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Soil structure as an indicator of soil functions: A review

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ABSTRACT

Since many processes in soil are highly sensitive to soil structure, this review intends to evaluate the potential of observable soil structural attributes to be used in the assessment of soil functions. We focus on the biomass production, storage and filtering of water, storage and recycling of nutrients, carbon storage, habitat for biological activity, and physical stability and support. A selection of frequently used soil structural properties are analyzed and discussed from a methodological point of view and with respect to their relevance to soil functions. These are properties extracted from soil profile description, visual soil assessment, aggregate size and stability analysis, bulk density, mercury porosimetry, water retention curve, gas adsorption, and imaging techniques. We highlight the greater relevance of the pore network characterization as compared to the aggregate perspective. We identify porosity, macroporosity, pore distances, and pore connectivity derived from imaging techniques as being the most relevant indicators for several soil functions. Since imaging techniques are not widely accessible, we suggest using this technique to build up an open access “soil structure library” for a large range of soil types, which could form the basis to relate more easily available measures to pore structural attributes in a site-specific way (i.e., taking into account texture, soil organic matter content, etc.).

1. Introduction

Soil structure is recognized to control many processes in soils. It regulates water retention and infiltration, gaseous exchanges, soil organic matter and nutrient dynamics, root penetration, and susceptibility to erosion. Soil structure also constitutes the habitat for a myriad of soil organisms, consequently driving their diversity and regulating their activity (Elliott and Coleman, 1988). As an important feedback, soil structure is actively shaped by these organisms, thus modifying the distribution of water and air in their habitats (Bottinelli et al., 2015; Feeney et al., 2006; Young et al., 2008). Since many processes in soil proved to be linked to soil structure, this review intends to evaluate the potential of soil structure to be used in the assessment of soil functions. We refer to soil structure as the spatial arrangement of solids and voids across different scales without considering the chemical heterogeneity of the solid phase. Thus, the solid phase and pore space are complementary aspects of soil structure which can be approached from both perspectives.

The solid phase perspective, based on mechanisms of soil aggregation, has been supported by Tisdall and Oades (1982). Since their pioneering work, aggregation is conceptually viewed as a three-stage hierarchical organization of the soil solid phase, each stage involving characteristic binding agents. Primary particles ($< 20\,\mu m$) are bound together into microaggregates (20–250 μm), which are bound together to form macroaggregates ($> 250\,\mu m$). Follow-up studies favored a different sequence of aggregate formation: macroaggregates can form around particulate organic matter, then microaggregates are released upon breakdown of macroaggregates (Angers et al., 1997; Oades, 1984). The bonds within microaggregates are supposed to be more persistent than those between macroaggregates (Tisdall and Oades, 1982). This hierarchical order, responsible for the micro- and macroaggregate formation, was identified in soils where soil organic matter was the major binding agent, but could neither be found in oxide-rich nor in sandy soils (Christensen, 2001; Oades and Waters, 1991; Six et al., 2004).

Following a pore perspective, soil structure may not be defined as “the shape, size and spatial arrangement of primary soil particles and aggregates” but as “the combination of different types of pores” (Pagliai and Vignozzi, 2002), where surfaces of soil particles are assumed to be the walls of the pore space (Elliott and Coleman, 1988). Similar to the aggregate hierarchy, a hierarchy of pores can be defined (Elliott and Coleman, 1988). Depending on their size, pores are classified as macropores, mesopores, and micropores, although there are no generally agreed upon size thresholds between these categories. Pores resulting

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Abbreviations: BD, bulk density; DC, degree of compactness; LLWR, least limiting water range; MIP, mercury intrusion porosimetry; SOM, soil organic matter

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from the arrangement of soil primary particles are called textural pores, whereas bigger pores resulting from biological activity, climate, and management practices are called structural pores.

These two different perspectives rely on the perception of what is actively shaped: aggregates or pores. Considering the multitude of soil processes and their interactions, there is ample evidence that generally both are possible with changing balance depending on soil type and site conditions. Irrespective of these different perspectives, there are distinct methods available to characterize either the solid phase arrangement or the pore space, and the obtained results are expected to differ in sensitivity, cost, or relevance to soil functions.

Yet, there is no universally accepted way to characterize soil structure (Díaz-Zorita et al., 2002), and this is even more true for using soil structural measures as indicators for soil functions as we intend to do. Wallace (2007) describes ecosystem functions as a synonym of ecosystem processes. Therefore, soil functions refer to “what the soil does” (Seybold et al., 1998), i.e., intrinsic processes occurring in soils irrespective of any human interest. From this definition, we assume that it is possible to assess soil functions through information-bearing soil properties called indicators. Good indicators must be highly correlated with the function of interest (Reinhart et al., 2015), that is to say, with other soil properties governing soil processes (e.g., saturated hydraulic conductivity, air permeability, etc.). Their measurement must be reliable and reproducible. The monetary and human costs for their acquisition and the level of expertise needed are also important aspects. A wide number of methods and structural properties are currently used by soil scientists and farmers, from quick field observations to thorough laboratory characterizations. Our intention is to provide a critical analysis of their efficiencies as related to soil functions.

We will particularly focus on six soil functions: biomass production, storage and filtering of water, storage and recycling of nutrients, carbon storage, habitat for biological activity, and physical stability and support. Attention will be paid on structural soil properties representative at the scale of pedons and soil horizons, assuming that soil functions can be assessed for 1-D soil profiles in a meaningful way. Since it is essential that the methods used be reliable from a technical point of view, we will discuss corresponding advantages and limitations. We will also report to what extent simple methods can substitute more complex ones to find a trade-off between reliability of information and acquisition cost. We will evaluate the different methods in terms of sampling requirements, reproducibility, cost, and level of expertise required. We chose to separate the available approaches to characterize soil structure based on the solid phase arrangement from those based on the pore space perspective.

2. Characterization of the solid phase arrangement

2.1. Field methods

Methods available to characterize soil structure directly in the field mainly aim at describing the “macrostructure”, that is to say, visible to the naked eye (Baize et al., 2013). They can roughly be divided in two groups: the whole profile evaluation, developed from the fundamental methods of field surveys, and the topsoil evaluation, a simplified version especially designed for farmers.

2.1.1. Whole profile evaluations

Following the FAO (2006) guidelines and most of the national standards (e.g., Ad-hoc-AG Boden, 2005 in Germany; Baize and Jabiol, 2011 in France; Schoeneberger et al., 2012 in the USA), soil structure morphology and its variation with depth are evaluated visually as part of the soil profile description. The description of soil structure is mainly related to its grade, and the size and shape of aggregates (Ad-hoc-AG Boden, 2005; Baize and Jabiol, 2011; FAO, 2006; Schoeneberger et al., 2012). The term aggregates usually comprises peds, fragments, and clods. Aggregates formed by natural processes are called peds, small aggregates formed artificially during laboratory or field manipulations are called fragments, and large aggregates formed artificially by cultivation operations are called clods. When soil material breaks into aggregates of higher order than the single grains (pedal soils), structure can be addressed by describing the grade of these aggregates. The grade describes the distinctness of the aggregates in place, qualified as strong, moderate, or weak. Qualifying the grade is realized by observing whether soil material breaks into fragments or “powder” when disturbed, and to what extent the surface of aggregates differs from their inner part (FAO, 2006). The aggregate shape is described according to several types of soil structure: among others, angular blocky, subangular blocky, granular, platy, prismatic, or columnar. In structureless soils (apedal soils), no aggregate are observed and the material is either compact or built up by single grains. Another approach is to distinguish soil clods based on a visual inspection of their internal structural porosity (Boizard et al., 2017; Roger-Estrade et al., 2004). It has to be noted that the size, abundance, orientation, and continuity of voids can be described in the field, with the naked eye or a hand-lens. However, the description of the complete void organization cannot be done (Baize and Jabiol, 2011).

The description of soil structure in the field highly depends on soil moisture, especially in swell-shrinking soils. Therefore, the FAO (2006) guidelines recommend performing this description when the soil is dry or slightly moist. The whole profile evaluations provide valuable information on the vertical sequence of soil structural properties. However, they are subjective, and since they require the digging of pits, they are also time consuming, and sufficient replication cannot always be done (Mueller et al., 2009).

Field observations of aggregate size, shape, and grade are rarely used as indicators for soil functions. Pulido Moncada et al. (2014c) used the aggregate shape (FAO, 2006) and showed that it was sensitive to soil type for the two studied soils, but poorly sensitive to land use (in this study, cereal monoculture vs. permanent pasture). By applying regression trees on a database gathering water retention measurements and field descriptions of soil structure, Pachepsky and Rawls (2003) found that the grade of soil structure, classified as strong, moderate, or weak, was the most informative to explain the water retention values, followed by the aggregates size and shape. In this case, water retention was correlated with the grade, because of the water capacity of small intra-aggregate pores. However, the overall discriminating power of the aggregate grade, size, and shape depended on the texture class.

2.1.2. Topsoil evaluation

Because accurate soil profile description requires considerable experience, simplified approaches based on field tests were designed to assess physical properties visually (Shepherd, 2000). They are particularly developed to estimate soil quality and are highly relevant for farmers or land managers, who wish to evaluate the quality of their soils and their management practices, easily, quickly, and cheaply. Indeed, the evaluation is often performed in < 20 min, with a spade being the main required equipment. Several “spade tests” were proposed, such as the Peerlkamp (1959) test, the “Visual Evaluation of Soil Structure” (Ball et al., 2007; Guimarães et al., 2011), the “Visual Soil Assessment” (Shepherd, 2009, 2000), or the “SOILpak score” (McKenzie, 2001). A similar approach exists for subsoil (Ball et al., 2015). In the topsoil evaluations, an undisturbed soil block is extracted from soil surface with a spade (e.g., full size of the spade and approximately 20 cm-thick) and manually broken or dropped from a 1 m-height to produce aggregates. Aggregates are then described in terms of size, porosity, shape, color, ease of breakup, together with the identification of the presence of a tillage pan, depth of root penetration, or number of earthworms. The soil samples are then compared to the photographs of a reference key to score soil structure (Fig. 1).

These visual soil evaluation methods usually demonstrated a good sensitivity to different management practices (Ball et al., 2007; Giarola et al., 2013; Guimarães et al., 2011), and were particularly useful to