard error n = 4.

List of Figures

Fig. 1. VESS scores, shown as overall and as individual layers under a grazed grass and no-till soybean cropping system and under a conserved (silage) grass and no-till soybean cropping system, Paraná state, Brazil. The vertical bars indicate the confidence interval (P≤0.05).

Fig. 2. Examples of soil slices after manual break-up according to VESS and used for the experimental data shown in Fig. 1 for a) Grazed by livestock area and b) Cut for silage area.

Fig. 3. The change in VESS scores from November 2011 through to September 2014 with an annual application of compaction treatments of mechanical compaction with a tractor (···), trampling by dairy heifers (– –) and no compaction (—). The ground pressure of both heifers and tractor was 200-250 kPa. The bars represent 2 x standard error.

Fig. 4. Water-filled pore space (WFPS) and water content at which greenhouse gases are emitted in a Kairanga silty clay soil under pasture and at varying degrees of structural degradation under increasing periods of continuous cropping and conventional tillage. Taken from Shepherd (2009).

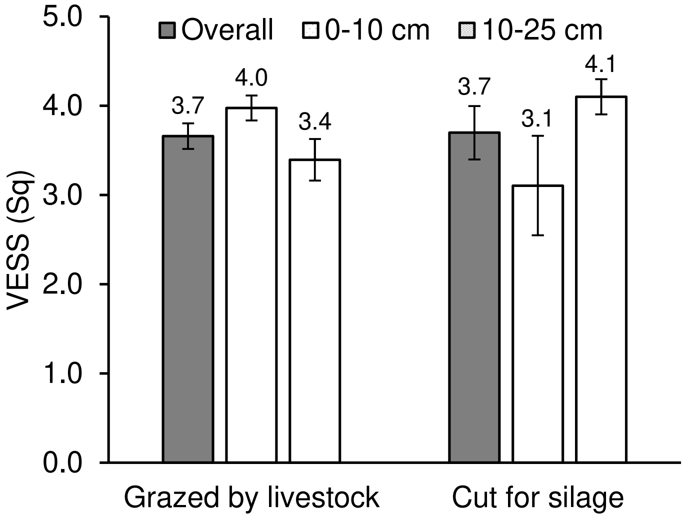
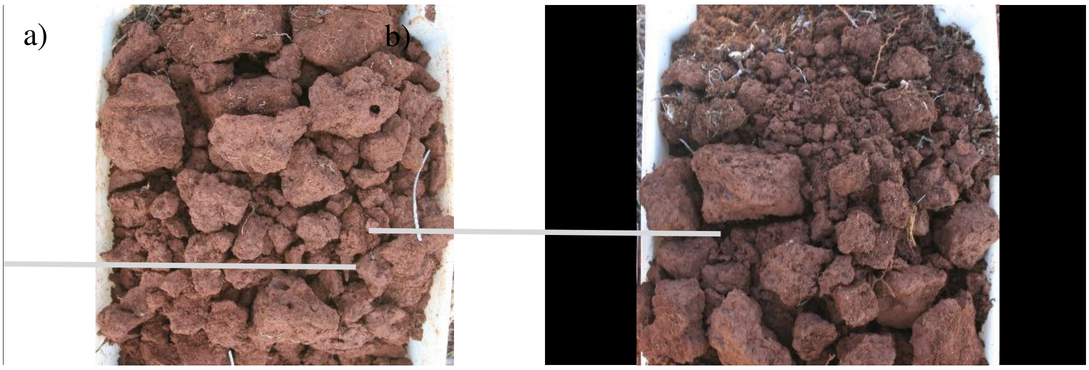


Fig. 1. VESS scores, shown as overall and as individual layers under a grazed grass and no-till soybean cropping system, and under a conserved (silage) grass and no-till soybean cropping system, Paraná state, Brazil. The vertical bars indicate the confidence interval (*P*≤0.05).



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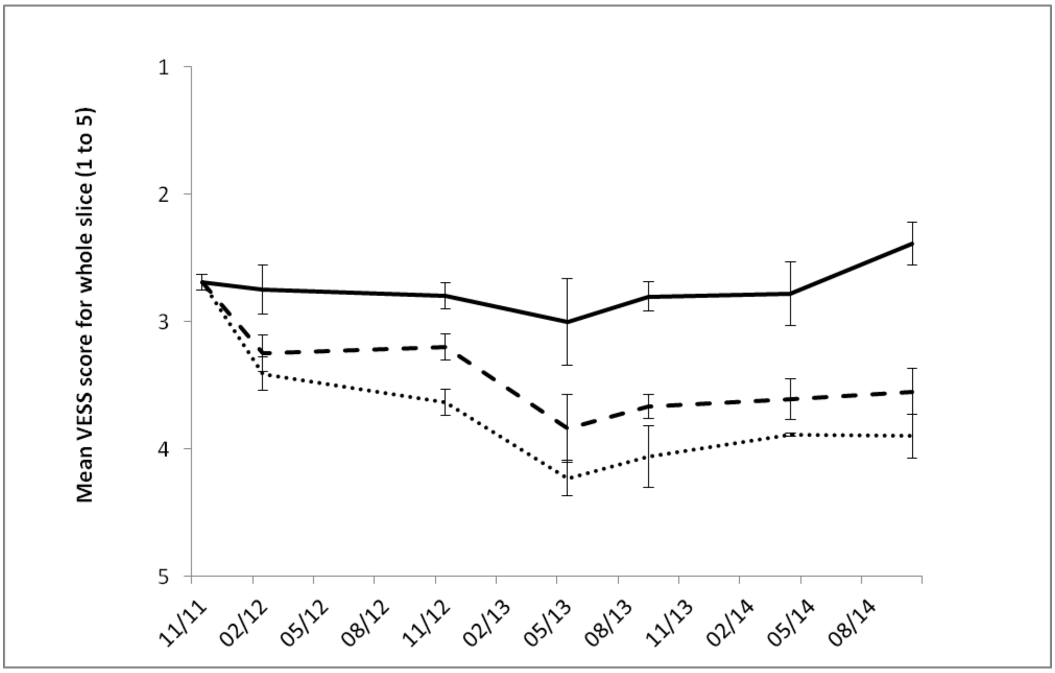

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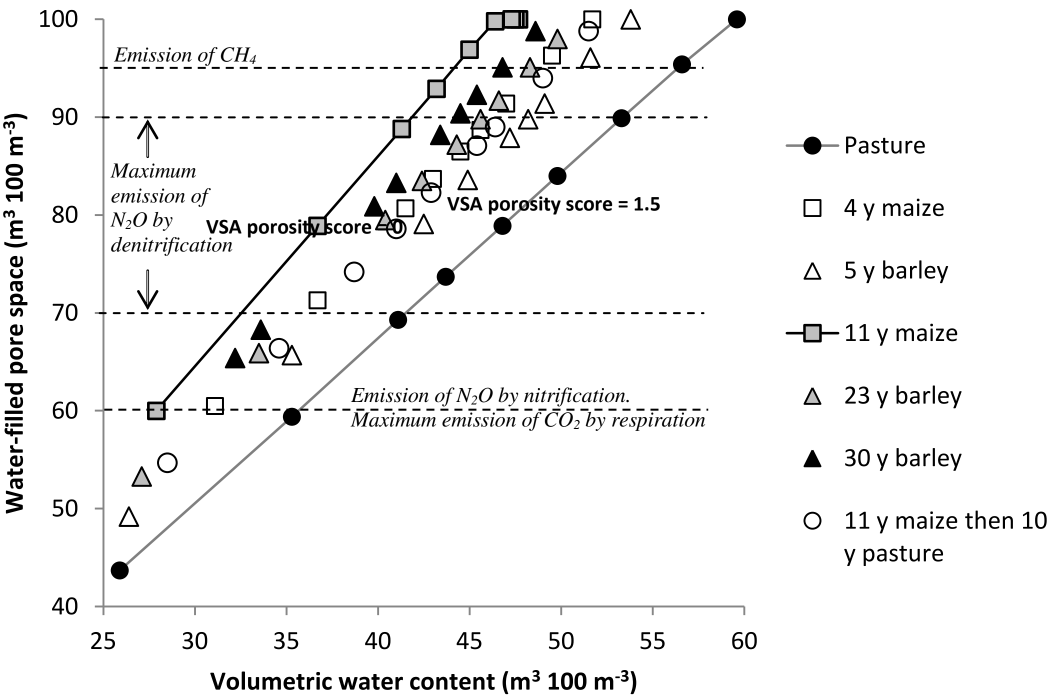

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