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Review

Towards digital soil morphometrics

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ABSTRACT

Digital soil morphometrics is defined as the application of tools and techniques for measuring and quantifying soil profile attributes and deriving continuous depth functions. This paper reviews how proximal soil sensing and other tools can be used in soil profile descriptions where techniques and toolkits have not changed in the past decades. The application of such tools is compared to standard soil profile descriptions for 11 common attributes: horizons, texture, color, structure, moisture, mottles, consistence, carbonates, rock fragments, pores and roots. These attributes are extensively used in soil classification and are indicative of many soil functions. There has been progress in distinguishing soil horizons, texture and soil color, mainly using vis–NIR, GPR and electrical resistivity. There is potential for in situ digital morphometrics for all attributes of a soil profile. Smaller depth increments can be sampled and analyzed, and that gives continuous depth functions of soil properties. The combined use of *in situ* digital morphometrics and continuous depth functions of soil properties may enhance our pedological understanding. It will take time before the toolbox of the field pedologists will be digitally enriched, but we think that digital soil morphometrics has the potential to complement existing description and analytical methods. It may yield new insights in soil horizonation, how soils form and how they could be classified.

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By sense of touch the feet assess
The nature of the wilderness
Of earth beneath. Yet human speech
Cannot express what feet can teach.
F.D. Hole (1913–2002)

1. Introduction

Pedology is a primary branch of soil science. It is equally significant to the soil science discipline as botany is to the plant sciences and zoology to the animal sciences. The term pedology was coined by Fallou (1862), who together with Senft (1857), prepared the way for V.V. Dokuchaev (Blume, 2002). Pedology has a somewhat different meaning in different parts of the world, but in essence it is about the study of soil in the field, its formation, distribution, and classification, and includes a wide range of observations, laboratory analyses and inferences.

The soil profile is at the center of pedology (Kellogg, 1974). Soil profile descriptions have largely relied on morphometrics by which soil attributes are mechanically measured and visually observed. These were then combined with chemical, physical and mineralogical data or thin sections from horizons in a soil pit. All that information is integrated to increase our understanding of soils and their distribution across the landscape, and is also essential for taxonomic classifications (Bockheim and Gennadiyev, 2000).

The search for standardization of methods has been driving much of the international soil science cooperation (van Baren et al., 2000). In particular, pedology has known a long period in which recording, sampling, and description of soils became standardized across the world. Official guidelines and handbook for describing soils were first published in the USA and the UK in the 1930s (Clarke, 1936; Soil Survey Staff, 1937) and these have led, for example, to the Soil Survey Manual (Soil Survey Division Staff, 1993), the *Field Book for Describing and Sampling Soils* (Schoeneberger et al., 2012) and the *FAO Guidelines for Soil Profile Descriptions* (FAO, 2006). Most national soil survey centers have developed such guidelines (Dent and Young, 1981).

Measurements and insights beyond the visible light range started in the 1920s using X-ray diffraction for determining the arrangement of atoms in minerals; there was the hope that it could be used for the partial classification of soils (Helms et al., 2002). It took some time before larger parts of the electromagnetic spectrum were tested in soil science (e.g. Baumgardner et al., 1985; Dalal and Henry, 1986). Currently, the entire spectrum is being used: from the long waves in electromagnetic induction to the short waves of X-rays and gamma radiometrics (McBratney et al., 2003). Electrical, electromagnetic, optical, radiometric, mechanical, acoustic, pneumatic, electrochemical and other geophysical measurement tools and sensors are now routinely used in agricultural and environmental soil studies (Adamchuk et al., 2004; Allred et al., 2008; Viscarra Rossel et al., 2010).

These sensors and tools have been valuable for measuring and predicting soil properties, processes and behavior in a *horizontal sense*, that is, across the landscape. They have been less applied for studying soils in the *vertical sense* and traditional pedological observations of soil profiles rely on the use of visible light and a toolbox that has not changed in the past decades. There is a need to develop technologies that can rapidly characterize the entire soil profile (Ben-Dor et al., 2008; Demattê et al., 2004; Stockmann et al., 2014; Viscarra Rossel et al., 2011). The objective of this paper is to review new tools and techniques for measuring and quantifying attributes in a soil profile (termed here digital morphometrics). The standard set of soil attributes (horizons, texture, color, structure, moisture, mottles, consistence, carbonates, rock fragments, pores and roots) is reviewed followed by a discussion on continuous soil depth functions, and some ideas on the role of soil mapping.

2. Soil pit observations — digital morphometrics

Detailed soil observations are made for a whole range of purposes (e.g. mapping, classification, land evaluation, pedological investigation). Commonly, a soil pit is dug but observations are also made using augers, samplers, push probes, slice shovels, trenches, road cuts, or in quarries. The overall purpose of describing a soil profile is to preserve the image of the soil and a full soil profile description consist of reference and geographic location, profile environment (climate, geology etc.), site and area description, and a description of the soil horizons and its attributes and properties (Legros, 2006).

The traditional field toolbox for soil profile descriptions may include augers, pickaxe, spade, knife, spatula, rock hammer, Munsell charts, maps, note book, water bottle, HCl, sample bags, tape measure, clinometer, compass, altimeter or GPS, and camera. These are used to measure and observe soil properties and attributes, and sample for chemical and physical analysis in the laboratory. Observed and measured soil properties and horizons are combined into classes and further aggregated into soil orders.

Remote sensing of surface soil properties was first attempted with aerial photographs and since the 1980s surface soil properties are being assessed using space borne or airborne approaches including surface soil mineralogy, texture, soil iron, soil moisture, soil organic carbon, soil salinity and carbonate content (Lagacherie et al., 2008; Mulder et al., 2011; Odeh and McBratney, 2000). From such information, subsurface soil properties may be inferred, but most knowledge on subsurface soil properties will have to come from (i) measurements or samples from a soil profile, or (ii) by using ground penetrating devices (Fine, 1954; Johnson et al., 1979; McBratney et al., 2000b).

In this section, the main attributes measured and observed in a soil pit are reviewed and discussed: horizons, texture, color, structure, moisture, mottles and redoximorphic features, consistence, carbonates, rock fragments, pores and roots. There are several other soil attributes (e.g. drainage, hydraulic conductivity, infiltration, cracks, crusts, odor, bulk density) but here we focus on the standard soil profile attributes that are used in soil classification and determine several of the key soil functions. For each attribute, its relevance and application are discussed, with some focus on diagnostics in *Soil Taxonomy* — there are several reviews available relating diagnostics of *Soil Taxonomy* to WRB and other systems (e.g. Esfandiarpour et al., 2013; Krasilnikov et al., 2009; Shi et al., 2010).

Table 1 summarizes the main attributes that are measured and recorded in a soil profile using (i) traditional methods, and (ii) a set of new tools that are termed here digital morphometrics. Legros (2006) named these tools: special equipment, that can be used in addition to field and office equipment for field programs in soil survey. We define digital soil morphometrics in broad terms as the application of tools and techniques for measuring and quantifying soil profile attributes and deriving continuous depth functions.

2.1. Soil horizons

Soil horizon designation was started by V.V. Dokuchaev, and C.F. Marbut was among the first to suggest that horizons should be used to classify and distinguish soils (Bockheim et al., 2005). Horizon designation was developed and the letters and numbers convey more than the place it occupies in the soil profile: these are interpretative symbols based on morphology and soil genesis (Bridges, 1993). Soil horizons are generally distinguished based on properties relative to those of an estimated parent material (Soil Survey Division Staff, 1993). Assessment in the field is based on differences in soil texture, color, coarse fragments, clay bridges, structural change, organic matter, mineralogy, concretions and accumulations, HCl effervescence, or the effect of frosts. The array of properties and features to distinguish horizons, and horizon topographies (e.g. smooth, broken), distinctness (e.g. abrupt, diffuse) and