Chapter 23
Digital Soil Morphometrics Brings Revolution to Soil Classification

Judit Nagy, Adam Csorba, Vince Lang, Marta Fuchs and Erika Micheli

Abstract Soil classification systems are grouping soils with similar properties. The distinguishing properties are the ones that we are able to observe or measure. As the state of knowledge and the need of users are changing, the definitions should be tested and changes should be accommodated. The recent boom of observation technologies, data storage, and data processing achievements provided new opportunities to predict similarities and differences in soils. The tools of digital soil morphometrics are resulting in new parameters and properties and in deriving continuous depth functions. This chapter reviews the criteria of soil parameters and their novel methods for field observation and definition (horizon depth, texture, color, structure, organic matter, mottling, and carbonates). The internationally endorsed soil classification systems could potentially be supported with these new approaches. The review is based on the WRB and is supplemented with an example of predicting soil diagnostic horizons using digital soil morphometrics. The application of faster, efficient, and more objective measurements can bring revolution to the classification of soils.

Keywords Soil classification · Digital soil morphometrics · Diagnostics · World reference base

23.1 Introduction

One of the main aims of soil science is to understand the relationships between soil properties, processes, and functions, and recognize and predict soil changes in space and time. To be able to define differences and changes, accessible and reliable

---

J. Nagy (✉) · A. Csorba · V. Lang · M. Fuchs · E. Micheli
Department of Soil Science and Agricultural Chemistry, Szent István University,
Gödöllő, Hungary
e-mail: nagy.judit@mkk.szie.hu

A.E. Hartemink and B. Minasny (eds.), *Digital Soil Morphometrics*,
Progress in Soil Science, DOI 10.1007/978-3-319-28295-4_23

soil information is essential. Most soil classification systems have definitions and criteria that are based on field observations supplemented by laboratory analyses. Field observations are often subjective, while laboratory analyses are often time and resource demanding and are performed on samples taken from certain portions of the profile. Digital soil morphometrics is defined as the application of tools and techniques for measuring, mapping, and quantifying soil profile attributes and deriving continuous depth functions (Hartemink and Minasny 2014).

In this chapter, we discuss the potential applications of digital soil morphometrics to predict the building blocks of the major differentiation criteria in soil classification systems. The review is based on selected soil attributes that are part of the definitions of diagnostic units of internationally endorsed soil classification systems. The selected properties are the major differentiation criteria in the definitions of the diagnostic units, hence the taxa of the World Reference Base for Soil Resources (IUSS WG WRB 2014). This chapter will review the potential application of digital morphometrics based on available literature. Some of the reviews will be discussed in the Results section.

23.2 Materials and Methods

The selected attributes as the major differentiation criteria in the definitions of the diagnostic units of internationally used soil classification systems are based on the World Reference Base for Soil Resources (IUSS WG WRB 2014). The review of the potential application of digital morphometrics is based on the available literature. Hence, some of the materials will be discussed in the Results section.

An example is based on reflectance spectroscopic measurements to predict diagnostic horizons. Thirteen soil profiles from different locations in Hungary were investigated by traditional and Vis–NIR laboratory spectroscopic methods. Using the field descriptions and the auxiliary laboratory data, the soils were classified to the reference soil group (RSG) level according to the WRB classification system. Samples collected from fixed depth intervals were investigated by laboratory Vis–NIR spectroscopic methods to infer the main soil horizons and derive parameters whose distribution along the soil profile can be related to certain key soil properties (organic carbon, $CaCO_3$, and clay content). For the spectral measurements, samples were collected at 5 cm depth intervals to 1.0 m depth and by 10 cm intervals between 1.0 and 1.5 m. The Vis–NIR reflectance spectra of the 325 air-dried, grounded, and sieved samples were acquired using the Analytical Spectral Devices (ASD) FieldSpec 3 MAX portable spectroradiometer with a contact probe attachment. The spectra were transformed to units of absorbance (log(1/reflectance)) and first derivatives were calculated using Savitzky–Golay method (Savitzky and Golay 1964). Principal component (PC) analysis was performed on the spectral dataset to reduce the high dimensionality. The PC scores were used as variables describing the spectral properties of the soils along the profile. To test the “profile description ability” of the spectral dataset, Fuzzy C-means clustering was performed on the matrix of the PC factor scores using KNIME software (Berthold et al. 2007). The number of clusters determined prior the analysis was determined by Silhouette analysis using the R statistical software package (R Development Core Team 2008).

For reference laboratory analysis (organic carbon, $CaCO_3$, and clay content), samples from genetic horizons were collected from each soil profile. To estimate the reference soil parameters in the fixed depth intervals, mass-preserving spline functions were fitted on the reference soil properties using the SplineTool v2.0 software (ASRIS 2011). The spline estimated reference values and the Fuzzy-C membership values were plotted against the depth.

23.3 Results

23.3.1 Review of Some Key Soil Properties, Important for Diagnostic Soil Classification

Table 23.1 summarizes the diagnostic horizons, properties, and materials which play a key role in the differentiation of the RSGs in the WRB 2014. The table lists the soil parameters whose determination is necessary to define the reviewed diagnostic units. Based on the study of Hartemink and Minasny (2014), only the soil parameters which can be effectively determined by digital soil morphometric methods are indicated. The parameter list includes soil texture, soil texture variations along the profile, and clay content (combined indication of the three is ST); soil matrix color (MC); soil structure (SS); soil organic carbon content (OC); redoximorphic features and mottles (RF); and calcium carbonate content (CB).

ST plays key role in defining 15 horizons, 9 properties, and 1 material. MC plays key role in defining 15 horizons, 9 properties, and 3 materials. SS defines 15 horizons, 4 properties, and 1 material. OC defines 15 horizons, 1 property, and 3 materials. RF defines 8 horizons and 2 properties. Based on soil carbonate (CB), 6 horizons, 4 properties, and 2 materials are defined.

Hartemink and Minasny (2014) gave an overview of soil properties that have been successfully measured or predicted by the tools of digital soil morphometrics. The following chapter is summarizing how the new tools are supporting the establishment of criteria of the major elements of the WRB soil classification system.

Horizon Depth

Ever since Dokuchaev (1883) introduced the horizons as a basic feature in differentiation of soils, the concepts have been accepted by the soil science community (Bockheim et al. 2005). Horizon boundaries provide data about the conditions and processes that have formed the soil. There are great varieties in shape and depth of

Table 23.1 Summary of diagnostic horizons, properties, and materials whose presence or absence defines the reference soil groups (RSGs)

Diagnostics[a]	RSG[b]	ST[c]	MC[d]	SS[e]	OC[f]	RF[g]	CB[h]
Anthraquic hor.	**AT CM**		X	X		X	
Argic hor.	TC AN *FR GY CA* **RT AC LX AL LV**	X		X			
Calcic hor.	LP **CH KS CA**						X
Cambic hor.	**CM**	X	X	X	X	X	X
Chernic hor.	TC LP **CH**	X	X	X	X		X
Cryic hor.	**CR**						
Duric hor.	TC **DU**						
Ferralic hor.	TC AN **FR**	X					
Ferric hor.	TC					X	
Folic hor.					X		
Fragic hor.	TC **CM**	X	X	X	X		X
Fulvic hor.			X		X		
Gypsic hor.	LP **GY**	X					
Histic hor.					X		
Hortic hor.	**AT**		X		X		
Hydragric hor.	**AT** TC **CM**		X	X		X	
Irragric hor.	**AT CM**	X		X	X		
Melanic hor.			X		X		
Mollic hor.	**GL KS PH UM**	X	X	X	X		X
Natric hor.	TC **SN**	X		X			
Nitic hor.	TC **NT**	X		X			
Petrocalcic hor.	TC LP **CA**						X
Petroduric hor.	TC LP **DU**						
Petrogypsic hor.	TC LP **GY**						
Petroplinthic hor.	TC LP AN **PT** NT **CM**					X	
Pisoplinthic hor.	TC AN **PT** NT **CM**					X	
Plaggic hor.	**AT CM**	X	X		X		
Plinthic hor.	TC AN **PT** NT **CM**					X	
Pretic hor.	**AT CM**		X		X		
Protovertic hor.		X		X			
Salic hor.	**SC CM**						
Sombric hor.		X	X	X	X		
Spodic hor.	TC LP AN **PZ**	X	X	X	X		
Terric hor.	**AT CM**		X				
Thionic hor.	SC **CM**					X	
Umbric hor.	**GL UM**		X	X	X		
Vertic hor.	TC **VR** NT **CM**	X		X			
Abrupt text. diff.	**PL**	X					
Albeluvic glossae		X	X	X			
Andic prop.	**AN CM**						
Anthric prop.		X	X	X	X		X
Aridic prop.		X	X				
Continuous rock	**HS TC LP AN ST AC AL**						X
Geric prop.							
Gleyic prop.	**GL**		X			X	
Lithic discontinuity		X					
Protocalcic prop.				X			X

(continued)

Table 23.1 (continued)

Diagnostics[a]	RSG[b]	ST[c]	MC[d]	SS[e]	OC[f]	RF[g]	CB[h]
Reducing cond.	**GL PT PL ST**						
Retic prop.	**RT**	X	X	X			
Shrink-swell cracks	**VR**						
Sideralic prop.			X				
Stagnic prop.	**PT PL ST**	X	X			X	
Takyric prop.		X	X				
Vitric prop.	**AN CM**						
Yermic prop.		X	X				
Albic mat.			X				
Artifacts	**TC**						
Calcaric mat.							X
Colluvic mat.							
Dolomitic mat.							X
Fluvic mat.	**FL**	X	X	X	X		
Gypsiric mat.							
Hypersulfidic mat.							
Hyposulfidic mat.							
Limnic mat.							
Mineral mat.					X		
Organic mat.	**HS**				X		
Ornithogenic mat.							
Soil organic carbon							
Sulfidic mat.							
Technic hard mat.	**HS TC LP AN ST AC AL**						
Tephric mat.							

Soil attributes whose determination is necessary to define the diagnostic unit are marked by X. Based on Hartemink and Minasny (2014); the soil attributes that can be efficiently determined by digital soil morphometric tools are indicated

HS Histosols, *AT* Anthrosols, *TC* Technosols, *CR* Cryosols, *LP* Leptosols, *SN* Solonetz, *VR* Vertisols, *SC* Solonchaks, *GL* Gleysols, *AN* Andosols, *PZ* Podzols, *PT* Plinthosols, *NT* Nitisols, *FR* Ferralsols, *PL* Planosols, *ST* Stagnosols, *CH* Chernozems, *KS* Kastanozems, *PH* Phaeozems, *UM* Umbrisols, *DU* Durisols, *GY* Gypsisols, *CL* Calcisols, *RT* Retisols, *AC* Acrisols, *LX* Lixisols, *AL* Alisols, *LV* Luvisols, *CM* Cambisols, *AR* Arenosols, *FL* Fluvisols, *RG* Regosols

[a] Diagnostic horizons, properties, and materials

[b] Reference soil group—**Bold codes** represent RSGs where the presence of the diagnostic unit is a criterion

Normal codes represent RSGs where the absence of the diagnostic unit is a criterion

Italic codes represent RSGs where the absence of the diagnostic unit is a criterion unless it fulfills further requirements

[c] Soil texture, texture differences, clay content

[d] Matrix color

[e] Soil structure

[f] Organic matter, organic carbon

[g] Redoximorphic features, mottles

[h] Carbonates

horizon boundaries ranging from abrupt to diffuse and from smooth to broken. The depth and width of horizons are the criteria for almost all diagnostic units in many soil description or classification systems. Soil scientists spend significant time and often argue during the establishment of depth and width of the horizon depth based on key soil properties, it is expected that digital soil morphometrics may enhance soil horizon determination. Encouraging research results have been published by Doolittle and Collins (1995), Rooney and Lowery (2000), Legros (2006), Weindorf et al. (2012), Steffens and Buddenbaum (2013), and others on the application of the ground-penetrating radar (GPR), electrical resistivity (ER), hyperspectral imaging spectroscopy, and X-ray fluorescence (XRF) (all cited from Hartemink and Minasny 2014) (Table 23.2).

Soil Texture

Soil texture refers to the relative proportions of sand, silt, and clay within the fine earth fraction. Flowcharts are available presenting the way soil texture can be estimated (Rowell 1994; Thien 1979). A frequently used way to describe soil texture in the field is the “finger test” or determining by feel. Texture can be estimated by gently pushing the soil out between the thumb and the forefinger. The success greatly depends on the senses and the experience of the expert, performing the estimation, hence is subjective and final results can be concluded only after laboratory determination. The initial field decision on several diagnostic units and taxa has to be followed after the laboratory results are available. This often does not happen and causes inconsistences in data bases.

Texture plays a major role in the differentiation of albeluvic glossae, retic, vertic properties, fluvic material, lithic discontinuity, abrupt textural difference, further in the case of argic, cambic, fragic, irragric, natric, nitic, vertic horizons, and for the Vertisols reference soil group. Texture differences have significant importance as a criterion for argic horizon in the case of Acrisols, Alisols, Lixisols, and Luvisols, natric horizon in the case of Solonetz; further texture differences are a diagnostic criterion for fluvic material, abrupt textural difference, and retic properties.

Digital morphometrics provides tools to improve objectivity with regard to the determination of the soil texture in the field, making the establishment of many classification units.

Weindorf et al. (2012) tested portable XRF for the determination of soil texture in situ and on cores ex situ in the laboratory. Zhu et al. (2011) measured samples which covered a wide range of soils, and concluded that in situ determination of soil texture with pXRF yielded promising results for relatively dry soils as well as wet soils supplemented with portable moisture sensors. Ge et al. (2005) stated that soil moisture can affect the XRF signal but also offered an algorithm to mitigate similar problems. This issue is discussed further in Stockmann et al. (2015).

Diffuse reflectance spectroscopy was tested by Waiser et al. (2007) for in situ quantification of clay content of soils from a wide range of parent material types. A method based on in situ spectroscopic measurements coupled with chemometric

Table 23.2 Diagnostic horizons of the world reference base (WRB) with strong criteria related to horizon depth

WRB diagnostics	Criteria (simplified)
Anthraquic horizon	Thickness ≥15 cm
Argic horizon	Thickness of ≥7.5 or 15 cm
Calcic horizon	Thickness of ≥15 cm
Cambic horizon	Thickness of ≥15 cm
Chernic horizon	Thickness ≥25 cm
Cryic horizon	Thickness of ≥5 cm
Duric horizon	Thickness of ≥10 cm
Ferralic horizon	Thickness of ≥30 cm
Ferric horizon	Thickness of ≥15 cm
Folic horizon	Thickness of ≥10 cm
Fragic horizon	Thickness of ≥15 cm
Fulvic horizon	Combined thickness of ≥30 cm with ≤10 cm non-fulvic material in between
Gypsic horizon	Thickness of ≥15 cm
Histic horizon	Thickness of ≥10 cm
Hortic horizon	Thickness of ≥20 cm
Hydragric horizon	Thickness of ≥10 cm
Irragric horizon	Thickness of ≥20 cm
Melanic horizon	Combined thickness of ≥30 cm with ≤10 cm non-melanic material in between
Mollic horizon	Thickness of ≥10 cm or ≥20 cm
Natric horizon	Thickness of ≥7.5 or 15 cm
Nitic horizon	Thickness of ≥30 cm
Petrocalcic horizon	Thickness of ≥10 or 10 cm or ≥1 cm
Petrogypsic horizon	Thickness of ≥10 cm
Petroplinthic horizon	Thickness of ≥10 cm
Pisoplinthic horizon	Thickness of ≥15 cm
Plaggic horizon	Thickness of ≥20 cm
Plinthic horizon	Thickness of ≥15 cm
Pretic horizon	Combined thickness of ≥20 cm
Protovertic horizon	Thickness of ≥15 cm
Salic horizon	Thickness of ≥15 cm
Spodic horizon	Thickness of ≥25 cm
Terric horizon	Thickness of ≥20 cm
Thionic horizon	Thickness of ≥15 cm
Umbric horizon	Thickness of ≥10 cm if directly overlying continuous rock, technic hard material or a cryic, petroplinthic, or petroduric horizon, or ≥20 cm
Vertic horizon	Thickness of ≥25 cm

methods was successfully applied by Viscarra Rossel et al. (2009) to estimate soil color, mineral composition, and clay content of samples from multiple depths. Lagacherie et al. (2008) showed how reflectance spectrometry can be used in the laboratory to estimate clay and calcium carbonate content (Table 23.3).

Table 23.3 Diagnostic units (horizons, properties, materials) of the WRB with criteria related to soil texture

WRB diagnostics	Criteria (simplified)
Argic horizon	Defined texture classes (texture class of loamy sand or finer and ≥8 % clay)
Cambic horizon	Defined texture classes
Ferralic horizon	Defined texture class of sandy loam or finer
Fragic horizon	Defined texture classes (same as in Cambic horizon)
Chernic horizon	Defined texture classes if first color criterion is not fulfilled
Mollic horizon	Defined texture classes if first color criterion is not fulfilled
Natric horizon	Defined texture classes texture class of loamy sand or finer and ≥8 % clay
Nitic horizon	Defined clay content (≥30 %), and silt to clay ratio (<0.4)
Plaggic horizon	Defined texture classes
Protovertic horizon	≥30 % clay throughout
Vertic horizon	≥30 % clay throughout
Takyric properties	Texture class of clay loam, silty clay loam, or clay
Argic horizon	Defined textural differentiation to the overlying horizon
Cambic horizon	Defined clay increase compared to the directly underlying layer
Fragic horizon	Defined clay increase compared to the directly underlying layer
Irragric horizon	Higher clay content, particularly fine clay, than the underlying original soil; and defined differences in sand, silt, and clay contents between parts of the horizon
Natric	Defined textural differentiation to the overlying horizon
Nitic	<20 % difference (relative) in clay content over 15 cm to layers directly above and below
Abrupt textural difference	(within ≤5 cm) Doubling of the clay content or ≥20 % (absolute) increase in clay content (based on the clay content of the overlying layer)
Lithic discontinuity	Defined differences in particle-sized distribution between layers directly superimposed on the other
Albeluvic glossae	Clay content of the stronger colored parts is higher compared with the lighter colored parts, a specified for the argic horizon
Retic properties	Clay content of the stronger colored parts is higher compared with the lighter colored parts, as specified for the argic or natric horizon
Fluvic material	Stratification (may be) reflected in variation in texture

Soil Color

The result of soil color assessment in the field is affected by personal experience. The Munsell Color Theory has brought standardization to color communication as within the system each color has a logical and visual connection to the other colors. Color readings in the field depend on the moisture status of the current soil profile and the quality of light (Pendleton and Nickerson 1951; Post et al. 1993; Simonson 1993). The determination of color is difficult even for experts due to several factors affecting the readings including the quality and age of Munsell charts. Soil color is a diagnostic criterion in WRB for anthraquic horizon, cambic, chernic, fragic, fulvic, hortic, melanic, plaggic, pretic, sombric, umbric horizons, albeluvic glossae, gleyic, retic, sideralic, stagnic properties, and albic material (IUSS WG WRB 2006).

Table 23.4 Diagnostic units (horizons, properties, materials) of the WRB with criteria related to soil color

WRB diagnostics	Criteria (simplified)
Anthraquic horizon	A puddled layer with defined Munsell colors
Cambic horizon	Defined color change compared to the directly underlying layer
Chernic horizon	Defined Munsell colors
Fragic horizon	Defined color change compared to the directly underlying layer (same as in Cambic horizon)
Fulvic horizon	Defined Munsell colors
Hortic horizon	Defined Munsell color
Melanic horizon	Defined Munsell color
Mollic horizon	Defined Munsell color
Plaggic horizon	Defined Munsell color
Pretic horizon	Defined Munsell color
Sombric horizon	Lower Munsell color value or chroma than the overlying horizon
Spodic horizon	Defined Munsell color
Umbric horizon	Defined Munsell color
Albeluvic glossae	Defined Munsell color
Gleyic properties	Defined Munsell color
Retic properties	Defined Munsell color
Sideralic properties	Defined Munsell color chroma
Stagnic properties	Defined differences in Munsell colors to the surrounding materials
Albic materials	Defined Munsell colors

Soil color is the major differentiation criterion for the mollic and umbric horizons which defines Chernozems, Kastanozems, Phaeozems, and Umbrisols reference soil groups.

In the case of cambic and fragic horizons, MC has a basic significance. Fulfillment of the criteria depends on the defined color change compared to the directly underlying layer (WRB). The stagnic properties' criteria fulfillment also depends on the defined differences in Munsell colors to the surrounding material.

Viscarra Rossel (2009) used Vis–NIR to define soil color in the field and in the laboratory and their results were compared to Munsell color. They have found compatibility between spectroscopic measurements and Munsell readings (Table 23.4).

Soil Structure

Soil structure refers to the arrangement of the soil particles into soil units (ped, aggregates) resulting from several pedogenic processes (FAO 2006). Alternation of the dry and wet conditions, root activity, and fauna is important in the formation of SS (Materechera et al. 1992).

Structure is a differentiation criterion in the WRB in the case of mollic and umbric horizons; anthraquic, cambic, chernic, nitic, vertic, irragric, petrocalcic, calcic, further, in the case of Solonetz columnar or prismatic (or blocky) structure should present to fulfill the criteria.

Table 23.5 Diagnostic units (horizons, properties, materials) of the WRB with criteria related to soil structure

WRB diagnostics (horizons, properties, materials)	Criteria (simplified)
Anthraquic horizon	Platy or massive structure in ≥25 % of its volume
Cambic horizon	Soil aggregate structure in ≥50 % of the volume of the fine earth fraction
Chernic horizon	Granular or fine subangular blocky soil structure
Fragic horizon	Soil aggregate structure in ≥50 % of the volume of the fine earth fraction (same as in Cambic horizon)
Mollic horizon	Sufficiently strong structure
Natric horizon	Columnar or prismatic (or blocky) structure
Nitic horizon	Strong blocky structure breaking into polyhedral or flat-edged or nut-shaped elements
Protovertic horizon	Wedge-shaped soil aggregates or slickensides
Umbric horizon	Sufficiently strong structure
Vertic horizon	Wedge-shaped soil aggregates or slickensides
Takyric properties	Platy or massive structure
Anthraquic horizon	Platy or massive structure in ≥25 % of its volume
Cambic horizon	Soil aggregate structure in ≥50 % of the volume of the fine earth fraction
Chernic horizon	Granular or fine subangular blocky soil structure

The correct determination of SS is critical especially in the case of natric—columnar, prismatic (or blocky) structure required—because it determines the Solonetz reference soil group.

The notion of "strong structure" for mollic and umbric surface horizons is required because they are diagnostic for Umbrisols, Chernozems, Kastanozems, and Phaeozems reference soil groups. The definition of "strong" is too broad and the determination can be subjective even with expert knowledge. Either the clarification of phrasing of the definition "sufficiently strong structure" or the reformation of tools used for the structure determination is needed.

NIR and MIR spectroscopy have been applied to estimate soil organic carbon and clay content (Gomez et al. 2013) but no device is available that can measure the distinct aspects of the SS in the field (Hartemink and Minasny 2014). Hirmas and Hasiotis (2010) used laser imaging for measurement of structure (Table 23.5).

Organic Matter

Organic matter plays a crucial role in each existing classification system.

Organic matter content of surface horizons can determine Histosols, Chernozems, Kastanozems, and Phaeozems through mollic, chernic, and umbric surface horizons.

There are several measurement methods for determining organic matter and organic carbon in the laboratory but two results of two different measurement methods cannot be compared with each other.

Table 23.6 Diagnostic units (horizons, materials) of the world reference base (WRB) with criteria related to organic carbon (OC) content

WRB diagnostics	Criteria (simplified)
Cambic horizon	Does not form part of other horizons with OC criteria
Chernic horizon	Minimum organic carbon content (1 %) and thickness of the horizon (high base)
Folic horizon	Presence and minimum thickness of organic soil material (dry/aerated?) conditions)
Fragic horizon	<0.5 % soil organic carbon
Fulvic horizon	Specific organic matter nature[a] minimum organic carbon content (6 % weight average), and thickness of the horizon
Histic horizon	Presence and minimum thickness of organic soil material (wet conditions)
Hortic horizon	Minimum organic carbon content (1 %) and thickness of the horizon (anthropogenic influence, high phosphate content)
Irragric horizon	Minimum organic carbon content (0.5 % weight average) and thickness of the horizon (with anthropogenic influence)
Melanic horizon	Specific organic matter nature (higher[a] minimum organic carbon content (6 % weight average), and thickness of the horizon
Mollic horizon	Minimum organic carbon content (0.6 %) and thickness of the horizon (high base)
Plaggic horizon	Minimum organic carbon content (0.6 %) and thickness of the horizon (mollic like with anthropogenic influence and artifacts)
Pretic horizon	≥1 % organic carbon
Sombric horizon	Higher content of soil organic carbon respect to the directly overlying horizon or illuvial humus in some parts
Spodic horizon	Minimum organic carbon content (0.6 %) (subsurface accumulation)
Umbric horizon	Minimum organic carbon content (0.6 %) and thickness of the horizon (low base)
Anthric properties	Minimum organic carbon content (0.6 %) and thickness of the horizon (mollic like with anthropogenic influence)
Fluvic material	Irregular change in organic carbon content not relate to pedogenesis
Mineral material	Maximum organic carbon content (20 %)
Organic material	Minimum organic carbon content (20 %)

[a] Higher humic acid ratio compered to fulvic acids in the melanic horizon than in the fulvic horizon, determined by the melanic index (IUSS WG WRB 2006)

As the present definitions are hard to handle, clarification or simplification of limits are recommended (Michéli et al. 2014). Steffens et al. (2014) studied the soil organic matter content and composition applying imaging spectroscopy. They concluded that Vis–NIR imaging spectroscopy is an effective tool for mapping soil organic matter quality even if the layers are not distinguishable visually.

Viscarra Rossel and Hicks (2015) concluded that Vis–NIR spectroscopy is a useful, cheap technique to observe and monitor organic carbon composition. Other studies used Vis–NIR spectroscopy to estimate organic layers in forests (Chodak et al. 2002). Viscarra Rossel et al. (2008) applied a simple digital camera and found correlations for OC and Fe contents (Table 23.6).

Table 23.7 Diagnostic units (horizons, properties, materials) of the WRB with criteria related to redoximorphic features and mottles

WRB diagnostics	Criteria (simplified)
Anthraquic horizon	Iron manganese mottles or coatings
Ferric horizon	Defined presence of coarse mottles, concentrations, or nodules
Hydragric horizon	Fe or Mn coatings or concentrations, or redox depletions
Petroplinthic horizon	Yellowish, reddish, and/or blackish concentrations or nodules or concentrations
Pisoplinthic horizon	Yellowish, reddish, and/or blackish concentrations and/or nodules (strongly cemented to indurated)
Plinthic horizon	Discrete concentrations or nodules, or concentrations
Thionic horizon	Mottles or coatings (with accumulations of iron or aluminum sulfate or hydroxysulfate minerals)
Gleyic properties	>5 % (exposed area) mottles
Stagnic properties	Mottles and/or concentrations and/or nodules

Mottling

Mottles are differently colored spots in a soil matrix and are mostly the result of reduction and oxidation of Fe. Concreted mottles of oxides are diagnostic for the hydragric, ferric, plinthic, petroplinthic, and pisoplinthic horizons and for the stagnic color pattern. Fe or Mn coatings or concentrations or redox depletions are diagnostic criteria for hydragric horizon according to WRB. Mottles and redoximorphic features are key differentiation criteria for Stagnosols and Gleysols.

The presence of Fe^{II} ions can be determined in the field with a 0.2 % α, α dipyridyl solution in 10 % acetic acid solution, but these chemicals are slightly toxic. Steffens and Buddenbaum (2013) concluded that laboratory imaging spectroscopy facilitate the spatially correct soil classification including the quantification of soil mottling (Table 23.7).

Carbonates

Determination of calcium carbonate content in the field is established by adding a few drops of 10 HCl to the soil. The degree of effervescence refers to the presence and amount of calcium carbonate. The rate of reaction depends on soil texture and other materials such as plant tissues. Determination of the 15 % calcium carbonate content—which is the required amount for calcic horizon—has a decisive role in differentiation for Calcisols, Chernozems, Kastanozems, and Leptosols. Furthermore, determination of the origin of the carbonate in the field also requires field experience and could provide information about the processes under the current soil has been formed (FAO 2006).

In WRB, evidence of the leaching of carbonates from the cambic horizon is a diagnostic criterion for Cambisols. Differences in calcium carbonate content between parts of a horizon are part of the definition of the irragric horizon. Calcic

Table 23.8 Diagnostic units (horizons, properties, materials) of the WRB with criteria related to $CaCO_3$

WRB diagnostics	Criteria (simplified)
Calcic horizon	≥15 % $CaCO_3$, and ≥5 % (by volume) secondary carbonates, or ≥5 % $CaCO_3$ higher than an underlying layer and no lithic discontinuity, and does not form part of a petrocalcic horizon
Cambic horizon	≥5 % less carbonates
Chernic horizon	≥40 % (by mass) $CaCO_3$
Fragic horizon	Does not show effervescence after adding a 1 M HCL solution
Mollic horizon	If color is lighter than value of 3 moist and 5 dry and the chroma of 3 than ≥40 % $CaCO_3$ content
Petrocalcic horizon	Very strong effervescence after adding 1 M HCl solution, and shows induration or cementation at least partially by secondary carbonates
Continuous rock	Not part of a petrocalcic horizon
Protocalcic properties	Soft calcium carbonate accumulations in different forms
Dolomitic material	Strong effervescence with heated 1 M HCl solution

horizon or a layer with protocalcic properties is also a requirement for Calcisols, Chernozems, and Kastanozems (WRB) (Table 23.8).

23.3.2 Vis–NIR Spectroscopy for Distinguishing Soil Horizons

A previous study (Csorba et al. 2014) showed that Vis–NIR reflectance spectroscopy coupled with principal component variables (PC factor scores) can be effectively used as variables describing the spectral properties along the soil profile. This study focuses on the definition of diagnostic horizons.

The Silhouette analysis performed prior to the Fuzzy C-means clustering showed that the PC factor score values can be classified into three clusters (Clusters A, B, and C). Figure 23.1 shows the distribution of the samples along the first three principal components that explained 92 % of the total variance. The color coding and the symbols in Fig. 23.1a refer to the field-determined WRB diagnostic horizons, while Fig. 23.1b shows the classes obtained from the Fuzzy C-means clustering. Based on the visual inspection of the scatterplots, the clustering of samples is in good accordance with the determined diagnostic horizons. Major part of Cluster A samples were taken from a calcic, Cluster B from a mollic, and Cluster C from an argic horizon.

Three examples of the comparison of the Fuzzy-C membership values and the spline-resampled organic carbon, $CaCO_3$, and clay content values versus the depth are shown in Fig. 23.2. The cluster membership values of the Cluster A show similar pattern as the spline estimated $CaCO_3$ values. The membership values of the Cluster B show similar pattern as the spline estimated organic carbon values. The explanation of the distribution of the membership values of the Cluster C along the

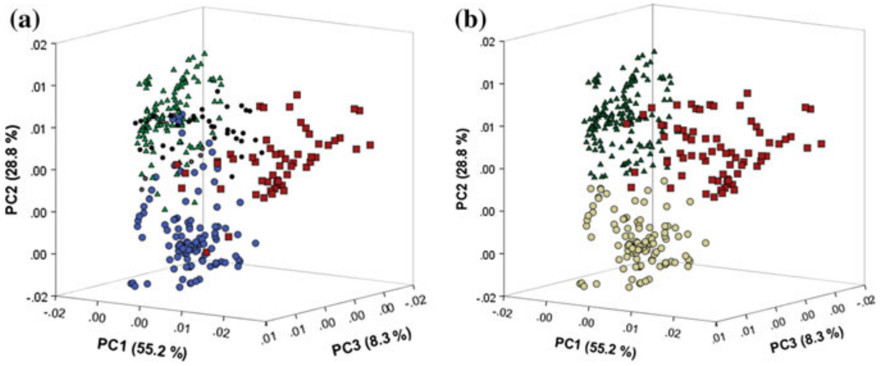

Fig. 23.1 The 3D scatterplots showing the distribution of samples along first three principal components. **a** The coloring and symbology refer to the WRB diagnostic horizon the samples belong to. Calcic *filled blue circle;* Argic *filled red square;* Mollic *filled green triangle;* Mollic—Calcic *open circle* Non-diagnostic horizon *black circle*. **b** The coloring and symbology refer the Fuzzy C-means clusters the samples belong to Cluster A *filled ash circle;* Cluster B *filled red square*; and Cluster C *filled green triangle*

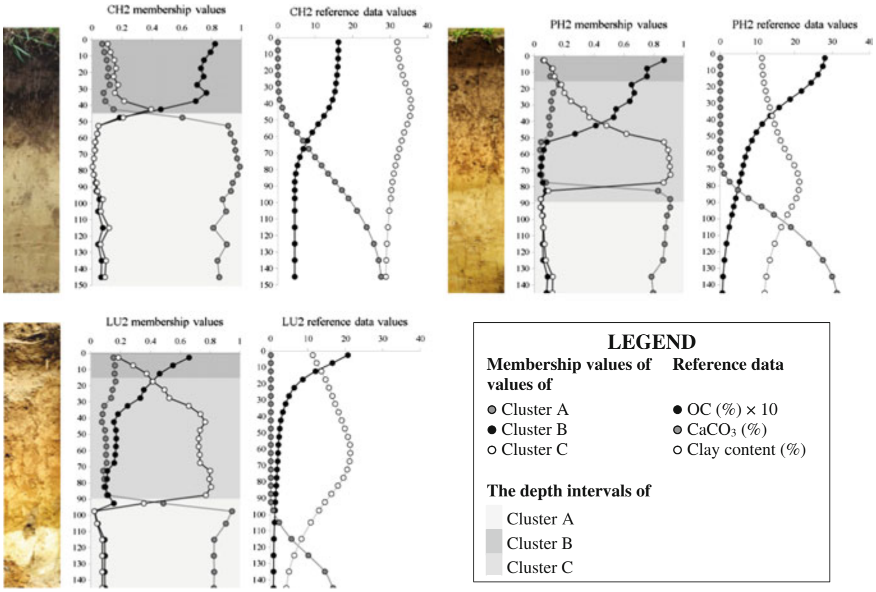

Fig. 23.2 Three examples of the distribution of the cluster membership values and the reference spline-resampled OC, $CaCO_3$, and clay content values (with *circles*). On the plot showing the membership values versus the depth, the depth intervals of the clusters are also indicated (with the *rectangles* of different shades of *gray*)

profile needs a different approach. Their distributions show similarity with the clay content only in the case of soil profiles where considerable clay illuviation has occurred.

23.4 Summary and Conclusions

During this study, the digital soil morphometric tools proved to be efficient in the determination of soil parameters playing key role in the definition of diagnostic units of the WRB were reviewed. Six soil parameters were investigated based on their role of defining the diagnostic criteria. The reviewed digital soil morphometrics tools and methods are supporting the prediction of properties that are part of the criteria of diagnostic units of WRB. Some of these attributes are determined or estimated in the field with subjective element and supported by laboratory analysis. The new tools can bring a revolution to soil classification and to soil science in general, as they provide cost effective and quick measurements and results to assist in the field decisions and the process of soil classification.

Effectiveness is not the only benefit of these methods; compared to the standard methods, these tools can provide a cleaner technology with minimizing or cease the environmental impacts of measurements.

The example study demonstrated the significance of Vis–NIR reflectance measurements in predicting diagnostic horizons. Because the technology supplies integrative measurements of soil, it can facilitate the collection of large amount of soil data and provide more information than the conventional—accurate but expensive—survey methods.

In summary, digital morphometrics provides the potential of less subjective, more time and cost efficient and environment friendly support or replacement of field and laboratory methods applied in soil classification.

Acknowledgement This work was supported by Research Centre of Excellence—9878-3/2015/FEKUT.

References

ASRIS (2011) ASRIS—Australian soil resource information system. http://www.asris.csiro.au. Accessed 21 Dec 2014

Berthold MR, Cebron N, Dill F, Gabriel TR, Kötter T, Meinl T, Ohl P, Sieb C, Thiel K, Wiswedel B (2007) KNIME—Konstanz information miner. Studies in classification, data analysis and knowlodge organization. Springer, pp 319–326

Chodak M, Ludvig B, Khanna P, Beese F (2002) Use of near infrared spectroscopy to determine biological and chemical characteristics of organic layers under spruce and beech stands. J Plant Nutr Soil Sci 165(1):27–33

Csorba A, Lang V, Fenyvesi L, Micheli E (2014) Identification of WRB soil classification units from vis-NIR spectral signatures. In: Kim PJ, Kang H-W et al (eds) 20th world congress of soil science: in commemoration of the 90th anniversary of the IUSS. Jeju, South-Korea, 08.06.2014–13.06.2014. IUSS, Paper P4–539

Dokuchaev VV (1883) The Russian Chernozem Report to the Imperial Free Economic Society. St. Petersburg

Doolittle JA, Collins ME (1995) Use of soil information to determine application of ground penetrating radar. J Appl Geophys 33:101–108

Ge L, Lai W, Lin Y (2005) Influence of and correction for moisture in rocks, soils and sediments on in situ XRF analysis. X-Ray Spectrom 34:28–34

Gomez C, Le Bissonnais Y, Annabi M, Bahri H, Raclot P (2013) Laboratory Vis-NIR spectroscopy as an alternatibe method for estimating the soil aggregate stability indexes of Mediterranean soils. Geoderma 209–210, 86–97

Hartemink AE, Minasny B (2014) Towards digital soil morphometrics. Geoderma 230–231

Hirmas D, Hasiotis ST (2010) Field application of multistripe laser triangulation (MLT) scanning to enhance and quantify descriptions of soil and exogenic trace morphology. GSA Annual Meeting 31 Oct - 3 Nov 2010. Denver Colorado USA

IUSS Working Group WRB (2006) World Reference Base for Soil Resources 2006 World Soil Resources Report No. 103, FAO, Rome

IUSS WG WRB (2014) World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome

Materechera SA, Dexter AR, Alston AM (1992) Formation of aggregates by plant roots in homogenised soils. Plant Soil 142: 69–79

Michéli E, Owens PR, Láng V, Fuchs M, Hempel J (2014) Organic Carbon as a major differentiation criterion in soil classification systems. In: Hartemink AE, McSweeney K (eds) Soil carbon. Progress in soil science. Springer, pp 37–45

Lagacherie P, Baret F, Feret JB, Madeira Netto J, Robbez-Masson JM (2008) Estimation of soil clay and calcium carbonate using laboratory, field and airborne hyperspectral measurements. Remote Sens. Environ. 112, 825–835

Legros JP (2006). Mapping of the soil, Science Publishers, pp:1–35

Pendleton RL, Nickerson D (1951) Soil colors and special Munsell soil color charts. Soil Sci. 71, 35–43

Post DF, Bryant RB, Batchily AK, Huete, AR, Levine SJ, Mays MD, Esadafal R (1993) Correlations between field and laboratory measurements of soil color. In: Bigham, J. M., Ciolkosz, E. J. Soil Color Soil Sci Soc Am., Madison, WI. pp 35–49

R Development Core Team (2008) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Rooney DJ, Lowery B (2000) A profile cone penetrometer for mapping soil horizons. Soil Sci Soc Am J 64:2136–2139

Rowell DL (1994) Soil science: methods and applications. Longman, Harlow, England

Savitzky A, Golay MJE (1964) Smoothing and differentiation of data by simplified least squares procedures. Anal Chem 36:1627–1639

Simonson RW (1993) Soil color standards and terms for field use - history of their development. In: Bigham JM, Ciolkosz EJ Soil Sci Soc Am. Madison, WI. pp. 1–20

Steffens M, Buddenbaum H (2013) Laboratory imaging spectroscopy of a stagnic Luvisol profile-High resolution soil characterization, classification and mapping of elemental concentrations. Geoderma 195–196:122–132

Steffens M, Kohlpaintner M, Buddenbaum H (2014) Fine spatial resolution mapping of soil organic matter quality in a Histosol profile. Eur J Soil Sci 65(6):827–839

Stockmann U, Malone B, McBratney A, Minasny B (2015) Landscape scale exploratory radiometric mapping using proximal soil sensing. Geoderma 239:115–129

Thien SJ (1979) A flow diagram for teaching texture by feel analysis. J Agron Educ 8

Viscarra Rossel RA, Fouad Y, Walter C (2008) Using a digital camera to measure soil organic carbon and iron contents. Biosyst Eng 100(2): 149–159

Viscarra Rossel RA, Cattle SR, Ortega A, Fouad Y (2009) In situ measurements of soil colour, mineral composition and clay content by vis-NIR spectroscopy. Geoderma 150:253–266

Viscarra Rossel RA, Hicks W (2015) Estimates of soil organic carbon and its fractions with small uncertainty using visible–near infrared transfer functions. European Journal of Soil Science 66:438–450

Waiser TH, Morgan CLS, Brown DJ, Hallmark CT (2007) In Situ Characterization of Soil Clay Content with Visible Near-Infrared Diffuse Reflectance Spectroscopy. Soil Science Society of America Journal 71(2): 389–396

Weindorf DC, Zhu Y, Haggard B, Lofton J, Chakraborty S, Bakr N, Zhang W, Weindorf WC, Legoria M (2012) Enhanced pedon horizonation using portable X-ray fluorescence spectrometry. Soil Sci Soc Am J 76:522–531

Zhu Y, Weindorf DC, Zhang W (2011) Characterizing soils using a portable X-ray fluorescence spectrometer: 1 Soil texture. Geoderma 167–168:167–177