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Opportunities and future directions for visual soil evaluation methods in soil structure research

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ABSTRACT

As the use of visual soil evaluation (VSE) methods has spread globally, they have been exposed to different climatic and pedological scenarios, resulting in the need to elucidate limitations, encourage refinements and open up new avenues of research. The main objective of this paper is to outline the potential of VSE methods to develop novel soil structure research and how this potential could be developed and integrated within existing research. We provide a brief overview of VSE methods in order to summarize the soil information that is obtained by VSE. More detailed VSE methods could be developed to provide spatial information for soil process models, e.g. compaction models. VSE could be combined with sensing techniques at the field or landscape scale for better management of fields in the context of precision farming. Further work should be done to integrate plant vigour, roots and soil fauna into VSE methods to provide general indicators of soil quality and for estimation of environmental risk factors related to soil C storage, GHG emissions and nutrient leaching, with particular reference to temporal changes. There is a great potential in combining (rather than comparing) VSE with measurements of soil structure, i.e. integrating VSE in soil structure and compaction research, as these methods provide spatial information that is difficult to obtain with other methods.

1. Introduction

Soil structure comprises the physical habitat of soil living organisms, and controls many important physical, chemical and biological soil functions and associated ecosystem services. Soil structure is typically defined as the spatial arrangement of soil constituents and voids (i.e. soil pores), which may also be defined as the spatial distribution of soil properties (Dexter, 1988). However, soil structure is more than just the physical arrangement of particles and pores (that was referred to as "structural form" by Kay and Angers (2001)), and includes structural stability (i.e. the ability to resist external stresses) and structural resilience (i.e. the ability to recover upon stress removal) (Kay and Angers, 2001).

Different methods can be used to evaluate the different aspects of soil structure. For example, computed tomography (CT) imaging is excellent at visualizing and quantifying the form of soil structure (for an overview, see Taina et al., 2008; Peth, 2011; Wildenshild and Sheppard, 2013) and can be used to study the dynamics of soil structural pore spaces (i.e. the dynamics of the form of soil structure) by multiple scanning as demonstrated by Peth et al. (2013), but cannot directly assess soil structure stability or resilience. Visual soil evaluation (VSE) cannot reveal as much information on the geometrical arrangement of pores and constituents as CT imaging does, but assesses both the structural form and the structural stability (e.g. DVWK, 1995a, 1997; ATV-DVWK, 2001; Boizard et al., 2007; Guimarães et al., 2011), and may reveal information on the resilience through biological indicators (e.g. Boizard et al., 2017). Unlike the texture of a soil that can be considered a static property, the soil structure is a dynamic trait. Soil structure is influenced by both natural and anthropogenic

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processes. The natural processes include abiotic processes induced by drying-wetting and freeze-thaw phenomena, as well as biotic processes leading to the creation of new pore spaces by the penetration of plant roots and burrowing fauna, soil aggregate stabilization by plant roots, fungi, and soil fauna (enmeshing, excretions), and soil shrinkage due to plant water uptake (Kay, 1990; Dexter, 1991; Horn et al., 1994; Horn, 2003; Hallett et al., 2013). Anthropogenic influences on soil structure are primarily related to soil management including soil tillage, soil compaction due to vehicle traffic, incorporation of organic fertilizers and amendments, as well as crop selection and fertilization (for an overview, see Kay, 1990; Bronick and Lal, 2005; Kay and Munkholm, 2011). Such aspects have significant influence on structural stability and resilience as well as structural form, all of which influence soil function (Horn, 1990; Horn et al., 1994).

Despite the recognized importance of soil structure for soil functioning, its characterization and quantification of the complex interactions (as stated above) that drive soil structure formation remain a challenge (e.g. Hallett et al., 2013; Peth et al., 2013). Visual soil evaluation (VSE) methods have been developed to assess the structural state of soil (for a review see Boizard et al., 2007). Most VSE methods were developed as a practical diagnostic tool in agricultural extension service. Various visual methods to assess soil structure and soil quality have been developed and used for many years in different parts of the world, and these have mainly been published in reports, booklets and notes (e.g. Görbing, 1947; Peerlkamp, 1959; Preuschen, 1983; Gautronneau and Manichon, 1987; DVWK, 1995a; Shepherd, 2000; Munkholm, 2000; McKenzie, 2001; Nievergelt et al., 2002). More recently, methods have been refined, combined, and published in scientific journals (for an overview see e.g. Ball et al., 2015). In the remainder of this paper, we use 'visual soil evaluation (VSE) methods' as a general term for all methods, whereas specific methods (e.g. 'Profil Cultural'; Gautronneau and Manichon, 1987) will be referred to by their specific name. Furthermore, there has been a growing interest to (re-)use VSE methods in research, that primarily have been used to characterize the impact of soil management on soil structure and to help identify the type and location of measurements for further characterization of soil physical properties (Ball et al., 2015; this special issue).

Only a few studies have used VSE methods with regards to soil structure dynamics. Roger-Estrade et al. (2000) used the 'Profil Cultural' method (Gautronneau and Manichon, 1987) to quantify the temporal evolution of soil structure under contrasting tillage systems, and Boizard et al. (2013) used the same method to study recovery after compaction in a reduced tillage experiment. Ball and Munkholm (2015) showed that the 'Visual Evaluation of Soil Structure' (VESS) method (Guimarães et al., 2011) was able to reveal variations in soil quality and recovery, over a four-year period of evaluation, when assessing compaction by tractor and animal trampling. These authors also highlighted that repeating VSE measurements over time enables the monitoring of soil quality evolution.

All VSE methods are mainly used within an agronomic context, with the purpose of assessing soil management effects and providing soil management recommendations. Thus, it is important that VSE scores have veracity and are nearly reproducible. Therefore, soil structure is systematically evaluated according to manuals and instruction videos to reduce operator dependence for most VSE methods. In general, different operators typically find very similar scores (e.g. Ball et al., 2007; Guimarães et al., 2011). Subjectivity is, however, still considered a modest limitation to VSE methods, e.g. in relation to the isolation of structural units and the assessment of their properties and efforts to further reduce this limitation continue. Other limitations include possibly confusing soil moisture effects on soil strength with those of compaction and difficulty in use in soils of extreme textures and insufficient emphasis on porosity, particularly with spade methods (Ball and Munkholm, 2015; Munkholm and Holden, 2015). Scale is also an important aspect to take account for any soil structure description method. Babel et al. (1995) proposed an initial description of soil structure (shape and surface of the structural units, geometrical arrangement, aggregate strength, bioturbation, etc.) at a given scale, and then to reproduce observations at various scales applicable across land uses and across scientific disciplines.

VSE methods yield information on the vertical thickness and depth of natural and anthropogenic soil layers, and on the spatial arrangement of structural features (profile methods) or the size distribution of soil fragments (spade methods). Such information is not available, for example, from sampling at discrete (pre-defined) depths with small volumes (e.g. undisturbed cylindrical soil cores that may have a typical volume of 100 cm^3), which are typically used in soil structure research. Several studies have demonstrated significant correlations between the various structural features (as e.g. obtained by VSE methods) and a range of soil properties (mainly soil physical properties such as, bulk density, penetration resistance, saturated hydraulic conductivity, among others; see e.g. Horn, 1990; Shepherd, 2003; Dörner and Horn, 2009; Guimarães et al., 2013; Moncada et al., 2014; Ball et al., 2017). Moreover, the shape of the fragments and an estimate of the tensile strength of the fragments is obtainable from VSE methods. The 'Profil Cultural' reports detailed information regarding the spatial arrangement and distribution of soil properties (e.g. aggregates, pores, roots, organic residues), whereas other methods such as VESS (Guimarães et al., 2011), the Visual Soil Assessment (VSA) method (Shepherd, 2009) and SOILpak (McKenzie, 1998), for example, combine this information into a score or soil quality index, either for each layer or for a whole soil profile. The reason for combining this information into a single index is that such an index will be useful for assessing the overall physical quality of a soil, for comparing soil quality across soils, and for providing soil management recommendations. However, valuable information on soil structure can be lost through the combination process. We will argue in this paper that this information could be useful in research aiming at better understanding the impact of soil structure on soil functioning (including plant growth) and better understanding of soil structure dynamics.

A joint workshop of the ISTRO working groups on Visual Soil Examination and Evaluation (VSEE) and Subsoil Compaction held in May 2014 brought together scientists dealing with characterization of soil structure and its dynamics with a focus on soil management impacts (soil tillage, soil degradation by compaction). A main aim of the workshop was to jointly discuss and possibly outline (i) research needs of visual soil evaluation methods, new approaches (ii) to combine VSE methods with "traditional" soil physical methods and analysis as well as with remote and proximal sensing techniques, and (iii) to integrate VSE in soil structure research for better quantification of soil structure and better understanding of soil structure dynamics caused by soil management. This article summarizes and synthesizes the discussions from the workshop. Although the workshop had an emphasis on tropical conditions, most of the discussions were relevant to all soils.

The main objectives of this paper are to outline (i) research needs for improvement of VSE methods, and (ii) the opportunities of VSE methods in soil structure research. We will provide a brief overview of VSE methods, in order to summarize the soil information that is obtained by VSE. We will describe research needs for further development of VSE methods and their better integration in soil structure research. Finally, we propose ways of