The numeric visual evaluation of subsoil structure (SubVESS) under agricultural production

Ball, BC; Batey, T; Munkholm, LJ; Guimares, RML; Boizard, H; McKenzie, DC; Peigne, J; Tormena, CA; Hargreaves, P

Published in:
Soil and Tillage Research

DOI:
10.1016/j.still.2014.12.005

Print publication: 01/01/2015

Document Version
Peer reviewed version

Link to publication

Citation for pulished version (APA):
Ball, BC., Batey, T., Munkholm, LJ., Guimares, RML., Boizard, H., McKenzie, DC., ... Hargreaves, P. (2015). The numeric visual evaluation of subsoil structure (SubVESS) under agricultural production. *Soil and Tillage Research*, *148*, 85 - 96. https://doi.org/10.1016/j.still.2014.12.005

The numeric visual evaluation of subsoil structure (SubVESS) under agricultural production

B. C. Ball[a*], T. Batey[b], L. J. Munkholm[c], R. M. L. Guimarães[d], H. Boizard[e], D. C. McKenzie[f], J. Peigné[g], C. A. Tormena[h], P. Hargreaves[a].

[a]SRUC, West Mains Road, Edinburgh, EH9 3JG, UK
[b]125 Blenheim Place, Aberdeen, AB25 2DL, UK
[c]Department of Agroecology, Aarhus University, Blichers Allé 20, P.O. Box 50, 8830 Tjele, Denmark
[d]Department of Agronomy, Federal University of Technology-Paraná, Via do Conhecimento, km 1 – 85503-390, Pato Branco, PR, Brasil
[e]INRA, UPR1158 Agro-Impact, Estrées-Mons, BP 50136, 80203 Péronne, France
[f]22 Kite Street, Orange, NSW 2800, Australia
[g]ISARA Lyon, 23 rue jean Baldassini, 69364 Lyon cedex 07, France
[h]Department of Agronomy, State University of Maringa. Av. Colombo, 5790 - 87020-900, Maringá, PR, Brasil

*Corresponding author: B.C. Ball.
Tel. +44 1315354379; fax +44 1315354144
E-mail: bruce.ball@sruc.ac.uk

ABSTRACT

Subsoil degradation in agriculture is an increasing problem worldwide, particularly due to compaction caused by heavy machinery. Here we describe a numeric assessment of subsoil structural quality in relation to soil as a crop growth medium and illustrate its utility with results from compaction experiments and from fields under minimum tillage. The scoring scheme resembles the topsoil visual evaluation of soil structure (VESS) (Guimarães et al., 2011) with more emphasis on examination of the profile wall and of soil fragments. The focus is on identification and evaluation of the anthropic 'transition layer' immediately below the topsoil, usually > 30 cm depth. Layers of contrasting hardness and colour were identified and the overall subsoil quality of each layer was scored from separate, sequential assessments of soil mottling, soil strength, visible soil porosity, the pattern and depth of root penetration and aggregate size and shape using a colour diagnostic flowchart. Use of the method enabled identification of extent and severity of compact transition layers in both well-drained and imperfectly drained soils. Porosity and strength assessments were particularly relevant. Reference soils under forest or long-term grassland helped to distinguish whether subsoil structural quality resulted from the natural soil composition or from degradation by land management. The derived scores may be used to judge the requirement for amelioration by subsoil loosening by mechanical inputs (e.g. deep tillage) and/or natural processes (e.g. shrinkage crack formation).The method was also used to identify differences in subsoil structural quality within fields associated with field traffic levels (Oxisol in Brazil) and with moisture status (Luvisol in France). The focus of SubVESS on structure rather than on texture may not permit recognition of effects such as low water holding capacity that influence agronomic potential. In such cases the more comprehensive evaluation of overall agronomic potential by methods such as the 'profil cultural' is required.

*Keywords***:** structural quality, compaction, soil profile, VESS, transition layer, flowchart, subsoil

Highlights:

- Scores of structural quality are given to layers detectable in soil profiles
- The method identifies the 'transition layer' in the upper subsoil that is often compacted
- Limiting scores for layers that require loosening were identified in a range of soils
- Identifying anthropogenic degradation was helped by comparison with reference soils under long-term grassland or forest

1. Introduction

The subsoil is highly important for the storage of plant available water, particularly in semi-arid regions or in areas with frequent water shortages, and for the conduction of water and air, particularly in humid areas where drainage of excess rainfall is required. It also stores nutrients for plant growth. The subsoil regulates rooting depth and is seen as increasingly important for storing recalcitrant carbon (Lorenz and Lal, 2005). The subsoil structure may influence the suitability of the topsoil for tillage through its influence on the water status of the soil (Mueller et al., 1994). Lying between the topsoil and parent material, the development of structure in the subsoil is predominantly physical through the processes of drying and wetting, freezing and thawing. The concentration of soil organic matter (SOM) is low and fed by the entry of roots and their subsequent decomposition. Subsoil structure tends to be stable and soil organic matter neither features in its development nor in its stability as it does in the topsoil. Exceptions include sodic subsoils that can disperse and then be prone to tunnel erosion (So and Aylmore 1993) or soils with spodic B horizons where there is accumulation of organic matter and Fe/Al oxides/hydroxides (Petersen, 1976).

Where the emphasis is on pedology *i.e.* the morphology and genesis of soils, subsoils are normally described in considerable detail during soil profile description. Such methods include the FAO standard for the World Reference Base for Soil Resources (FAO, 2006), general soil surveying (Hodgson, 1974 in the UK; NCST, 2009 in Australia) and land evaluation and soil management (Batey, 2000). More recently the increasing influence of human activity leading to soil degradation such as salinisation, disturbance (e.g. by mining or pipeline installation; Batey (2014)) and compaction by machinery has led to the need for a functional evaluation of the subsoil. Conventional pedological methods are insufficient to detect management-induced differences in soil, particularly in the upper subsoil where human activity such as compaction or deep tillage can transform the structure of the soil; descriptors that are more relevant to crop yield potential are required (Mueller et al., 2012). If the soil in its natural condition is considered to be the ‘genoform’, then ‘phenoforms’ with differing soil indicators can subsequently develop according to management practice (Droogers and Bouma, 1997). Since compaction and tillage principally influence structure, emphasis is on the assessment of subsoil structure such as SOILpak for cotton growers (McKenzie, 1998), ‘le profil cultural’ for soil management (Peigné et al, 2013) and morphological descriptions for water management in wet soils (Mueller et al., 1994). Detailed tests of the potential of the soil for crop productivity already exist. The rating scheme of Mueller et al. (2012) uses a combination of hazard and potential indicators to give an overall assessment of soil quality at the national or trans-national scale. The scheme of McKenzie (2013) operates at the field scale.

Subsoil compaction is one of the major threats to future crop productivity because farm machinery is becoming heavier and is used more frequently in unsuitable conditions. Thus large areas of Europe are vulnerable to degradation (Jones et al., 2003). In tropical and sub-tropical areas of developing countries, the increase of size and weight of agricultural machinery also increases the risk of subsoil compaction, particularly in the upper subsoil. In parts of the world where climate change results in increased rainfall, the risk of damaging effects of compaction in both topsoil and subsoil will increase. Visual assessments have proven valuable in detecting compaction with emphasis on the upper soil layers (Guimarães et al., 2011; McKenzie, 2001). Subsoil assessment is also important for the determination of the permeability of clay subsoils (Swarz et al., 2003).

Descriptions of topsoil structure and subsoil structure are not identical. Many of the methods developed for visual assessment of topsoil attach great importance to compaction status. However, the bulk density of subsoil can be high initially for some types of soil, and consequently the increase in bulk density is possibly small. For example Arvidsson (1998) showed that the increase of bulk density in Sweden was only 0.00-0.13 Mg m^{-3} after 4 passes with a sugar beet harvester weighing 38 tonnes. Boizard et al. (2000) also showed a significant effect of cropping systems on subsoil compaction in the Estrées-Mons long term experiment. However, the change in bulk density was very small (0.01-0.04 Mg m^{-3}) even though the penetration resistance increased significantly and the hydraulic conductivity decreased sharply after compaction. They deduced that the network of cracks and macropores facilitating vertical transfers of air and water should be better taken into account.

The rapid numerical assessment of subsoil structure is thus a priority and the systematic and careful examination of the subsoil is to be encouraged. The Visual Soil Examination and Evaluation Working Group of ISTRO recognised this at their meeting in Peronne in 2005 and further encouraged its development at their next meeting in Flakkebjerg in 2011. Subsoil structure classifications e.g. Mueller et al. (1994) mainly depend on the description of component aggregates or lumps of soil with emphasis on the shapes of aggregates or lumps and the presence and shape of pores and cracks. We take a similar approach, but integrate information on rooting, colour and biotic activity. A visual key is included to help identification of limiting layers in a method similar to that used in developing the VESS (Ball et al., 2007). We decided to adopt a separate scoring scheme from the VESS as conditions are clearly different in the subsoil where the scale is greater and there is more emphasis on profile wall investigation and examination of soil fragments. In our approach to assessing soil structural quality we broadly followed the four fundamental aspects of soil structure identified by Kay (1997) as form, stability, resilience and vulnerability, with emphasis on form. We propose a numeric assessment of subsoil structural quality in relation to soil as a crop growth medium and illustrate its utility with results from compaction experiments.

2. Development of the evaluation

The test has been designed as a rapid method for practitioners with some soils knowledge in order to evaluate whether the management practices in use by farmers have resulted in soil damage. It can also be used to assess compaction damage in land disturbed during surface mineral extraction, the installation of cables or pipelines, or after landscape re-shaping. A further objective was to indicate from the profile the depth and thickness of layers where remedial operations can be targeted. With some training, non-soils experts should be able to use the system. The emphasis is on how the intrinsic potential of the upper subsoil (~30-60 cm) has been reduced with a view to identifying remedial work in relation to overall land capability. Our proposed method is thus less detailed than those used for the comprehensive examination of the physical properties of subsoils in formal surveys of soils.

Nevertheless it is important to assess those properties that determine the inherent capability of the soil as a whole. Much of this capability relates to the abilities of the soil to supply water to the crop and to allow good drainage. This is related to texture and to the content of coarse fragments in the root zone. We realise the importance of texture in influencing the function of soil structure. For example, in subsoils dominated by sand, root penetration may be poor without obvious signs of compaction or hardness (Batey, 2000). Also the development of shrinkage cracks is a major process in clay soils and depends on the soil moisture deficit and on the type and content of clay (Batey, 2000). The effect of weather conditions on producing cracking can also be effective in soils of coarser texture as demonstrated by (Boizard et al., 2013) in a silt loam of about 19% clay content.

In addition to cracking, Peigné et al. (2013) stressed the importance of quantification of earthworm macropores. McKenzie et al. (2009) buried a mesh layer horizontally in the soil so as to prevent root penetration to the subsoil. The mesh was punctured to create a defined number of holes per unit area. Results showed that crops grown with controlled, limited access to the subsoil performed better than those with no access and the performance was generally related to amount of access. So it is important to have visual evaluation that is able to reveal channels and cracks. The evaluation of the current state of the soil and how this might be improved here are based on visual and tactile soil structural quality assessment.

2.1 Choice of assessment depth

The depth of subsoil to be evaluated is not a constant (compared to a spade depth for the VESS assessment of topsoils). Here we consider the upper limit of assessment as being below the top 30 cm layer that is commonly cultivated. Soil above this upper limit can be evaluated by a topsoil spade test such as VESS or VSA (Guimarães et al., 2011; Shepherd, 2009) or on the vertical surface of the pit with SOILpak (McKenzie, 2001) or 'profil cultural' method (Manichon, 1987). The lower limit of assessment should be at least 1 m so that the zone of subsoil tillage and any limiting layer that will influence root growth will be revealed. Alternatively if the rooting depth under good conditions for the crop grown is > 1 m then the lower limit should extend to this depth. Compaction has a major effect on root growth, by modifying soil properties. Resistance to penetration increases sharply and can limit the depth of root growth, particularly when soil moisture at the time of the root growth decreases (Gubiani et al., 2010).

2.2 Timing

The assessment can be done at any time in the cropping cycle, though the best time is when the soil is moist *i.e.* at field capacity or drier because digging wet soil can cause damage. The method cannot be used if the soil is waterlogged resulting in the pits filling with water or near wilting point when cohesion is too high. The optimum time is at full extension of the roots when they can be better assessed. Also for ease of access and to avoid crop damage during excavation, a convenient time is soon after harvest while roots of the past crop can still be seen.

In drier climates, digging and assessment conditions would be better during active crop growth when the soil would be moister.

2.3 Site selection and digging the pit

Wherever possible sites should be selected to present contrasting soil conditions such as may occur between high yielding and low yielding sections of a field. In a large field, split the field into sections where the crop or soil surface looks uniform and evaluate within each section. Pits may be examined both in compacted turning areas at field edges and within the main body of the field. To identify the intrinsic potential of the soil to develop good structure with minimal anthropic damage, examine a nearby profile in a 'fenceline' or under native forest. Although holes may be dug by hand, it is recommended that a trench is dug using a mechanical digger. The width should be comfortable enough to stand in, i.e. >60 cm wide, if possible. The length can be varied but not less than 2 m. It can be orientated across the direction of the principal tillage, crop rows or method of harvest, to cut through any potential compacted features. For safety reasons the depth should not exceed 1.4 m. Most profiles will be between 1-1.4 m deep. If a high potential soil moisture deficit (PSMD) demands inspection to greater depth in order to look for roots, use a spade to dig a small hole in the base of the trench or extract soil with an open-threaded auger. To allow convenient access, a step should be cut on one end of the trench.

2.4 Method of assessment of subsoil structure

Evaluation of the subsoil has a major objective of identifying any anthropic 'transition layer', lying just beneath the topsoil, that may have been compacted or smeared by machinery during tillage, planting or harvest. For ploughed soil normally cultivated to ca. 25 cm depth the transition layer will probably start at the upper assessment depth. However, for no-tilled or shallow tilled soil the transition layer may start closer to the surface and thus can be partly or fully described by topsoil methods. A critical zone may range in thickness from a few cm to over 30 cm. It usually shares the properties of both topsoil and subsoil. Continuous porosity through this zone is particularly important to allow root exploration and permeability to drainage water. A transition layer that is compacted or smeared can restrict the number of roots penetrating into it and below (Peigné et al., 2013). Roots in such layers are often thickened and distorted. A mat or an increased density of roots can occur above the surface of a compact transition layer (Batey, 2000). If unsure, compare with the physical properties of a non-compacted soil in a more natural condition (e.g. long-term grassland) nearby (Batey, 2000) or with soil structure specification targets for provision of ‘ideal’ plant growth as in the SOILpak system (McKenzie, 1988). Assessment may also be helped by reference to a local description of the soil such as from a soil survey.

2.4.1 Identify layers for assessment

Remove soil from any surfaces compacted or smeared during digging the pit using a spade, spatula or knife. Observe the soil below the topsoil and to the expected rooting depth (~ 30 cm to up to 1.4 m depth). Aim to record information on the score sheet (completed examples are shown in Tables 1 and 2).

Identify layers of contrasting colour and hardness by prodding with the point of a knife or a pen. We stress the importance of distinguishing man-made features of the subsoil from natural features. The signs of compaction are hardness due to high density, reduced hydraulic conductivity leading to accumulation of water above the compact layer, and a marked change in structure with horizontal, laminated or platy aggregates and low or absent porosity (Batey, 2000). The upper part of a compacted layer can be assessed readily, though it is often more difficult to determine how far down the compaction persists. Usually there are only two or three layers. Mark the layers with a knife or, preferably, by inserting plastic tags and measure their depths. Each layer is then assessed separately. Take a picture of the profile. This may need to be split into two or more sections to cover the whole depth. Use labels for subsequent identification. Examples of labelled profiles are given in Fig. 1. More information on identifying transition layers that accompanies the flowchart and is given in the supplementary material at the end of the paper.

2.4.2 Allocate a Subsoil quality score (Ssq) for each layer

Score each layer, starting with the top layer, Layer 1. Examples of completed forms are given in Tables 1 and 2. Key diagnostic factors subject to anthropic variation are considered and are used to arrive at an Ssq score for each layer. Factors are mottling (a), strength (b), porosity (c), the pattern and depth of root penetration (d), and aggregate size/shape (e). These are assessed in order from mottling (a) to aggregates (e). Assign a score between 1 and 5 to each factor where 1 is best and 5 is worst. These are shown in context in the colour flowchart (Fig. 2) that is used to help scoring. Factors also appear as headings in the flow chart. Factors are assessed in order from left to right with the objective of focusing down on the best description of quality, Ssq. This is usually identified from the most frequently occurring score of the five factors, with a rather greater weight being given to the last factors assessed, (c) and (d). Working from left to right, a score is given for each factor so that an overall Ssq score for subsoil quality in the layer is produced at the end based on the dominant score of the five factors. Some adjacent scores are combined if there is no means of distinguishing between them e.g. 1a/2a.

Mottling (a) refers mainly to the degree of anaerobism as revealed by the extent of mottling (patches or spots of orange/rusty red colour) and grey/blue soil that is likely to be evidence of anthropic waterlogging. The best score (1a/2a/3a) is where there is either no mottling or where mottling is faint and diffuse indicating that, although the water table can rise into that zone, aeration is unlikely to affect productivity. Soils without mottling have a wide range of strong, bright, uniform colours. Any non-uniformity is due to inclusions of material from adjacent horizons such as organic material from the topsoil.

Poorer scores (4a/5a) correspond to progressively more distinct mottling in a layer that is uniformly grey/blue with rust coloured mottles only present around pores or blocked channels. Mottles become more distinct when the water table is high for a long period of the year. In cracking soils, the colour on the face of cracks is often paler due to the removal of iron and other elements under temporary anoxic conditions associated with the decomposition of roots (Batey, 2000). Note that the soil colour/mottle status is associated with the severity of anthropic compaction by, for example, heavy machinery. Waterlogging symptoms linked to other processes (eg. position in landscape, presence of springs) are a separate issue.

Strength (b) refers to the resistance of the soil to penetration by a knife or to the removal of soil fragments. Strength is a function of the vulnerability of the soil structure. Soil resistance is assessed either by jabbing the side of the profile with a knife progressively moving from the top to the bottom or by extracting fragments of the layer. Fragments of soil (~5- 10 cm deep by 2-5 cm thick) can be removed by inserting a knife at 45˚ to the horizontal (Fig. 3).

Break these fragments apart by holding the ends and snapping like a twig (Fig. 3D). Strength is determined by the ease of break down of these fragments. Fragments may fall apart when removed (1b/2b), may keep their shape but are readily broken (3b) or have an angular shape and are difficult to extract and break (4b/5b). This information can be amplified by the use of a pocket penetrometer directly into the layer. Limiting values of penetrometer resistance indicative of high soil strength are given in Arshad et al. (1996).

Porosity (c) distinguishable by eye is macroporosity. Porosity is one of the ‘form’ components of soil structure. Macropores are taken to be of several types: between sand grains or aggregates or within aggregates or fragments (< 0.5 mm across), tube-like worm, and/or root channels (1-10 mm diameter) and vertical cracks or fissures (from a few mm or more wide and up to l m deep). Picking at the vertical face of the soil profile with a knife will reveal channels and cracks. Earthworm holes are usually stable and may become filled with casts made up of fine crumbs. The smaller pores are best revealed on an unsmeared surface such as a freshly broken fragment. To help distinguish internal pores from surface imperfections, hold fragments in the shade. In assessing the large vertical pathways, try to find continuous pores that may run through several layers. In fine-textured soils, shrink-swell cycles create shrinkage cracks between aggregates that open up as the soil dries. These shrinkage cracks play a critical role in the movement of air, water and roots. Vertically orientated continuous macropores – such as those made by earthworms, ants and/or roots of former plants – can be highlighted through the application of dilute white paint (McKenzie, 1998). The better scores correspond to high porosities, usually small pores which occur throughout (1c) or with occasional less porous zones (2c). The intermediate score (3c) is where the pores are larger and are mainly cracks and earthworm holes. Poor scores are where porosity is low (<5 pores 100 cm^{-3} of profile face, 4c) or where no porosity is visible (5c).

Roots (d) are evaluated if present. Roots are geotrophic and respond sensitively to soil physical conditions. Live roots are pale in colour. After a crop is removed, roots become darker, shrivelled and brittle after a few months but may not disappear for a year or more, dependent on species and climate. Graminaceous plants have thin, multi-branched fibrous roots; other crops may have fewer, thicker roots such as field beans or onions. Roots are biologically responsive indicators and tend to grow more vigorously in zones that show least physical resistance, for example down earthworm channels or shrinkage cracks (e.g. Ehlers et al., 1983). Annual dicotyledonous crop roots are the most sensitive to soil conditions, especially compaction (Arvidsson and Håkansson, 2014). Maize is also very sensitive to soil compaction (Tardieu, 1988). Factors other than compaction can influence root growth such as soil acidity, aluminium toxicity, pathogens or pests. These factors need to be discounted before scoring root growth in relation to structural form.

Rooting is assessed from frequency and distribution within the layer and the extent of any distortion. The best score (1d/2d) is where roots grow throughout the layer with no signs of restriction. Poorer scores correspond to roots localised within cracks and worm channels (3d) and thickening (4d). The poorest score is no roots (5d). A dense interlocking web of roots may develop on the surface of a compact layer or roots will follow cracks or wormholes. Rooting depth is also important as it indicates whether any transition layer can be successfully penetrated and is assessed by looking for roots at depth. To find such roots it is necessary to pick at the vertical face of the soil profile, penetrating with the point of a knife the profile face by only a few mm. The rooting depth can be determined by the presence of the deepest root detected.

Aggregate shape/size (e) is the primary determinant of Ssq as it is the main ‘form’ component of structure and is thus the last diagnostic factor leading to Ssq (Fig. 2). Aggregate shape/size is determined by looking at the profile face and by crumbling or breaking apart fragments. It ranges from aggregates that are small, rounded and friable (1e) or larger and more angular (2e/3e). The poorer structures (4e/5e) are less well-developed and defined and extraction of fragments leaves knife marks visible on the profile face. Single grain structures such as distinct, coarse sand grains are included as structureless (4e). The poorest structures are tough, massive, plastic and hard to break up. Reference images, aggregate and clod morphology definitions and relative sizes are available in soil survey manuals (e.g. Hodgson, 1974; McKenzie, 2001a; NCST, 2009).

More information on mottling, porosity, rooting depths and soil structural forms and sizes is provided in a sheet of supplementary material that accompanies the flowchart and is shown at the end of the paper. In addition charts for estimating the relative proportions of mottles and coarse fragments and for estimating the size and abundance of pores are given in the Guidelines for Soil Description (FAO, 2006).

2.4.3 The Ssq subsoil quality classes

Ssq is given for each subsoil layer according to the most frequently occurring quality with structure usually being the dominant factor (Tables 1 and 2). There are five classes with Ssq1 best, Ssq2-4 intermediate and Ssq5 worst (Fig. 2). The overall score of subsoil quality, Ssq, that is produced at the end is based on the dominant score of the five factors.

Ssq1

The structure is friable and crumbles easily with high porosity and fissures. The colour appears natural and is appropriate to the parent material. Drainage and aeration are good. This class is most likely to occur in the layer immediately below the topsoil and there may be no break in consistence or moisture content between topsoil and subsoil. Live roots or those of recent crops are plentiful and evenly distributed. Aggregates are readily broken apart by hand when wet or dry and the internal structure of larger aggregates appears crumb-like. In fine-textured soils frequent vertically-orientated fissures may contain inclusions of topsoil that fall in while the fissures are open. Channels made by earthworms or other soil fauna may provide significant pathways for roots and improve permeability.

Ssq2

The structure is friable with sub-angular aggregates. The colour is similar to Ssq 1. Any mottling due to anaerobism is diffuse and scattered. There are slightly fewer pores and fissures than Ssq1, but this only has a minor effect on rooting. As for Ssq 1, this layer may occur immediately below the topsoil and may contain ploughed-down organic material that under wet conditions may result in anaerobism.

Ssq3

The structure is angular or weak-grained with some compaction as either natural or man-made layers. Aggregates are likely to have amorphous internal structure. Fragments are angular with sharp edges and snap in two easily but without crumbling. Visible porosity occurs mainly as fissures, isolated pores and root and earthworm channels. Permeability to air and water is likely to be low unless there is a network of prismatic or polyhedric cracks (e.g. in orthic luvisols). This layer can restrict rooting depth and length. Few roots are able to penetrate the larger aggregates and are mostly confined to earthworm channels or shrinkage cracks. Such cracks may be hard to locate even when dry. Fibrous roots can be thickened if unable to penetrate compacted zones. A zone of ploughed-in organic matter is possible that may be anaerobic. Some mottles may be present due to anaerobism within aggregates caused by periodic impairment of water movement and aeration, but mottles are diffuse and faint.

Ssq4

Aggregates are large and may be natural peds, possibly prismatic, columnar, laminated or single grained. There is little or no porosity, earthworm channels are rare and roots are usually distorted. Fragments are angular, retain their shape and may be hard to break, especially when dry. If drainage is poor, grey colours and marked mottling are common due to anaerobism. Aggregates may be strongly mottled within and show pale-coloured iron-depleted zones on the edge of cracks.

Ssq5

The structure is massive or the structural units are dense or highly compacted with smooth, unbroken faces or weak, single-grained structures, possibly laminated. The soil is very hard when dry and difficult or impossible to break apart by hand. When wet it is tough and plastic or so dense that it remains brittle when saturated. When broken apart no internal structure is visible with individual grains or micro-aggregates pressed tightly together. No porosity, channels or roots are present. Roots may form a web on the upper surface of the layer because they are unable to penetrate further. Similarly, after rain the upper surface of this layer may be visibly wet due to very low permeability. If drainage is poor, the colour is mostly grey and brightly mottled with rust coloured zones around blocked pores where air can enter. Grey-blue redoximorphic colours are dominant and there may be grey anaerobic pockets with a sulphidic smell.

3. Examples of application of the evaluation

3.1 Application in soils of contrasting compaction status under a temperate climate in Denmark and in Scotland

The method is illustrated using two profiles from a well-aerated soil and two from a poorly-aerated soil. The well-aerated soil is from a compaction experiment initiated in 2010 at Research Centre Aarslev, Denmark (10°27´E. 55°18´N). The soil is a sandy loam developed on Weichselian moraine deposits and classified as a Glossic Phaeozem according to the World Reference Base (WRB) system. Six levels of compaction were applied prior to sowing with spring barley (Schjønning et al., 2011). The compaction treatment studied was the most compact, 8 Mg wheel load at high inflation pressures. This treatment was applied early spring in 2010, 2011 and 2012 by using a tractor with a slurry trailer with maximum wheel load of ca. 8 Mg to create wheel tracks covering the entire plot. Subsequently, spring barley (*Hordeum vulgare* L.) was established (Fig. 4).

The poorly aerated soil (Fig. 1) is an eutric gleysol from a compaction and trampling experiment at SRUC Crichton in South-west Scotland. Compaction was applied by a laden tractor and trampling by heifers on conserved grass at a target ground pressure of 250 kPa.

The profiles at Aarslev were on the non-compacted reference plot and on a plot of the most compacted treatment. The profiles at Crichton were on discard areas either adjacent to the entrance to the tractor compacted plot and subjected to heavy wheel traffic or on an adjacent area where wheel and cattle traffic were much lower.

Completed score sheets for Aarslev are shown in Table 1 and for Crichton are shown in Table 2. As might be expected, the heavy compaction at Aarslev resulted in Ssq5, a substantial increase over the reference, Ssq2. Compaction did not extend beyond 75 cm. The compaction at Crichton resulted in Ssq3/4, a less dramatic increase over the reference than Ssq2/3 than at Aarslev. Compaction did not extend beyond 64 cm where the subsoil quality was good, Ssq2.

3.2 Application in soils under different levels of compaction under a tropical climate

For testing the methodology under tropical conditions we choose a Latosol (Oxisol of clay content ~70%) under long term no-tillage, in a crop rotation with soybean, corn, wheat, oats and barley. Within the same field, areas at the ends where tractors manoeuvred were compared with areas without visible machinery compaction. The soil structure under adjacent native forest was evaluated as a reference. Evaluations of VESS were made in the 0-25 cm layer and SubVESS in the layers below. Four pits were assessed for each treatment. The soil layers were not well defined by strength or colour (Fig. 5), therefore the pit face from 0.25 - 1.0 m was divided into three layers each 0.25 m thick.

Where Ssq score was judged to differ within the same 0.25 m layer it was assigned a mean score. The results (Fig. 6) showed that the subsurface soil structure was poorer throughout the field than under the forest. The greatest impact was in the 25-50 cm transition layer, which is agronomically significant for these soils. The lowest two layers can be taken as a single layer as the result was the same.

3.3 Application in soils of contrasting types within a field under a temperate climate in France

The variability of Ssq within a field was illustrated by assessments made by postgraduate students in each of six pits (labelled A, B, C, D, E and F) dug in a regular grid across a 5.8 ha arable field near Lyon, France. The soil type was a Luvisol (WRB classification) with impeded drainage. The field was under minimum tillage wheat and had recently been sown with a cover crop of vetch-Egyptian clover-oat. The students also described the pits using the ‘profil cultural’ method (Manichon (1987); results not shown).

The pits were on a sloping area, with A, B and C at the base of the slope and D, E and F on the plateau. Ssq assessments (Table 3) showed clearly hydromorphic conditions and problems with low macro-porosity in the third soil layer that restricted deep rooting. The poorest scores (Ssq 4 and 5) were found in pit D due to very high clay content in the subsoil and, as a consequence, more intense hydromorphic conditions than elsewhere. This pit was on the highest point in the field.   Pit F contrasted with all the other pits by containing fine soil (clay and sands) and 60- 90 % of stones in all layers. Thus Ssq is 1 even though the agronomic potential of the pit is quite low (very poor water retention and low rooting). This pit is on a slope break and contains fluvial deposits from a former river bed. The results show that overall variability is mainly due to the slope position, with soil profiles at the base of the slope (A, B and C) having similar properties.

4. Discussion

4.1. Utility of SubVESS for structural quality assessment

The method is based on collective extensive experience in evaluating subsoil structural quality under a wide range of conditions from clayey Australian vertisols to sandy Northern European podsols. The method proved good at identifying the severity and depth extent of compaction in all soils tested. In practice, scores for the different properties could vary within a layer and the overall layer score (Ssq) tended to reflect the strength and porosity scores. The extraction of fragments proved helpful for these assessments. In most cases, colour was not an important factor. At Aarslev, Ssq score in the transition layer was similar to topsoil Sq in the lower topsoil. By contrast, at Crichton, the Ssq in the transition layer was better than the topsoil Sq in the lower topsoil. This may result from the greater emphasis on description of cracking and porosity patterns than in the VESS spade test.

The method showed the wide spatial variability of structure to 1.3 m depth in the Luvisol (Table 3). The poor structures (Ssq>=4) were below 55 cm depth. Pore and crack arrangement are particularly important in distinguishing Ssq3 from Ssq4 in these soils. At another experimental site at Estrées-Mons, northern France on Haplic Luvisol, the presence of vertical pores as polyhedric networks of cracks and biological channels is very favourable for drainage and rooting and scored Ssq3 despite low structural porosity. However with subsoil compaction, although there was little effect on structural porosity, the extent and continuity of the network of cracks and macropores was drastically reduced. This led to unfavourable conditions of low hydraulic conductivity, higher penetration resistance and anaerobic conditions and was scored Ssq4 (Boizard et al., 2000). In contrast in the Oxisol with abundant medium pores throughout, aggregate size, shape and strength and root characteristics were more important in deciding the boundary between Ssq3 and Ssq4.

4.2 Ease of use and comparison with other methods

The method was tried out amongst ourselves and with postgraduate students and proved relatively easy to teach. Some prior knowledge of soil science, particularly the terminology, is useful. In such cases a short talk followed by a demonstration in two or three locations proved enough to provide a working knowledge of the method. After a pit was dug, each profile location could be characterised within 20 minutes. As with the topsoil VESS, it is best to work with at least two well-trained operators who should regularly cross-check evaluations.

We compared the method with the 'profil cultural' (Manichon, 1987). Although the 'profil cultural' method focuses on topsoil assessment, it also allows estimation of the capacity of roots and earthworms to explore the subsoil and thus assesses the agronomic potential of the soil (Peigné et al., 2013). The profil cultural assessed a wide face of the soil profile, typically 3 m across. In the topsoil, there is emphasis on the way the clods and aggregates are assembled together. Three structural states are defined: o, b or c (o for an open structure, b for a blocky structure and c for a continuous structure). A second criterion is the internal state of aggregates and clods in relation to tillage and compaction (Γ with visible structural porosity, Δ with massive structure, no visible macropores and high cohesion and Φ, originating from clods and with cracks appearing due to weathering). The subsoil observation combines different criteria used by soil scientists in pedology (structure as prismatic, polyhedric) or developed by agronomists such as root mapping or biological activity or abundance of soil fauna. The technique extends down to at least the upper part of the transition layer by counting the number of earthworm burrows on a horizontal surface (Peigné et al., 2013).

The detailed analysis, labelling and recording required for 'le profil cultural' demands up to 2 hours. The main difference between methods lies in the ease of use and the combination of observations for diagnosis. In the French study (Table 3), the students found the Ssq technique easier to learn and liked the quantitative output. The flowchart and 'scoring' helped them to make qualitative observations objectively and to combine these observations to obtain a simple diagnosis. The 'profil cultural' gave a detailed picture of the quality of the structural units and of upper layers of the profiles and helped to better understand the impact of cultural practices, biological activity and climate. However the method is more time consuming and requires training and expert knowledge. In conclusion, the two methods are complementary and can be made together: the ‘profil cultural’ method provides an overall picture of the topsoil and upper subsoil and how it functions whereas Ssq (combined with Sq) allows relatively objective visual observation and scoring of the whole soil profile.

Other relevant techniques are SOILpak (McKenzie, 2001a) and M-SQR rating (Mueller et al., 2012). SOILpak is a scoring technique applicable to the top 90 cm of soil. SOILPak resembles SubVESS in that pits are dug, faces prepared and clods extracted for inspection. Structural factors assessed are more detailed than SubVESS and include resistance to deformation, shape, size and porosity of clods with macropore continuity, presence of smearing and crusting overriding the scoring. The system was also developed for agricultural use, specifically to determine the suitability of the soil for cotton growing. The method takes between 10 and 60 minutes to apply and includes optional field and laboratory tests. The M-SQR rating is a very comprehensive agronomic assessment. In addition to soil structural assessment it includes properties such as profile available water, wetness, slope and soil hazard indicators such as contaminants, drought, slope, flooding and extreme waterlogging. A global rating between 0 and 100 is supplied at each site.

4.3 Limitations of the method

In order to identify anthropic features, it is important to distinguish shrink/swell (interpedal) pores from pores created by biological or climatic action. The continuity and size of biopores for root exploration are of great importance. They could be identified from the presence of elongated macropores, though they can be underestimated. Initial visual estimations could be confirmed using white paint as described in the Porosity section or, if there is time, by counting macropores and roots on the profile wall. For example, Mueller et al. (1994) use classes of biological macropores that are: very low <60 mm^2 m^{-2}, medium 60-600 mm^2 m^{-2} or high >600 mm^2 m^{-2}. The evaluation of macropore density and connectivity can be supplemented with measurement of field saturated hydraulic conductivity using the method of open-thread auger hole (Amoozegar, 2002) or the simplified falling head method using core samples as suggested by Keller et al. (2013) to yield information on soil functionality.

A limitation that we commonly encountered was the difficulty in distinguishing compacted layers of anthropic origin from changes in compaction status due to differences in texture between horizons and due to indurated layers in some coarser textured soils which are relics from the Ice Age (Fitzpatrick, 1956). Other dense layers may occur due to the downward movement of clay and cementation by iron and other oxides and oxyhydroxides (Batey, 2000). However, anthropic compaction is usually most severe in the transition layer and decreases with depth. Fragipans, indurated layers and clay accumulation layers in many cases are located deeper in the profile. If the profile is relatively uniform, as at Aarslev, (Table 1 and Fig. 4) then comparison between layers may be enough to reveal anthropic change due to compaction. In cases of doubt it is best tackled by comparing with a reference soil under natural conditions.

Although structure is the main criterion for determining Ssq, other factors may sometimes dominate quality such as aeration where saturated soil directly overlies rock. Stone content within a soil profile can also have an effect on aeration, water movement and rooting as shown by the data from France. Also for some specific soil types such as Vertisols, supplementary evaluation may be required. When assessing field variability in the luvisol, at soil pit F (Table 3) the subsoil was mainly composed of stones and granular material and was scored Ssq1. However, when using the 'profil cultural' method the agronomic potential was found to be very low due to low water-holding capacity. This was confirmed by the low frequency of roots. This discrepancy results from the focus of SubVESS on structure rather than on texture or stoniness effects on agronomic potential. In such cases, the more comprehensive evaluation of the overall agronomic potential by the 'profil cultural' or the M-SQR is required.

4.4 Utilization of the method for sustainable management

Interpretation of the subsoil quality scores in terms of management recommendations requires at least some local or regional knowledge about soil management options. It is important to distinguish, if possible, the extent to which a given score can be ascribed to natural conditions and to management history e.g. whether compaction is anthropic or natural.

Having established that the agronomic potential is being influenced by compaction or other management problems, it is worthwhile considering how the subsoil structural quality could be maintained or improved. The potential effect of poor quality at a specific depth on plant production will differ substantially between soil types, climates and cropping systems (Andersen et al., 2013; Håkansson and Reeder, 1994). Håkansson and Reeder (1994) also suggested that the magnitude of the compaction in the 25-40 cm layer (transition layer) varies considerably and its persistence can be underestimated. Clearly, under all circumstances the transition layer between the topsoil and the subsoil is of utmost importance. Severe compaction and impermeability in this layer will be harmful for plant production under almost all conditions. Subsoil compaction below this depth may not have much effect on crop growth if the soil above 50 cm supplies enough water to satisfy transpiration demands (Batey, 2014).

When answering the “what to do” question it is important to distinguish between indicator and management thresholds as discussed by Schjønning et al. (2004). An indicator threshold indicates critical low or high values for specific soil properties (e.g. nutrients, pH and penetration resistance). Indicator thresholds may be chosen during assessment of soil quality to relate to specific hazards in the soil such as susceptibility to drought and flooding (Mueller et al., 2012). In contrast, a management threshold denotes “the most severe disturbance any management may accomplish without inducing significant changes towards an unsustainable condition” (Schjønning et al., 2004).

The Ssq is an indicator threshold value and is expected to differ markedly, across soil types and climates. Nevertheless, depending on cropping, a Ssq value of >3 may be critical for a fertile and highly productive soil whereas Ssq5 may be critical for e.g. sandy soils in a cold and humid climate. Despite these differences we are proposing threshold values of the upper subsoil down to 60 cm depth (Table 4). Although some subsoilers can penetrate below 50 cm, in general the soil moisture is too high for the fracturing of the soil by the subsoiler. Emphasis should be given to avoid or prevent deep compaction and to protect loosened soil from further compaction damage (Håkansson and Reeder, 1994). In addition, the retention of a lightly compacted transition layer that permits transmission of roots, water and nutrients may help to protect deeper subsoil from compaction (Spoor et al., 2003).

Ssq values of 1, 4 and 5 are assessed as good, fair and poor, respectively. For Ssq1, there is only a need to focus on how to maintain good quality, whereas for Ssq5 there is a need for short term improvement. Ssq values of 4 (and 3 under intensive production) indicate a need to consider management options to improve the subsoil quality in the medium to long-term. Where Ssq is 3 or 4, it may be worthwhile monitoring any change of the Ssq over the season before changing crop management.

Although it is important to distinguish man-made features from natural features that can increase density due to a change in soil texture with depth, such a layer, dependent on thickness, may also be capable of being loosened by a subsoiler or through biological processes. Mole drainage also may be an option.

The type and intensity of soil management needed to maintain or improve subsoil quality will also differ between sites. For instance, traffic with lower axle weights, or the minimisation of compaction via GPS-guided controlled traffic systems will most likely be needed to maintain Ssq1 or 2 for a clayey humid soil than for a sandy soil in a semi-arid climate. For Ssq=4/5 where immediate action is needed, subsoiling may be the answer in order to improve conditions down to approximately 45 cm depth (Spoor, 2006). However, subsoiling disturbs the *a priori* network of macropores in the soil and there is a great risk of recompaction after subsoiling as shown by e.g. Munkholm et al. (2005). Subsoiling may thus be a useful tool on some soils such as those supporting crops prone to drought stress (e.g. Marks and Soane, 1987) but not on others such as sandy soils with high winter rainfall (e.g. Olesen and Munkholm, 2007). There are a wide range of other management options available to alleviate subsoil compaction and it is beyond the scope of this paper to go into further details - please consult the recent review by Batey (2009).

5. Conclusions

The assessment of subsoil quality by visual scoring within soil pits enables identification of anthropic layers due to compaction that limit the agronomic potential of soil. These were mostly in the zone immediately below the topsoil, the ‘transition layer’. The method could identify the severity and depth extent of compaction in all soils tested. The use of a decision flowchart for the separate assessment of mottling, strength, porosity, rooting and aggregate size and shape in each layer enables a relatively objective and rapid assessment of subsoil quality. Porosity and strength assessments were particularly relevant. Distinguishing whether the quality of these subsoil layers reflects the natural soil composition or degradation by land management is helped by comparison of the test soils with reference soils nearby under forest or long-term grassland. The scores of structural quality derived can be used to judge the requirement for amelioration by soil management, mainly by subsoiling.

Acknowledgements

Lothar Mueller and Mandy Liesch helped in the early stages of development. Britton Wilkinson and Mansonia Pulido provided helpful comments. Anne Weill provided some photographs and helped with the chart. Masters students from ISARA, Lyon, France suggested several improvements of the method. The work was partly supported by the Scottish Government and by a soil compaction project granted by Knowledge Center for Agriculture, Denmark.

References

Amoozegar, A., 2002. Auger-hole method (saturated zone), in: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Physical Methods, Soil Science Society of America, Madison, Wis., pp. 870-877.

Andersen, M.N., Munkholm, L.J., Nielsen, A.L., 2013. Soil compaction limits root development, radiation use efficiency of three winter wheat (*Triticum aestivum L.*) cultivars. Acta Agric. Scand. B 63, 409-419

Arshad, M.A., Lowery, B., Grossman B., 1996. Physical tests for monitoring soil quality, in: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. Soil Sci. Soc. Amer. Special Publn. 49, Soil Sci. Soc. Amer., Madison, WI, pp. 123-141.

Arvidsson, J., Håkansson, I., 2014. Response of difference crops to soil compaction – Short-term effects in Swedish field experiments. Soil Till. Res. 138, 56-63.

Arvidsson, J., 1998. Soil compaction caused by heavy sugar beet harvesters: measurements with traditional and new techniques, in: Marlander, B.; Tijink, F. G. J.; Hoffmann, C., Beckers, R. (Eds.), Soil compaction and compression in relation to sugar beet production. Adv. Sugar Beet Res. 1, 35-42

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

Batey, T., 1988. Soil husbandry. Soil and Land Use Consultants Ltd, Aberdeen, UK.

Batey, T., 2000. Soil profile description and evaluation, in: Smith, K.A., Mullins, C.E. (Eds.), Soil and environmental analysis: physical methods. 2nd Edn.. Marcel Dekker Inc., New York, pp. 595-628.

Batey, T., 2009. Soil compaction and soil management – a review. Soil Use Manage. 25, 335-345

Batey, T., 2014. The installation of underground pipelines: effects on soil properties. Soil Use Manage. (in press).

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

Boizard, H., Richard, G., Brancourt-Hulmel, M., Guérif, J., 2000. Effect of cropping systems on change in bulk density, penetration resistance and hydraulic conductivity in subsoil. Adv. Geoecol. 32, 233-241.

Droogers, P., Bouma, J., 1997. Soil survey input in exploratory modelling of sustainable management practices. Soil Sci. Soc. Amer. J. 61, 1704-1710.

Ehlers, W., Kopke, U., Hesse, F., Bohm, W., 1983. Penetration resistance and root growth of oats in tilled and untilled loess soil. Soil Till. Res. 3**,** 261-275.

FAO, 2006. Guidelines for soil description. 4th Edition. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Fitzpatrick. E.A., 1956. An indurated soil horizon formed by permafrost. J. Soil Sci. 7, 248-254.

Gubiani, P., Reichert, J.M., Reinert, D.J., Somavilla Gelain, A., 2010. Soil resistance to penetration under the dynamic and predictive perspective of restriction to crop yield. 19th World Congress of Soil Science, Soil Solutions for a Changing World 164, 1-6 August 2010, Brisbane, Australia.

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., 2011. Improvements in visual evaluation of soil structure. Soil Use Manage. 27, 395-403.

Håkansson, I., Reeder, R.C., 1994. Subsoil compaction by vehicles with high axle load – extent, persistence and crop response. Soil Till. Res. 29, 277-304.

Hodgson, J.M., 1974. Soil survey field handbook: describing and sampling soil profiles. Lawes Agricultural Trust, Harpenden, Herts, UK.

Jones, R.J.A., Spoor, G., Thomasson, A.J., 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil Till. Res. 73, 131-143.

Kay, B., 1997. Soil structure and organic carbon: a review, in: Lal, R., Kimble, J.M., Follett, F., Stewart, B.A. (Eds.), Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL, pp.169-182.

Keller, T., Sutter, J.A., Nissen, K., Rydberg, T., 2012. Using field measurement of saturated soil hydraulic conductivity to detect low-yielding zones in three Swedish fields. Soil Till. Res. 124, 68-77.

Lorenz, K., Lal, R., 2005. The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. In: Sparks, D.L. (Ed.), Adv. Agron. 88, 35-66.

Manichon, H., 1987. Observation morphologique de l’état structural et mise en evidence d’effects du compactage des horizons travaillés, in: Monnier, G., Goss, M.J. (Eds.), Soil compaction and regeneration. Balkema, Rotterdam, the Netherlands, pp. 35-52.

Marks, M.J., Soane, G.C., 1987. Crop and soil response to subsoil compaction, deep incorporation of phosphorus and potassium fertilizer and subsequent soil management to a range of soil types. Part 1: Response of arable crops. Soil Use Manageme. 3, 115-123.

McKenzie, B.M., Bengough, A.G., Hallett, P.D., Thomas, W.T.B., Forster, B., McNicol, J.W., 2009. Deep rooting and drought screening of cereal crops: a novel field-based method and its application. Field Crops Res. 112, 165–171.

McKenzie, D.C. 1998 (Ed.), SOILpak for Cotton Growers. 3rd Edn. Orange, NSW, Australia: NSW Agriculture. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0009/167499/soilpak-cotton-Part-C.pdf
Page C4-11 (Accessed 12th August 2014)

McKenzie, D.C., 2001a. Rapid assessment of soil compaction damage. I. The SOILpak score, a semi-quantitative measure of soil structural form. Austr. J. Soil Res. 39, 117-125.

McKenzie, D.C., 2001b. Rapid assessment of soil compaction damage. II. Relationships between the SOILpak score, strength and aeration measurements, clod shrinkage parameters and image analysis data on a Vertisol. Austr. J. Soil Res. 39, 127-141.

McKenzie, D.C., 2013. Visual soil examination techniques as part of a soil appraisal framework for farm evaluation in Australia. Soil Till. Res. 127, 26-33.

Mueller, L., Schindler, U., Dexter, A.R., 1994. Subsoil structure characteristics of river lowland clay soils with shallow water tables, in: Proceedings of the 13th Triennial Conference of ISTRO: ISTRO 13, Copenhagen, Denmark, July 24-29, pp. 567-572.

Mueller, L., Schindler, U., Shepherd, T.G., Ball, B.C., Smolentseva, E., Hu, C., Hennings, V., Schad, P., Rogasik, J., Zeitz, J., Schlindwein, S.L., Behrendt, A., Helming, K., Eulenstein, F., 2012. A framework for assessing agricultural soil quality on a global scale. Archiv. Agron. Soil Sci. 58, No. S1, S76-S82.

Munkholm, L.J., Schjønning, P., Ruegg, K., 2005. Mitigation of subsoil recompaction by light traffic and on-land ploughing I. Soil response. Soil Till. Res. 80, 149-158.

NCST, 2009. Australian Soil and Land Survey Field Handbook – 3rd Edn., Australian Soil and Land Survey Handbooks, Series 1, CSIRO Publishing, Melbourne, Australia.

Olesen, J.E., Munkholm, L.J., 2007. Subsoil loosening eliminated plough pan in a crop rotation for organic farming with mixed effects on crop yield. Soil Till. Res. 94, 376-385.

Peigné. J., Vian, J.F., Cannavaciuolo, M., Lefevre, V., Gautronneau, Y., Boizard, H., 2013. Assessment of soil structure in the transition layer between topsoil and subsoil using the profil cultural method. Soil Till. Res. 127, 13-25.

Petersen, L., 1976. Podzols and Podzolization, DSc thesis, DSR Forlag, Copenhagen, p. 293.

Schjønning, P., Elmholt, S., Christensen, B.T., 2004. Soil quality management - concepts and terms, in: Schjønning, P., Elmholt, S., Christensen, B.T. (Eds.), Managing soil quality: challenges in modern agriculture. CABI Publishing, Wallingford, UK, pp. 1-15.

Schjønning, P., Rasmussen, S.T., Lamandé, M., Nielsen, J.M., Christensen, B.B., Nørgaard, H., Bak, H., Nielsen, J.A., 2011. Startkarakterisering af arealer til jordpakningsforsøg (In Danish). Intern rapport nr. 108. Aarhus University, Denmark, pp.1-39.

Shepherd, T.G., 2009. Visual Soil Assessment. Field Guide for Pastoral Grazing and Cropping on Flat to Rolling Country, vol 1, 2nd edn. Horizons Regional Council, Palmerston North, New Zealand.

So, H.B., Aylmore, L.A.G., 1993. How do sodic soils behave – the effects of sodicity on soil physical behaviour. Austr. J. Soil Res. 31, 761-777.

Spoor, G., Tijink, F.G.J., Weisskopf, P., 2003. Subsoil compaction: risk, avoidance, identification and alleviation. Soil Till. Res. 73, 175-182.

Spoor, G., 2006. Alleviation of soil compaction: requirements, equipment and techniques. Soil Use Manage. 22, 113-122.

Swarz, M., Misstear, B.D.R., Daly, D., Farrell, E.R., 2003. Assessing subsoil permeability for groundwater vulnerability. Qu. J. Engng Geol. Hydrogeol. Part 2, 36, 173 -18.

Tardieu, F., 1988. Analysis of the spatial variability of maize root density. I Effect of wheel compaction on the spatial arrangement of roots. Pl. Soil 107, 259-266.

Supplementary material for the SubVESS soil profile scoring.

Identifying a transition layer

The transition layer is just below the normal depth of cultivation (usually 25 cm in conventional systems) and usually has properties of topsoil and subsoil. If it is more compact or more poorly aerated than the soil below then the full agronomic potential of the soil is not being used. The transition layer may have been compacted or smeared by machinery during tillage, planting or harvest. Thickness can range from a few cm to >30 cm. The signs of compaction include high strength, low porosity and platy aggregates. The upper part of a compacted layer can be assessed readily, but it is more difficult to determine how far down the compaction persists. If possible, try to compare with a non-compacted soil nearby. It is important to distinguish man-made features from natural features that result from a change in soil texture with depth. Dependent on thickness, this layer may also be capable of being loosened by a subsoiler or improved by mole drainage.

Identifying gleying/mottling

Gleying refers to the grey colour of soil that has undergone long periods of waterlogging and reducing conditions. Mottles are spots or small patches of yellow, grey or rusty-reddish spots scattered through the main colour of the soil. They are produced by alternating wetting (reducing) and drying (oxidising) conditions within the soil profile. A high abundance of distinct, well-marked mottles surrounding pores in an otherwise grey volume indicates long periods of waterlogging.

Looking for macropores

Macropores are taken to be of three main types: (1) between particles or aggregates (<1 mm across), (2) tube-like worm and root channels (1-10 mm diameter) and (3) cracks or fissures (from a few mm to several cm long). Picking at the vertical face of the soil profile with a knife will reveal channels and cracks. Earthworm holes are often filled with casts made up of fine crumbs. The smaller pores are best revealed on an unsmeared surface such as a freshly broken fragment. To help distinguish pores from surface imperfections, hold fragments in the shade.

Maximum root lengths of different crops

Root growth requires pores of similar or greater diameter to the roots for entry or soil that is loose enough to be pushed aside. If the soil pores and cracks are too narrow or the soil is too rigid then root growth is restricted and the roots may react by becoming thick, stubby and twisted. Thus a dense interlocking web of roots may develop on the surface of a compact layer or roots will follow cracks or wormholes. In addition to compaction the depth to which roots grow depends on how long the crop has been growing, the rate of crop growth, availability of soil water, overall soil depth, transition layer depth and the type of crop. Although rooting depth depends on growth stage, typical rooting depths for different UK crop types are:

Winter wheat	1.8-2.0 m
Spring barley	1.2-1.5 m
Perennial grasses	1.2-2.0 m
Sugar beet	1.2-1.8 m

Some typical rooting depths for crops grown in warmer regions are:

Alfalfa	1.2-2.5 m
Cotton	0.9-2.0 m
Grain	0.6-1.5 m
Maize (corn)	0.6-1.2 m
Vegetables and soft fruit	0.3-0.9 m

The plant’s rooting characteristics determine how much soil moisture can be extracted by the plant. A deep rooted crop can access more soil moisture than a shallow rooted crop. Clearly there is a difference in ability of roots to grow in compacted soil – especially a better performance of perennials such alfalfa and chicory. Also there are differences between annuals in general tap rooted dicotyledonous plants are better than monocotyledons at penetrating compacted soil. However, even though there are differences between species, a hard soil would be difficult to penetrate for all the normal field crops and would strongly affect spatial distribution, branching etc. The emphasis in scoring is mainly on evaluating whether there is restricted growth within the different layers and not just rooting depth. Usually the presence of roots at or near ‘normal’ maximum rooting depth confirms that at least some roots succeeded in penetrating any transition layer. Note that roots will need to grow to their biological potential depths if they are to maximise their access to soil water, particularly where the potential soil moisture deficit (PSMD) is > 225 mm. If the climatic demand is less with a PSMD of 75-225 mm then roots need only extend to 1-1.5 m depth. If the climate is cooler or wetter and PSMD is < 75 mm, then the roots will have no need to extend below 0.5 m. To find roots at depth, it is necessary to pick at the vertical face of the soil profile, penetrating to a depth of only a few mm, with the point of a knife.

Soil moisture storage

Stony and coarse sandy soils may receive good SubVESS scores (Ssq 1or 2) even though they have a low agronomic potential associated with poor water holding capacity. This results from the SubVESS focus on structure and not on texture effects on agronomic potential. In such cases a more comprehensive evaluation of the overall agronomic potential is required.

Soil structural terms

Aggregate/ped	Particles held together by clay and/or organic matter
Single grain/loose sand	No detectable sticking together to form aggregates
Friable	Soil that readily breaks up into small aggregates (1-15 mm)
Sub angular and angular	More compact aggregates with sharp edges and triangular shapes (angular) or more rounded edges (subangular), usually medium to large (1-15 cm).
Platy	Compact structure that breaks into horizontal plates
Prismatic	Large (5-30 cm across) vertically oriented peds bounded by cracks

Table 1. Ssq subsoil quality and Sq topsoil quality score sheets from compaction experiment, Denmark, where a) is the non-compacted reference and b) is heavy compaction.

a) Profile label/descriptor: Reference Operator: Lars J. Munkholm Date: 9 July 2012
Soil and site description: Aarslev, Denmark, compaction experiment, Glossic Phaeozem (WRB)

Subsoil Visual Evaluation of Soil Structure (SubVESS)

	Layer depth (cm)	Mottling	Strength	Porosity	Roots	Aggregate size/shape	**Structure quality (Ssq1-5)**
Layer 1, transition	25-40	1a-3a	1b-2b	1c	1d-2d	2e	**Ssq2**
Layer 2	40-100	1a-3a	3b	3c	3d	2e	**Ssq3**
Layer 3	100-140	1a-3a	3b	4c	3d	3e	**Ssq3**

Overall depth (cm): 140 Rooting depth (cm): 130 **Overall Ssq:** **Ssq2/3**

Topsoil Visual Evaluation of Soil Structure (VESS)

	Sample 1 layer depth (cm)	Sample 1 Sq (1 to 5)
Layer 1 (upper)	0-8	Sq2
Layer 2	8-25	Sq2.5

Overall Sq: Sq2/Sq2.5 (2.3)

b) Profile label/descriptor: 8Mg wheel load, high inflation pressure. Operator: Lars J. Munkholm Date: 9 July 2012. Soil and site as for (a).

Subsoil Visual Evaluation of Soil Structure (SubVESS)

	Layer depth (cm)	Mottling	Strength	Porosity	Roots	Aggregate size/shape	**Structure quality (Ssq1-5)**
Layer 1, transition	25-40	1a-3a	4b	5c	4d-5d	5e	**Ssq5**
Layer 2	40-75	1a-3a	4b	4c-5c	5d	5e	**Ssq5**
Layer 3	75-130	1a-3a	3b	4c	5d	3e	**Ssq3**

Overall depth (cm): 130 Rooting depth (cm): 40 **Overall Ssq:** **Ssq5/3**

Topsoil Visual Evaluation of Soil Structure (VESS)

	Sample 1 layer depth (cm)	Sample 1 Sq (1 to 5)
Layer 1 (upper)	0-8	Sq1.5
Layer 2	8-25	Sq5

Overall Sq: Sq1.5/Sq5 (3.9)

Table 2. Ssq subsoil quality and Sq topsoil quality score sheets from the grassland compaction and trampling field experiment, Scotland, where a) is the non-compacted reference and b) is heavy compaction and animal trampling.

a) Profile label/descriptor: Reference Operator: Bruce Ball/Paul Hargreaves. Date: 17th June 2013. Soil and site description: DairyCo compaction field experiment, Eutric Gleysol (WRB)

Subsoil Visual Evaluation of Soil Structure (SubVESS)

	Layer depth (cm)	Mottling	Strength	Porosity	Roots	Aggregate size/shape	**Structure quality (Ssq1-5)**
Layer 1, transition	24-39 cm	1a-3a	1b-2b	2c	1d-2d	2e	**Ssq2**
Layer 2	39-64 cm	1a-3a	3b	3c	3d	3e/4e	**Ssq3**
Layer 3	64-90 cm	1a-3a	1b-2b	2c	n/a	1e	**Ssq2**

Overall depth (cm): 90 cm Rooting depth (cm): 70 cm **Overall Ssq: Ssq2/3/2**

Topsoil Visual Evaluation of Soil Structure (VESS, Sq)

	Sample 1 layer depth (cm)	Sample 1 Sq (1 to 5)
Layer 1 (upper)	0-3 cm	Sq1
Layer 2	3-23 cm	Sq3

Overall Sq: Sq2.7

b) Profile label/descriptor: Compacted discard area. Operator: Bruce Ball/Paul Hargreaves Date: 17th June 2013. Soil and site as for (a)

Subsoil Visual Evaluation of Soil Structure (SubVESS)

	Layer depth (cm)	Mottling	Strength	Porosity	Roots	Aggregate size/shape	**Structure quality (Ssq1-5)**
Layer 1, transition	25-40 cm	1a-3a	4b-5b	3c	3d	3e	**Ssq3**
Layer 2	40-64 cm	4a-5a	4b-5b	4c	n/a	4e	**Ssq4**
Layer 3	64-90 cm	1a-3a	1b-2b	3c	n/a	2e	**Ssq2**

Overall depth (cm): 90 cm Rooting depth (cm): 75 cm **Overall Ssq: Ssq3/4/2**

Topsoil Visual Evaluation of Soil Structure (VESS, Sq)

	Sample 1 layer depth (cm)	Sample 1 Sq (1 to 5)
Layer 1 (upper)	0-1 cm	Sq1
Layer 2	1-25 cm	Sq5

Overall Sq: Sq5

Table 3. Ssq assessments in six pits in a Luvisol under a minimum tillage cover crop in France.

	Layer depth (cm)	Mottling	Strength	Porosity	Roots	Aggregate size/shape (1e -5e)	**Structure quality by layer (Ssq1-5)**	**Overall Ssq and rooting depth**
Pit A	25-55	1a-3a	1b-2b	2c	1d-2d	1e	**Ssq1**	**Ssq1/3/4**
	55-90	1a-3a	3b	3c	3d	4e	**Ssq3**	**90 cm**
	90-130	4a-5a	3b	4c	5d	5d	**Ssq4**	
Pit B	25-85	1a-3a	1b-2b	3c	1d-2d	3e	**Ssq3**	**Ssq3/4**
	85-130	4a-5a	4b-5b	4c	5d	4e	**Ssq4**	**85 cm**
Pit C	25-55	1a-3a	1b-2b	3c	3d	3e	**Ssq3**	**Ssq3/4/4**
	55-70	1a-3a	3b	3c	5d	4e	**Ssq4**	**70 cm**
	70-130	4a-5a	4b-5b	4c	5d	3e	**Ssq4**	
Pit D	25-40	1a-3a	3b	3c	1d-2d	4e	**Ssq3**	**Ssq3/4/5**
	40-60	1a-3a	1b-2c	3c	3d	3e	**Ssq3**	**80 cm**
	60-80	1a-3a	3b	3c	4d	4e	**Ssq4**	
	80-130	4a-5a	4b/5b	5c	5d	5e	**Ssq5**	
Pit E	25-65	1a-3a	1b-2b	2c	3d	2e	**Ssq2**	**Ssq2/3/4**
	65-90	1a-3a	3b	3c	3d	4e	**Ssq3**	**90 cm**
	90-130	4a-5a	3b	4c	5d	4e	**Ssq4**	
Pit F*	30-130	1a-3a	1b-2b	1c	1d-2d	1e	**Ssq1**	**Ssq1** **50 cm**

* Pit F is mixture of stones (60-90%) and fine soil with sands.

Table 4. Threshold Ssq values for sustained agricultural productivity.

Ssq score	Subsoil structural quality	Management needs
1, 2, 3	Good	No changes needed
4	Fair	Medium to long-term changes needed
5	Poor	Short-term changes needed

Figure captions.

Figure 1. Profiles showing the labels marking the boundaries between layers of differing Sq. The soils are poorly drained eutric gleysol, compacted (left) and not compacted (right), Crichton, Dumfries. They are described in Table 2.

Figure 2. Flowchart for assessing the quality of diagnostic factors for scoring subsoil quality, Ssq. Red shading in the flowchart signifies soil structure problems that require attention from soil managers.

Figure 3. Method of extraction of fragments of soil. The knife is inserted into the layer (A), a fragment is dislodged (B), caught in the hand (C) and broken (D) to allow assessment of strength, compaction and porosity.

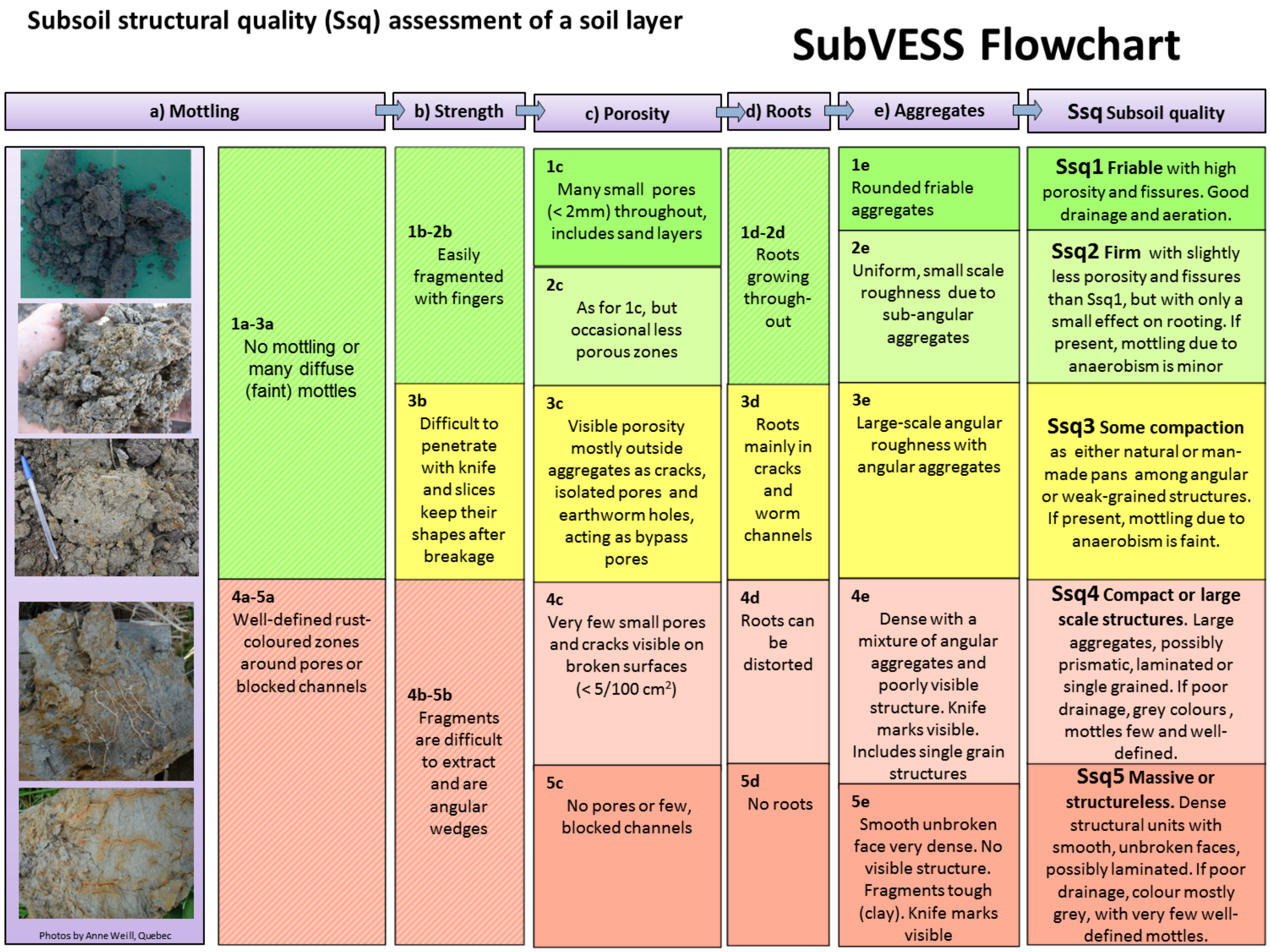
Figure 4. Subsoil layers 1 (transition) and 2 from the compaction experiment, Denmark. See Table 1 for the layer descriptions.

Figure 5. Soil profiles in a no-till field on an Oxisol in Brazil. Crop area refers to the non-compacted main growing area, border area refers to where machinery turns and is compacted. Native forest refers to an adjacent undisturbed area taken as a reference. The insertions show the fragmented slices from each layer with the top insertion showing the fragmented topsoil VESS.

Figure 6. VESS and SubVESS in a no-till field in an Oxisol in Brazil. Crop area refers to the non-compacted main growing area and border area refers to where machinery turns and is compacted. Native forest refers to an adjacent undisturbed area taken as a reference.

Figure 1. Profiles showing the labels marking the boundaries between layers of differing Sq. The soils are poorly drained eutric gleysol, compacted (left) and not compacted (right), Crichton, Dumfries. They are described in Table 2.

Figure 2. Flowchart for assessing the quality of diagnostic factors for scoring subsoil quality, Ssq. Red shading in the flowchart signifies soil structure problems that require attention from soil managers.



Subsoil structural quality (Ssq) assessment of a soil layer

SubVESS Flowchart

a) Mottling

Photos by Anne Weill, Quebec

1a-3a No mottling or many diffuse (faint) mottles

4a-5a Well-defined rust-coloured zones around pores or blocked channels

b) Strength

1b-2b Easily fragmented with fingers

3b Difficult to penetrate with knife and slices keep their shapes after breakage

4b-5b Fragments are difficult to extract and are angular wedges

c) Porosity

1c Many small pores (< 2mm) throughout, includes sand layers

2c As for 1c, but occasional less porous zones

3c Visible porosity mostly outside aggregates as cracks, isolated pores and earthworm holes, acting as bypass pores

4c Very few small pores and cracks visible on broken surfaces (< 5/100 cm^2)

5c No pores or few, blocked channels

d) Roots

1d-2d Roots growing through-out

3d Roots mainly in cracks and worm channels

4d Roots can be distorted

5d No roots

e) Aggregates

1e Rounded friable aggregates

2e Uniform, small scale roughness due to sub-angular aggregates

3e Large-scale angular roughness with angular aggregates

4e Dense with a mixture of angular aggregates and poorly visible structure. Knife marks visible. Includes single grain structures

5e Smooth unbroken face very dense. No visible structure. Fragments tough (clay). Knife marks visible

Ssq Subsoil quality

Ssq1 Friable with high porosity and fissures. Good drainage and aeration.

Ssq2 Firm with slightly less porosity and fissures than Ssq1, but with only a small effect on rooting. If present, mottling due to anaerobism is minor

Ssq3 Some compaction as either natural or man-made pans among angular or weak-grained structures. If present, mottling due to anaerobism is faint.

Ssq4 Compact or large scale structures. Large aggregates, possibly prismatic, laminated or single grained. If poor drainage, grey colours, mottles few and well-defined.

Ssq5 Massive or structureless. Dense structural units with smooth, unbroken faces, possibly laminated. If poor drainage, colour mostly grey, with very few well-defined mottles.

Figure 3. Method of extraction of fragments of soil. The knife is inserted into the layer (A), a fragment is dislodged (B), caught in the hand (C) and broken (D) to allow assessment of strength, compaction and porosity.

Reference	8 Mg wheel load

20-37 cm depth

49- 72 cm depth

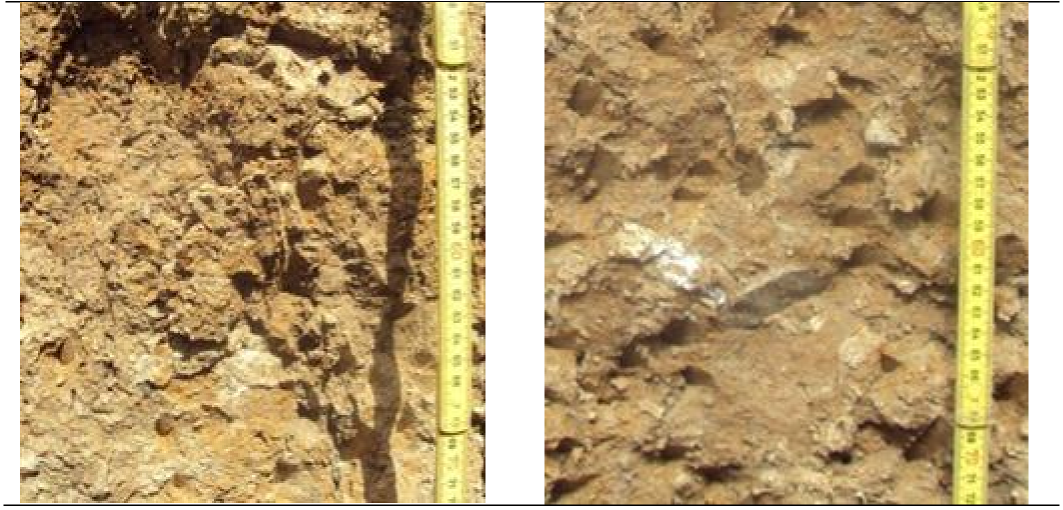


Figure 4. Subsoil layers 1 (transition) and 2 from the compaction experiment, Denmark. See Table 1 for the layer descriptions.

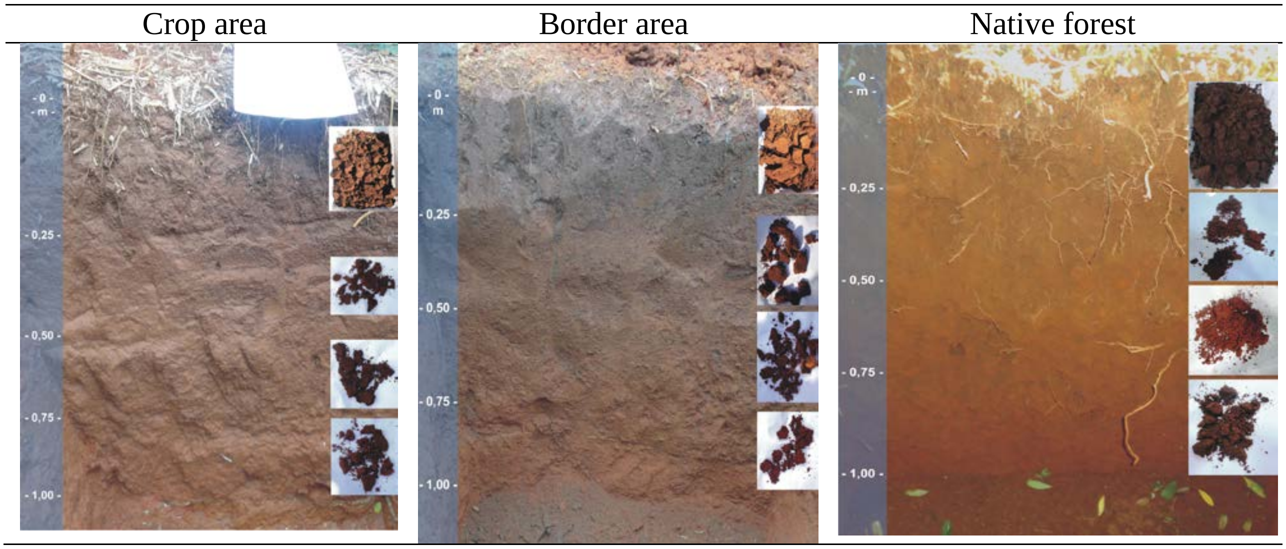


Figure 5. Soil profiles in a no-till field on an Oxisol in Brazil. Crop area refers to the non-compacted main growing area, border area refers to where machinery turns and is compacted. Native forest refers to an adjacent undisturbed area taken as a reference. The insertions show the fragmented slices from each layer with the top insertion showing the fragmented topsoil VESS.

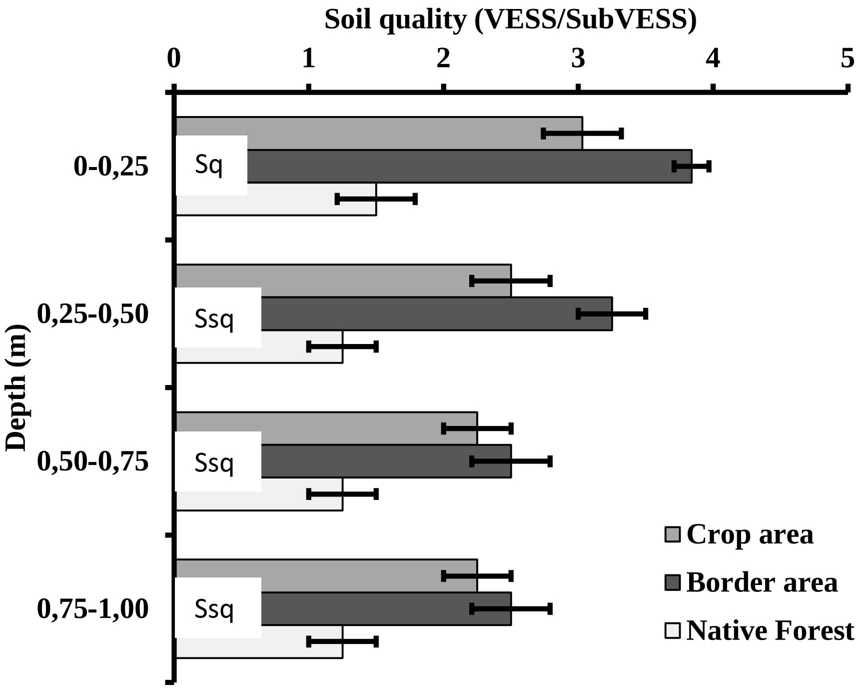


Figure 6. VESS and SubVESS in a no-till field in an Oxisol in Brazil. Crop area refers to the non-compacted main growing area and border area refers to where machinery turns and is compacted. Native forest refers to an adjacent undisturbed area taken as a reference.