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Review

Towards digital soil morphometrics

Alfred E. Hartemink [a,*], Budiman Minasny [b]

[a] University of Wisconsin — Madison, Department of Soil Science, FD Hole Soils Lab, 1525 Observatory Drive, Madison, WI 53706, USA
[b] The University of Sydney, Faculty of Agriculture and Environment, 1 Central Avenue, The Australian Technology Park, NSW, Australia

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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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* Corresponding author.
E-mail address: harteminik@wisc.edu (A.E. Hartemink).

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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

Table 1
Overview of standard and digital soil morphometrics of attributes observed and measured in a soil profile.

Attribute	Standard[a]	Digital morphometrics[b]	References
Horizon depth, and boundaries (pedogenically derived)	Visual, color, textural discontinuity, coarse fragments, clay bridges, structural change, organic matter, mineralogy, concretions and accumulations, frost	Electrical resistivity; radio-MT; GPR; profile cone penetrometer; XRF	Chaplot et al. (2001), Doolittle and Collins (1995), Rooney and Lowery (2000), Steffens and Buddenbaum (2013), Tabbagh et al. (2000), Weindorf et al. (2012a)
Texture	Field: hand texturing Laboratory: sieving; pipette; hydrometer	XRF; laser diffraction; vis–NIR	Beuselinck et al. (1998), Bricklemyer and Brown (2010), Castrignanò et al. (2012), Chappell (1998), Myers et al. (2011), Viscarra Rossel et al. (2009), Waiser et al. (2007)
Matrix color	Visually by Munsell soil color charts	Vis–NIR; GPR, mobile phones	Ben-Dor et al. (2008), Collins and Doolittle (1987), Gómez-Robledo et al. (2013), Viscarra Rossel et al. (2009)
Structure	Visually: grade, shape or type, size	Ultrasonics, X-ray CT, SEM	Garbout et al. (2013), North (1979), Samouëlian et al. (2005), Whelan et al. (1995)
Moisture	Feel; rod tests; gravimetric	TDR; GPR, electrical resistivity	Mahmoudzadeh Ardekani (2013), Minet et al. (2011), Samouëlian et al. (2005)
Redoximorphic features; mottles	Visually: quantity, size, contrast, color, state, shape, location	Hyperspectral scanner; XRF; digital cameras	O'Donnell et al. (2010), Steffens and Buddenbaum (2013), Weindorf et al. (2012a)
Rupture resistance, consistence	Rupture resistance: plasticity, toughness, stickiness, penetration resistance and excavation difficulties	X-ray CT and standardized drop-shatter	Munkholm et al. (2012)
Carbonates	10% HCl, degree of effervescence	Vis–NIR	Ben-Dor et al. (2008), Lagacherie et al. (2008), Zhu and Weindorf (2009)
Rock fragments	Visual, sieving, rupture resistance; quantity, size, shape and lithology	Electrical resistivity; radiometers	Post et al. (1999), Rossi et al. (2013), Tetegan et al. (2012)
Pores	Visually: quantity, size, location, and shape	X-ray CT; video digitizing; colored dyes; CAT scanning; image analysis	Dathe et al. (2001), Gantzer and Anderson (2002), McBratney et al. (1992), Peyton et al. (1992), Rab et al. (2014)
Roots	Visually: quantity, size, location	Image processing thin sections; GPR	Butnor et al. (2008), Moran et al. (1993)

[a] These attributes are described in for example: Burt (2004), FAO (1977), FAO (2006), Hodgson (1975), Legros (2006), McDonald and Isbell (2009), McDonald et al. (1990), McKenzie et al. (2008), Munsell (2000), Schoeneberger et al. (2002), Schoeneberger et al. (2012), Smith and Atkinson (1975), Soil Survey Division Staff (1993), and Soil Survey Staff (1951). There are also various ISO standards available for soil characterization (www.iso.org).
[b] Radio-MT = radio magnetotelluric-resistivity; GPR = Ground Penetrating Radar; XRF = X-ray fluorescence; vis–NIR = visible and near infrared; X-ray CT = X-ray computed tomography; SEM = Scanning Electron Microscope; CAT = computed axial tomography.

spatial variation (e.g. Vanwalleghem et al., 2010) require pedological experience.

In a sense, soil horizons are artificial concepts and in many soils, horizons are irregular, broken, or have nearly invisible boundaries. There are many soils with transitional horizons (e.g. AB) and some have combination horizons (E/B) where most of the individual parts of one horizon component are surrounded by the other. There is a degree of subjectivity in the assessment of soil horizons, and horizon concepts have also changed over time (Ciampalini et al., 2013).

Digital morphometric techniques have been used for diagnosing soil horizons, including: ground penetrating radar (GPR), electrical resistivity (ER), cone penetrometer, hyperspectral core scanner, and X-ray fluorescence (XRF). Several of these have been applied in the field, whereas some have been used in the laboratory on monoliths or soil cores.

Ground penetrating radar is a non-invasive soil survey tool that has been applied in soil science since the late 1970s. The GPR has been used to detect textural differences and it works best in soils with low clay content and low electrical conductivity. It needs calibration as the dielectric constant is a function of water and salt content, and the presence of clay minerals. Horizons with abrupt boundaries caused by sudden changes in texture, bulk density, moisture, SOC, or calcium carbonate produce strong reflections and GPR imagery (Doolittle and Collins, 1995). GPR has been used to estimate depths to soil horizons, hard pans, dense till, permafrost, thickness and characteristics of soil organic materials, assess the depth of the water table, lamellae and cemented layers, and infer soil color and SOC (Doolittle and Collins, 1995). The GPR is mostly used in small spatial areas (few hectares).

Tabbagh et al. (2000) used an electrical resistivity (ER) meter to assess a hardpan in a sandy soil in an arid area of Cameroon. The horizon was delineated by low resistivities $<100\ \Omega$ m (conductivities >10 mS/m) because of the disposition of clay particles around the quartz grains. ER has also been used to detect the depth of occurrence of a petrocalcic horizon (Legros, 2006). Radio magnetotelluric-resistivity was used to map field-scale hydromorphic horizons in France (Chaplot et al., 2001). They found no direct relationship between apparent resistivity and horizon type distribution, and the best correlations were between the electrical conductivity and depth to the upper boundary of saprolite and topsoil water content.

Monteiro Santos et al. (2011) developed an algorithm that takes measurements from an electromagnetic induction instrument and derived a quasi-3D conductivity image. This allows the mapping of soil horizons that have significant changes in soil texture and electrical conductivity.

A cone penetrometer was used to map soil horizons to 140 cm depth in Mollisols (Rooney and Lowery, 2000). Penetration is affected by soil texture, porosity, structure, water content, cementing agents and compaction, and no direct relationships were found between the cone index and specific soil physical properties. The combination of soil properties that are unique to diagnostic horizons (e.g. A, E, Bt, Btg, 2Bt, 2BC) resulted in a unique cone index profile. The penetrometer was capable of distinguishing changes in soil physical properties that are coupled to soil horizon thickness (Rooney and Lowery, 2000) and can be used to visualize soil layers (loess, glacial till) in 3D (Grunwald et al., 2001). Soil moisture and bulk electrical conductivity meters can also be incorporated in a penetrometer (Yurui et al., 2008).

Weindorf et al. (2012b) used a portable XRF to distinguish Spodic and Albic horizons in the field and in the laboratory on samples and monoliths. The XRF was used to scan volcanic-ash derived Spodosols, Andisols and Inceptisols at fixed depth intervals. Distinct patterns of elemental concentrations were found, and the Fe/Zr ratio was found to be useful in diagnosing Spodic horizons compared to relatively unweathered volcanic ash that contain more Fe. In another study they used the XRF in Ultisols, Alfisols, Vertisols and Inceptisols, and found that the portable XRF can be used to assist in horizon differentiation particularly in alluvial soils with little observable morphological differences (Weindorf et al., 2012a).

Finally, a laboratory hyperspectral scanner was tested for the mapping of diagnostic horizons of undisturbed soil samples (10 × 30 cm) with a high spatial resolution (Steffens and Buddenbaum, 2013). A geostatistical analysis of the hyperspectral data allowed diagnosis of O, Ah, and Eg horizons with an overall accuracy of 86%. The scanner was able to distinguish between the topsoil and the subsoil mainly as a result of differences in particular organic matter quality and quantity, but the reading was affected by Mn concretions (Steffens and Buddenbaum, 2013).

2.2. Soil texture

The texture of the soil is one of its most important characteristics. It strongly affects water and nutrient retention, infiltration, drainage, aeration, SOC content, pH buffering and porosity and affects many soil functions and mechanical properties. Soil texture is used at all levels in *Soil Taxonomy* (Soil Survey Staff, 2010) from the soil order level (e.g. to distinguish Vertisols or Alfisols) all the way to the family level of particle size classes. It is used in the diagnosis of some key epipedons but particularly for argillic, natric, kandic horizons (Bockheim and Hartemink, 2013a).

Soil texture refers to the weight proportion of soil particles smaller than 2 mm, and field texture (sometimes called *apparent* field textures) is usually estimated by placing soil in the hand, moistened and then kneaded between thumb and forefinger. Several flow diagrams exist to estimate soil texture (Rowell, 1994; Thien, 1979). Experienced soil surveyors are capable of accurately estimating soil textures and this has proven to reduce the number of samples needed for textural analysis (Legros, 2006). In soil survey laboratory analyses pipette, hydrometer or laser diffraction is used for particle size analysis.

Laser diffraction for the determination of grain-size distribution was first developed in sediment studies. Until the early 1990s the pipette method was the standard in soil science, and there was insufficient confidence in laser technology and its associated costs (Buurman et al., 1997). There are some inherent factors limiting the use of laser diffraction (Kowalenko and Babuin, 2013) that may affect use of the laser for the quantification of soil particle size analysis, and to our knowledge *in situ* assessment of soil texture using portable laser diffraction has not been tried.

Studies have used γ-radiometrics (Castrignanò et al., 2012; Viscarra Rossel et al., 2007), electromagnetic induction (EMI) and vis–NIR and mid-IR spectroscopy for the quantification of clay content and soil texture (Castrignanò et al., 2012; Demattê et al., 2004; Lagacherie et al., 2008; Minasny et al., 2008; Sudduth et al., 2005). For determining and mapping soil texture in the field EMI (e.g. Carroll and Oliver, 2005; James et al., 2003) and gamma radiometrics have been used. The sensors are typically mounted on a vehicle (on-the-go) and the EMI can effectively penetrate to 1 m soil depth, while the gamma radiometrics mainly reflects the soil surface signal. This requires the collection of field samples to calibrate the sensor outputs (bulk electrical conductivity or gamma radiometrics signal) against soil properties (e.g. particle size distribution for a particular depth range).

Field visual–Near infrared (vis–NIR) spectroscopy has been developed to allow direct and rapid measurement of soil. Empirical calibration of spectra with laboratory-measured soil properties is needed. Waiser et al. (2007) used vis–NIR spectra to predict total and fine clay content, and they found that vis–NIR is an acceptable technique for rapidly measuring soil clay content in situ for various moisture contents and parent materials (Waiser et al., 2007). Bricklemyer and Brown (2010) used on-the-go and laboratory vis–NIR for the assessment of soil clay. Laboratory based vis–NIR spectroscopy yielded slightly more accurate predictions than in situ vis–NIR sensing due to field moisture heterogeneity, consistent sample presentation, and a difference in spatial support. A statistical algorithm has been developed to remove the moisture effects on NIR spectra (Minasny et al., 2011), and it has been applied to predict clay content on field soil cores (Ge et al., 2014). In a laboratory study, vis–NIR was applied on soil cores taken from a catena with loess over glacial till (Myers et al., 2011). The cores were divided into 2.54 cm depth increments. Abrupt argillic transition was found in the soils on summit and shoulder positions, and clay and silt were successfully predicted in these soils (Myers et al., 2011).

Hand held or portable XRFs are commonly used by geochemists (Tonui and de Caritat, 2003) and have been used for the determination of soil texture in a range of soils in situ and on cores and monoliths in the laboratory (Weindorf et al., 2012a; Zhu et al., 2011). A portable measurement device with multiple sensors is under development to enable the measurement of clay content and using a neural network algorithm (Quraishi and Mouazen, 2013). Soil moisture interferes with the XRF signal but algorithms have been developed to alleviate such problems (Ge et al., 2005).

2.3. Soil color

In profile descriptions, the dominant soil color (matrix color) is used to distinguish horizons and as an indicator of SOC content, drainage conditions, aeration, iron content or mineralogy. Soil color is a diagnostic criterion throughout *Soil Taxonomy* e.g. in 6 of the 8 epipedons (mollic, anthropic, melanic, ochric, plaggen, umbric), in assessing cambic, sombric, spodic subsurface horizons and in albic and organic materials and aquic conditions (Soil Survey Staff, 2010), and for diagnosing Gleysols in WRB (IUSS Working Group WRB, 2006). In older classification systems color was widely used (e.g. black cotton soil, red tropical soils, yellow podzols) and also in folk classification color is an important criterion (Barrera-Bassols and Zinck, 2003).

The Munsell notation system (Munsell, 2000) is commonly used but readings may be subjective and affected by soil moisture condition, quality of the light, the time of the day, and degree of crushing and its effect on grain coatings (Pendleton and Nickerson, 1951; Post et al., 1993; Simonson, 1993). Another limitation is that the Munsell system with its hue, value and chroma notations cannot directly be used in numerical analysis. Various color models have been developed. Conversions of Munsell color codes to RGB and CIELab coordinates have been correlated with some physicochemical properties (Aitkenhead et al., 2013).

Soil color has been measured indirectly using vis–NIR (Islam et al., 2004) and Viscarra Rossel (2009) used vis–NIR to measure soil color *in situ* and in the laboratory. Measurements were compared to Munsell color chart readings. There was fair agreement between spectroscopic estimates of soil color and Munsell readings although vis–NIR tended to be slightly darker and more yellow. Ben-Dor et al. (2008) used a vis–NIR field spectrometer and an accessory to read subsoil reflectance to examine soil color in Alfisols, Inceptisols and Vertisols. The results were compared to traditional soil descriptions and it was found that using optical instruments it is possible to describe quantitatively and objectively the soil profile color in situ.

There are cheaper and more widespread tools available to sense soil color: mobile phones with cameras. A recent study showed that color determinations using mobile phones with an android application had lower errors than those described for the visual determination of soil color (Gómez-Robledo et al., 2013). This study was conducted under controlled light conditions in the laboratory, and needs to be further developed for field conditions.

2.4. Soil structure

Structure is a key characteristic of the soil and influences many biochemical and physical properties and processes, as well as soil erosivity and workability. Peds or structural units are built from primary particles mixed with organic materials (Bronick and Lal, 2005). Some soils are structureless (single grain, massive), others have a simple or compound structure in which large units are composed of smaller units separated by planes of weakness (Soil Survey Division Staff, 1993). Structure is usually described regarding the distinctness of the units (the grade: weak, moderate, strong), shape or type (e.g. angular, platy, columnar) and size, which is differently described for different shapes or types (Schoeneberger et al., 2012). In *Soil Taxonomy* it is used in the assessment of cambic horizons and fragic soil properties (Bockheim and Hartemink, 2013b).

Some recent studies have matched the visual assessment of structure with soil physical and chemical properties (Murphy et al., 2013), crop yield (Mueller et al., 2009) as well as biological properties (Peigné et al., 2013). Soil structure assessment is also important in programs that reward farmers to maintain a good soil structure (McKenzie and Batey, 2006).

Soil structure has been studied using thin sections, polished blocks, and ultrasonic measures (North, 1979), and a combination of image analysis and X-ray Computed Tomography (CT) is used since the 1970s (Moran et al., 1989). Morphometrics have been used in the 1990s by soil physics to quantify pore structures via image analysis (Bouma, 1990). There has been progress in measuring soil structure using SEM or optical scanning, by wet sieving methods (Dexter, 1988) and in relation to aggregates and soil C storage (Six et al., 2004). Structural stability has been assessed in the field using an air and water permeameter (Whelan et al., 1995). NIR and MIR spectroscopy predicts clay and SOC reasonably well and with that water stable aggregates (Gomez et al., 2013; Minasny et al., 2008). Field assessment of structure is difficult, and X-ray CT studies are only possible in the laboratory (Garbout et al., 2013; Sander et al., 2008). Electrical resistivity as a non-destructive mapping technique can be applied to map the soil structure (Samouëlian et al., 2005; Tabbagh et al., 2000). No tools have been developed that can rapidly, or even slowly, measure or quantify the grade, shape or size of soil structural peds in the field.

2.5. Soil moisture

Soil moisture is usually recorded for each horizon in a soil pit in relation to color measurements, consistence, crusts, concretions, cemented layers or hydric conditions. Common classes are dry (>1500 kPa), moist (1–1500 kPa) and wet (<1 kPa) and these classes are established in the field by feel and visually based on water film expression and presence of free water. There are also color value, ball, and rod tests and samples can be taken for gravimetric water content measurements (Soil Survey Division Staff, 1993). Soil moisture (long term means) is recognized at high levels in *Soil Taxonomy* through the soil moisture regimes that distinguish Histosols and Aridisols at the order level, and in many suborders.

Time-domain reflectometry (TDR) has been applied for measuring soil moisture in the field since the late 1970s (Topp and Davis, 1981) and in recent years TDR meters including bluetooth based data logging have become affordable. Frequency Domain Reflectometry (FDR) has also become popular because it is cheaper and has the ability to log via smart phones. In addition, soil moisture can be calibrated against vis–NIR, GPR, EMI and ER (Minasny et al., 2008; Viscarra Rossel et al., 2011).

2.6. Redoximorphic features, mottles

Soils with reduced drainage (e.g. hydric soils) often have soil horizons with repetitive color changes and these redoximorphic features are a type of mottling related to Fe (Soil Survey Division Staff, 1993). Such soils have periods of anaerobic and an aquic soil moisture regime. There are several methods to assess the redox potential in the field (Vepraskas and Wilding, 1983) and visual observations in a soil pit include the quantity, size, contrast, color, state and shape of mottles. Redoximorphic features are used in the classification at the suborder and lower levels in Alfisols, Spodosols, Mollisols, Ultisols, Inceptisols, and Vertisols. The drainage class of a soil is also established with the presence or absence of redoximorphic features.

Digital image processing of soil features has been long used in micromorphology (Aydemir et al., 2004). Redoximorphic features were assessed using digital cameras and image analysis of 18 horizons from exposed soil cores under controlled light conditions. The accuracy of color determination was almost 100% compared to Munsell for color identification of redoximorphic features (O'Donnell et al., 2010). In a follow-up study, O'Donnell et al. (2011) sampled 49 cores and used a digital camera to capture images of exposed core faces. They concluded that sampling diameters of at least 8 cm are necessary for soil classification purposes and the determinations of hydric soils. Soil mottling has been determined using a laboratory hyperspectral scanner in undisturbed soil samples (Steffens and Buddenbaum, 2013). A handheld XRF was used to assess reduced or depleted Fe in subsoils of Spodosols, Andisols and Inceptisols (Weindorf et al., 2012b).

2.7. Consistence (rupture resistance)

Resistance to rupture (consistence, friability) is dependent on soil moisture content and in the field it is assessed manually. The resistance is described from loose and soft to extremely hard and rigid; plasticity, toughness, stickiness, penetration resistance and excavation difficulties refer to the degree of cohesion and adhesion of the soil material (Soil Survey Division Staff, 1993). The rupture resistance influences several soil functions and has implications for engineering applications and soil tillage. Rupture resistance is used in the determination of anthropic, mollic and umbric epipedons, duripans, anhydrous conditions, fragic soil properties, spodic, densic and paralithic materials, lithic contact, in the classification of Aridisols, Entisols, Mollisols taxa, and at the family level where there is an entire rupture-resistance class.

Like soil structure, rupture resistance is determined by several individual soil properties and not many pedological studies have attempted to assess it in other ways than the traditional field methods. A drop-shatter test was used to assess an index of soil friability and high resolution CT scanning of pores explained only part of it (Munkholm et al., 2012).

2.8. Carbonates

Calcium carbonates in soils can be pedogenically derived as in soils of arid and semi-arid areas, or be residues of the parent limestone rock. Carbonates affect soil pH, nutrient availability (particular micronutrients), and the flocculation of particles. There is scientific interest in pedogenic carbonates in relation to the carbon cycle and assessment of carbon stocks (Throop et al., 2012). The presence of carbonate concentrations and parent rock remnants is determined by dripping 10% HCl on the soil matrix as well as the concentrations; the degree of effervescence (e.g. none, very slight, violently) is visually (sometimes auditively) recorded. In *Soil Taxonomy*, information on calcium carbonates, or free carbonates, is used for the determination of the anthropic, mollic and umbric epipedon, (petro)calcic and cambic subsurface horizon and durinodes, and in the lower taxa of Alfisols, Inceptisols and Mollisols, and at the family level (carbonatic, isotic).

Fig. 1. Two examples from *in-situ* observations and measurement in a soil pit. Left picture: Soil microscope with cross-slide stand attached to the wall of a soil pit; the leather box stores the battery for the oblique illuminator, from Kubiëna (1938). Right picture: portable XRF to determine contaminant metal depth migration in a soil profile (picture from David Weindorf).

The X-ray fluorescence is extensively used in, for example, soil archeology, geochemistry and pollution studies. Field portable X-ray fluorescence was used to determine soil calcium (Zhu and Weindorf, 2009) (Fig. 1) whereas Lagacherie et al. (2008) applied a vis–NIR spectro-radiometer (35–2500 nm) and traditional $CaCO_3$ analysis on samples from calcareous soils. Measurement was made in the field and laboratory and they found that calcium carbonate content can be estimated accurately from reflectance measurements in the laboratory (Lagacherie et al., 2008). Ben-Dor et al. (2008) used a vis–NIR field spectrometer to examine carbonates and the results were compared to soil descriptions and analysis. It was found that multivariant vis–NIR could be used to determine carbonates over the whole soil profile (Ben-Dor et al., 2008).

There are other types of concretions (e.g. oxides and hydroxides of Fe, Mn, Al) that have been measured in the soil profile using digital soil morphological techniques. For example, impregnated soil monoliths and image analysis have been used to estimate the concentrations of Mn and Fe nodules at different depths (Koppi and McBatney, 1991).

2.9. Rock fragments

Rock or coarse fragments (>2 mm) are estimated in a soil profile using a comparison chart for visual estimation (Folk, 1951), by sieving, or using the point-count method (Legros, 2006). In the USA quite wide classes are used for fragment abundance: <15%, 15–35, 35–60, 60–90, and >90% (Schoeneberger et al., 2012). Class boundaries are slightly different elsewhere. The quantity, size, shape, lithology and degree of weathering are usually recorded and a modifier is added to the soil textural class (e.g. gravelly ashy loam). Rock fragments impact soil porosity, water and nutrient storage, water flow, weatherable minerals, rootability and drainage, but also tillage, compaction, soil erosion (Peverill et al., 1999) and whether root crops can be cultivated. Estimates of the rock fragment quantity and size are semi-quantitative at best. In *Soil Taxonomy*, information on rock fragments can be needed for the characterization of duripans, secondary carbonates, lamellae, lithological discontinuities, cryoturbation and gelic materials (oriented rock fragments), paralithic materials, in the classification of Entisols (Psamments, Aquents, Wassents), Gelisols (Turbels, Othels) and at the particle size family level (Soil Survey Staff, 2010).

Surface rock fragment cover has been estimated with a portable radiometer held approximately 1 m above the soil (Post et al., 1999). Tetegan et al. (2012) used electrical resistivity signal to assess soil rock fragments, and a model was developed that uses the standard deviation of the apparent electrical resistivity (ER) measurements as an indicator of rock fragment contents. The estimation of the rock fragment content had an error estimation of about 6%. ER readings depend on the soil moisture content and the rock type, but this study showed that estimations of the rock fragment can be performed efficiently in the surface horizon and along the soil profile (Tetegan et al., 2012), as was confirmed by Rossi et al. (2013).

2.10. Pores and roots

Soil pores are filled with water or air. Porosity, and how the pores are filled, determines most biochemical processes in the soil. In a soil pit, porosity is described in terms of quantity, size and shape using a comparison chart for visual estimation (Folk, 1951). Also the shape may be described (e.g. dendritic tubular) but that requires lenses — if not a microscope (Fig. 1). In *Soil Taxonomy*, information on clay films lining pores may be needed for the classification of argillic and natric horizons, and for the assessment of the sombric horizon, jarosite, secondary carbonates, plinthite and aquic conditions.

Porosity has been well described in soil micromorphology (Brewer, 1964; Mermut and Eswaran, 2001). Koppi and McBratney (1991) impregnated undisturbed vertical soil monoliths with epoxy resin and used image analysis to estimate pore structure. The two dimensional pattern and the pore structure were discernible for three different horizons. A recent study analyzed total porosity, determined by image analysis, pore type and pore size distribution on impregnated soil blocks using a digital portable optical microscope (Pires et al., 2013). Other studies have used X-ray computed tomography, video digitizing, colored dyes, and image analysis (Dathe et al., 2001; Gantzer and Anderson, 2002; McBratney et al., 1992; Peyton et al., 1992; Rab et al., 2014). No field assessment using digital morphometrics has been attempted.

Roots are an indicator of many soil properties including drainage, soil depth, nutrient limitation, coarse fragments, toxicity, and texture. It is seasonally changing like many attributes, but often leaves an imprint in the soil. Roots are similarly described to pores, and quantity, size and shape are visually assessed. In *Soil Taxonomy*, information on roots is used extensively: for establishing a (petro)calcic and (petro) gypsic horizon, duripan, fragipan, fragic soil properties, plinthite, densic and (para)lithic contact and diagnosing organic materials, aquic soil moisture regimes, and root-limiting layers at the family level. Soil micromorphology and the techniques of image analysis have yielded information on the distribution of roots in the soil (Moran et al., 1993). In

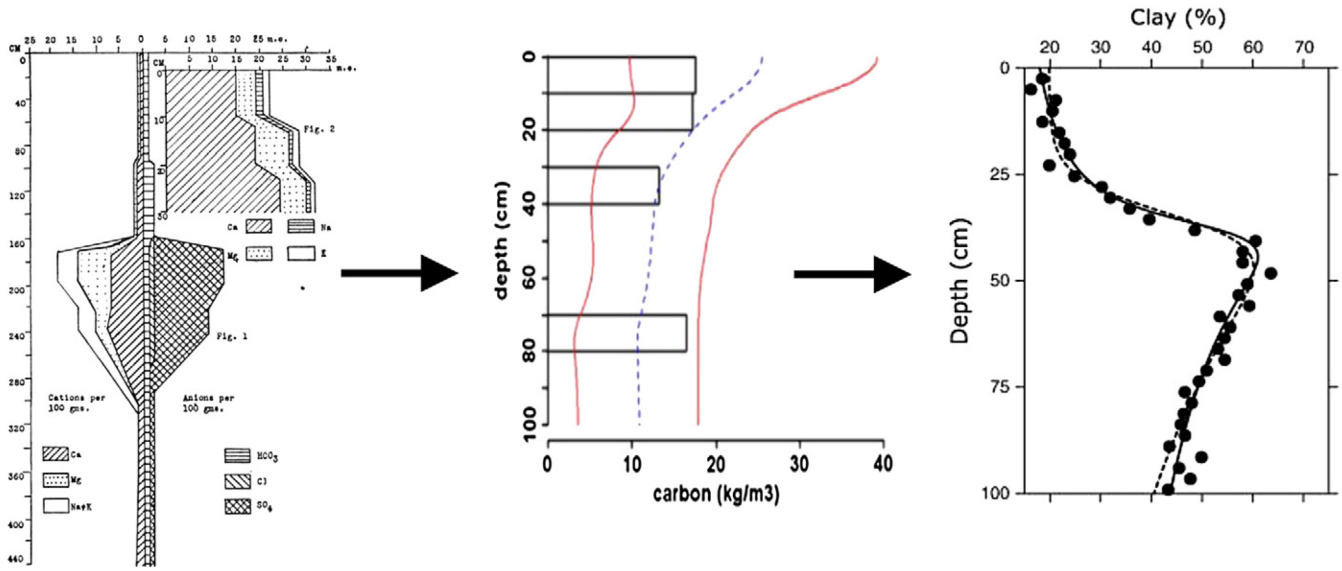

Fig. 2. From stepped horizons (left), to interpolated splines with uncertainties (middle), to a depth function with continuous soil properties (right). Images from: Joffe (1936), Malone et al. (2011), and Myers et al. (2011).

a field study in Florida, tree root mass and distribution were determined using GPR at a variety of frequencies to detect roots of different sizes (Butnor et al., 2003, 2008).

3. Continuous soil depth functions

Quantification of differences in soil properties with depth began in the 19th century, and a scan through the older pedological literature (<1930s) shows that most books and publications have tables of physicochemical data of horizons or layers. In some books, graphs of soil properties by depth were made, and Fig. 2 shows an example from Joffe (1936). These graphs revealed that most soils have vectorial anisotropic characteristics (Jenny, 1941).

Jenny (1941) emphasized that every soil property has its own vertical distribution pattern and depth function. Several authors have investigated those depth functions that approximate the anisotropic character of soil properties; for an overview of some historical literature see Bishop et al. (1999). The equal-area quadratic spline uses an average of adjacent horizons or layers in a soil profile, and Bishop et al. (1999) compared such splines to exponential decay and polynomial functions for pH, EC, clay content, SOC and gravimetric water content. The equal-area quadratic spline was found to be superior, but it was improved if additional samples and data from the top and bottom of the soil profile were available.

Malone et al. (2009) combined the spline depth functions with digital soil mapping and in a successive study introduced an uncertainty estimate for each depth (Malone et al., 2011). There are other soil depth functions (Myers et al., 2011), and characteristic of these functions is that they use a limited number of data points (usually from soil horizon data) and interpolate soil property values. It gives values for every possible soil depth increment, and creates a continuous function of which the uncertainty can be quantified (Malone et al., 2011) — see Fig. 2. The data can also be aggregated for specific depths as, for example, defined in the GlobalSoilMap specifications (Arrouays et al., 2014).

In Section 2, sensors that measure soil properties over the full depth of the soil profile were discussed. In some cases, measurements can be made in a soil pit at very small depth intervals, and in other cases the measurement is conducted in the lab and gives intervals in the micron range (e.g. Steffens and Buddenbaum, 2013) or few centimeters (e.g. Myers et al., 2011). In most cases, the increment is much smaller than the depth of soil horizons. It has the potential to create continuous depth functions of soil properties based on measurements rather than interpolations.

4. Discussion

In the previous sections, field assessment of standard soil attributes in soil profiles was reviewed using traditional methods and new technologies. These new technologies make high spatial resolution measurements that will in turn allow us to create continuous soil depth functions. This discussion will focus on the possibilities that these technologies offer for pedology, including some thoughts on soil classification, and the future of soil survey.

4.1. Digital morphometrics

Pedology has long been a descriptive activity with few scientific laws (Dijkerman, 1974). The discipline advances when increased data availability is combined with sound theoretical soil models and thinking that is tested across a wide range of conditions. Digital morphometrics follows the advances in proximal soil sensing devices, and attempts have been made to measure soil properties and attributes of soil profiles. There has been a call for the integration of pedological knowledge into digital soil mapping (Walter et al., 2006); here is a call to further use and integrate the proximal soil sensing technology and digital morphometrics in pedology and the description of soil profiles.

McBratney et al. (2011) defined proximal soil sensing through a variety of modalities: proximal or remote, in-situ and ex-situ (field and laboratory), non-invasive or intrusive and mobile or stationary. They proposed a narrow definition of proximal soil sensing which includes mobile measurement, principally as a mapping tool. In this paper, digital morphometrics is largely restricted to *in-situ* and *ex-situ* stationary measurements of soil morphology and properties with depth.

Different sensors and tools have been tested to measure different attributes. Compound attributes (horizons, structure) are harder to measure than single properties like clay content and soil moisture. Soil attributes that have been mostly assessed by digital morphometrics in the field are soil horizons, soil texture, soil color, and soil moisture. No attempts have been made to quantify soil structure in the field in a non-traditional way. Several studies focused on soil horizons using ground penetrating radar (GPR), electrical resistivity (ER) or the cone penetrometer. GPR and ER are non-invasive techniques and the

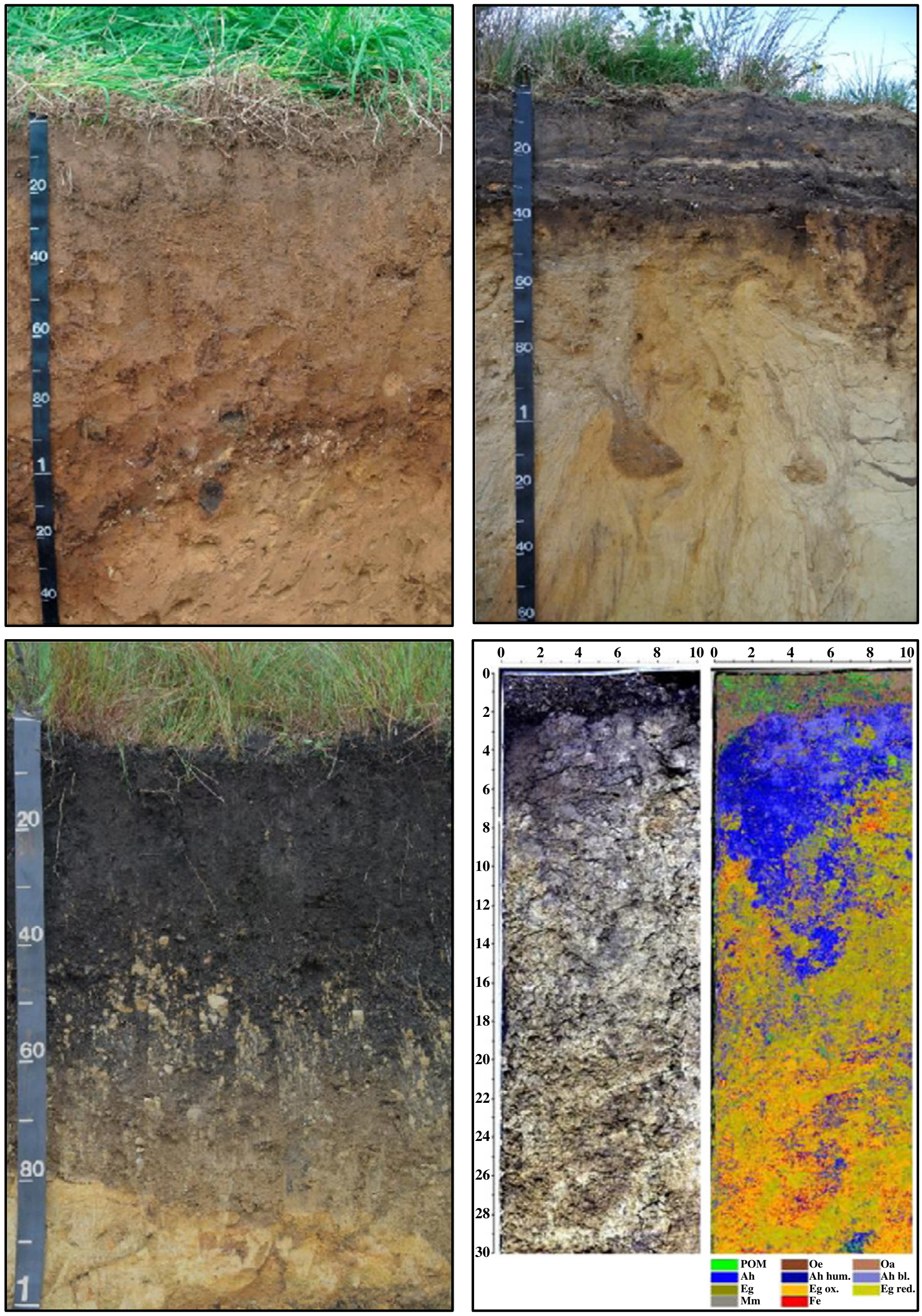

Fig. 3. Common variation in the soil profile: 1. Mollisol in loess over glacial outwash (Wisconsin, USA); 2. Spodosol in ice-pushed preglacial alluvium (Overijssel, Netherlands); 3. Inceptisol over rhyolite (Rio Grande do Sul, Brazil); 4. Aquic Alfisol (30 cm depth) in true color (left), spectral classification map (right) — image from Steffens and Buddenbaum (2013).

penetrometer is an invasive technique that can be used for the determination of some soil horizons — none of these require a soil pit. The nature of redoximorphic features (spotty, uneven) makes it highly suitable for digital morphometrics assessment using vis–NIR. Of all sensors, infrared spectroscopy (IR) has possibly the largest potential. There are limitations using IR sensors in a soil pit and that is related to the interference of signals not related to the soil, and the variation and unevenness of the soil surface itself as well as sample preparation (Ben-Dor et al., 2009; Reeves, 2010). The vis–NIR sensor is also sensitive to soil moisture and algorithms have been developed that remove the soil moisture from the spectra (Minasny et al., 2011).

Although this review provides a summary of available studies, the number of pedological applications of proximal sensors is still limited. These technologies are emerging and need time before tests show meaningful results. The soil conditions under which they can be tested are also very diverse and sensors may have limitations when used in the field and need extensive periods of calibration. Some sensors are in a developmental phase and are used in research, whereas others are used more routinely (Viscarra Rossel et al., 2011). Many of these sensors and technologies will change and may change faster than our abilities to explore and fully exploit its use in pedology. On the other hand, some of these have been around for decades and have never become the standard in soil survey and soil pit descriptions. The adoption rate of technology is a subject beyond the scope of this paper, but perhaps a fruitful research subject in soil science.

In many studies, samples from soil horizons or fixed depth intervals of soil cores were analyzed. The issue of a representative elementary area as discussed in micromorphology (O'Donnell et al., 2011), is equally important in a soil pit when it comes to sampling or scanning layers and horizons. Sampling protocols need to be developed to deal with the 2D and 3D variability in the soil pit (Fig. 3) and for the establishment of spectral calibration libraries (Minasny and McBratney, 2006). Core sampling (few cm diameter) ignores much of the horizontal variation in soil horizons, just like the soil profile (relative narrow vertical cross-sections) which ignores the three dimensional body of the soil (Hole, 1953). The advances in field sampling theory and design (de Gruijter et al., 2006; Webster and Lark, 2013) should be developed for the soil profile and for the general quantification of short range soil variation.

Proximal soil sensors require calibration with samples of known contents and concentrations — similar to wet chemistry procedures for soil analysis. Reflectance radiation signals are usually calibrated by multiple regressions or principal component analysis. Most researchers develop their own libraries of spectra and these are property or site specific (Minasny et al., 2008). The pedology subdiscipline should work on global spectral libraries, and such global soil spectral libraries have been promised for a while (Shepherd and Walsh, 2002; Stenberg et al., 2010). Although there are spectral libraries available for several areas and countries, the need remains for freely available global libraries for the entire electromagnetic spectrum. There are smart phone apps that offer music search and discovery and they can name a song playing from a speaker and also works if you sing or hum (e.g. Soundhound, Shazam, Tunatic). Something similar can be envisioned in soil science where any portable device that measures a soil signal compares it to a soil library (a sort of *SoilTunes*) — a global calibration repository of soil data.

4.2. Continuous soil depth functions

An analysis of the depiction of soil profiles in paintings and scientific publications over a 300 year period showed that an increasing detail was depicted following scientific explorations and enhanced understanding of the soil (Hartemink, 2009). That understanding came with (i) advances in analytical techniques, (ii) the progress in conceptual models of soil formation, and (iii) the development of a pedological language to describe what was observed and measured. Digital morphometrics and continuous soil depth functions fit these aspects in the progress of soil science.

The continuous function may decouple the horizon as support unit for the soil profile, and depth functions may not reflect soil horizons (McBratney et al., 2000a). A range of continuous soil depth functions from several sensors can be combined and aggregated, and compared to soil horizons and other morphological descriptions. It may give new insight in diagnostic horizons and the anisotropic character of the soil. The continuous soil depth function may yield the formation of new classes in existing classification systems (see Section 4.3). The soil depth information can also be connected to functional properties via pedotransfer functions and soil inference systems (Minasny et al., 2008).

The next step is that devices may be developed that scan the wall of the soil profile and compare a detailed 3D image of the profile to a global database of images — such as those used in facial and object recognition and plant species identification (Cope et al., 2012; Mou, 2010). Algorithms need to be developed that analyze for example the relative position, size, and intensity of structure elements, mottles, or coarse fragments. These features are then used to search for images in a global database with matching features and the individual features are combined into classes. Three-dimensional scanners and surface reconstruction are rapidly developing as well as numerical methods for shape-from-shading (Durou et al., 2008).

4.3. Digital morphometrics and soil classification

The discovery of the soil profile as a record of soil formation has yielded enormous insight and knowledge about soils (Kellogg, 1974). In particular, the concept of the soil horizon has been useful as it divided the soil profile into layers with distinct features, signatures and properties (Arnold and Eswaran, 1993; Bridges, 1993; FitzPatrick, 1980). Jenny (1941) already emphasized that rigorous criteria are needed for horizon identification as all scientific systems of soil classification and the theories regarding soil development rest on horizon interpretations. The delineation of soil horizons is comparable to difficulties of the delineation soil classes across a landscape. What the polygon is to soil mapping, is the soil horizon to the soil description. The short range variation in the soil profile is equally challenging to quantify than the soil variability across the landscape. In fact, the soil horizon should be considered a polytope or better: a polyhydron.

As long as soil horizons are essential building blocks in WRB (IUSS Working Group WRB, 2006) and *Soil Taxonomy* (Soil Survey Staff, 2010), alternatives like the soil horizon classification (FitzPatrick, 1993) or a fuzzy-set approach to horizon classes (Powell et al., 1992) may only resurface when new soil systems are being developed. In digital soil mapping, raster based, continuous maps are now commonly produced (e.g. Burrough et al., 1997; Odgers et al., 2011) — there are possibilities to advance the description and the mapping of the soil profile in a similar manner. With digital morphometrics rich soil information with depth can be incorporated into classification systems, creating soil layer classes (Ben-Dor et al., 2008; Triantafilis et al., 2001). We may also wish to rethink the standard set of soil profile attributes and its usefulness in classification and soil functioning.

4.4. Digital morphometrics and soil mapping

Pedologists are good in describing and discussing soil profiles; they are also quite good in thinking about the future (e.g. Bouma, 1994; Dobrovolskii, 2001; Finke, 2012; Grunwald et al., 2011; Hartemink, 2006; Hudson, 1992; Zinck, 1995). Pedology has suffered a period of reduced funding, and perhaps even relevance (Greenland, 1991), but recently, pedologists have come up with tools, data and insights in important issues like the understanding of C stocks and changes in relation to climate change, water scarcity or global food production. Important areas of research in several universities and soil survey centers now include the modeling of soil landscapes, pedogenetical processes and the predictions of soils across the landscape. Digital soil mapping has transformed soil survey and cartography more than anything else, and it is being tested and routinely used in soil mapping programs around the world (Boettinger et al., 2010; Hartemink et al., 2008; Lagacherie et al., 2006; Minasny et al., 2012).

The future of pedology and soil survey and mapping lies in the combination of:

- predict soils (properties, classes) across the landscape, globe
- timely and cost-effective collection of new data
- include the subsoil below 2 m
- make the data available for a wide range of users and increased stakeholder interaction
- act as catalysts and instigator in soil benchmark and monitoring studies
- increase our understanding of soils, how they form and should be classified.

Soil surveys are a window to the subsurface soil (Wysocki et al., 2005) and the need to investigate soils at greater depths than 2 m has long been recognized by geopedologists (Cremeens et al., 1994; Scott and Pain, 2009; Zanner and Graham, 2005), and in the international network of Critical Zone Observatories (Banwart et al., 2012).

Considerable progress has been made in digital soil mapping and the timely collection of new soil data and information. There is an increased demand for soil information by a range of users that drives many of the new soil projects (Hartemink and McBratney, 2008; Janzen et al., 2011) and that drive is related to issues around food, water, climate change, energy, ecosystems or biodiversity (McBratney et al., 2013). The wide array and use of proximal soil sensors contribute to increased data availability and soil information, and there is a potential using digital morphometrics for in situ soil characterization and the production of continuous soil depth functions.

There are differences on how soil survey organizations make their soil information available, and there are also differences in the format of the information and whether it can be easily used (Rossiter, 2004). Stakeholder interaction and increased communication are needed with the general public by, for example, presenting storylines for major soil types (Bouma, 2010). We also need to teach the next generation of soil scientists equipped with the right set of integrated competencies (Field et al., 2011; Hartemink et al., 2014). There has been some worry that soil scientists with field experience will become rare, if not extinct (Nachtergaele, 1990). The current challenge is the training of specialists that know field work as well as all new techniques (Walter et al., 2006). This is clearly demand-driven as a skill gap analysis in the UK has shown that soil science is among the top 10 of most wanted skills (NERC, 2012).

Over the years, many suggestions for the widening of soil survey tasks have been made, including archeology (Dekker and de Weerd, 1974), urban development (Lindsay et al., 1974), monitoring the state of soils (Young, 1991), land use management and political ecology (Dazzi et al., 2013), ethnopedology (Barrera-Bassols and Zinck, 2003), hydropedology (Lin, 2003), focus on spatial patterns of behavior (Finke et al., 1996), and the mapping of soil pollution, soil quality and other non-traditional soil survey aspects (Meuli et al., 1998). These are somewhat non-traditional roles for soil survey organizations. They are likely overshadowed by the current interest to produce fine resolution maps of soil C, available soil water, and other properties and soil functions (Arrouays et al., 2014). Most of that work is conducted at universities and that research needs to feed into the rebuilding of soil survey and mapping organizations across the world.

In the past, aspirations to understand how soils were formed and develop were mostly driven by the need to develop comprehensive soil classification systems. With the maturation of the systems and the past decline in soil survey activities, the quantification of soil genesis has become a somewhat understudied topic (Stockmann et al., 2014). With the advances of a new classification system (Hempel et al., 2013), the need for increased understanding of the soil resources will resurface. Digital soil morphometrics may guide these aspirations, or as the well-known pedologist J.P. Legros aptly summarized it "We must try to make progress."

5. Conclusions

The methods and quantification of soil profile descriptions have not changed much in the past decades. Commonly, a soil profile is divided into genetic horizons and the attributes are described, sampled and its properties analyzed in the laboratory. The information is used to classify soils and for interpretations of soil functions. Interpolative functions using the analytical data from soil horizons have been developed to estimate soil property values at any depth or depth class. Proximal soil sensors and some other tools are used that measure in situ a range of soil properties including standard attributes of a soil profile. The sensor may accumulate high spatial resolution data and information more rapidly compared to traditional methods of analysis. That may yet not be the case for all of the sensors and tools discussed in this paper.

The application of tools and techniques for measuring and quantifying soil profile attributes and deriving continuous depth functions is termed digital soil morphometrics. It potentially provides rapid measurements at small depth increments and yields continuous depth functions of soil properties. The combination of digital soil morphometrics and continuous soil depth functions has the potential to frame our understanding of soils and be valuable in the resurrection of pedology programs across the world.

Acknowledgments

Admittedly, the first author of this paper is not so rapid, pondered for a while, and worked on this paper for over seven years. Ideas in this paper matured after discussions with Alex McBratney, Jim Bockheim, Kevin McSweeney, Jon Hempel and several others, but we remain solely responsible for possible omissions in this paper, and the shallowness in its depth. We are grateful to three anonymous reviewers for their excellent comments and suggestions to improve the paper.

We wish to end with a somewhat inspirational saying by the Wisconsonite (and the Benjamin Franklin of American soil science), F.H. King: "Yes, I have copied from others and I have milked a thousand cows, but the cheese is all mine".

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