Chapter 1
Digital Soil Mapping Across Paradigms, Scales, and Boundaries: A Review

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Abstract Accurate spatial soil information is urgently needed for dealing with the global issues such as agricultural production, environmental pollution, food security, water security, and human health. This need has been motivating the development of digital soil mapping. We reviewed recent advances in digital soil mapping with respect to paradigms, scales, and boundaries, with the intent to improve our understanding on current status of soil mapping. Some important challenges thus research opportunities emerged recently were then outlined, such as 3D digital mapping of the soil properties beyond soil organic matter, soil mapping in areas with intensive human activities, and multi-source soil data integration for soil mapping.

1.1 Introduction

The series of the global workshops on digital soil mapping run under the umbrella of the International Union of Soil Sciences Working Group on digital soil mapping. The first global workshop on digital soil mapping was held in the year of 2004 at Montpellier, France. Its theme was "Digital Soil Mapping: An Introductory Perspective." A wide range of skills and tools that can be used for digital soil mapping were discussed in this workshop. The second workshop was held in the year of 2006 at Rio de Janeiro, Brazil. Its theme was "Digital Soil Mapping for Regions and Countries with Sparse Soil Data Infrastructures." The digital soil mapping techniques and applications that focused on areas with limited soil data were emphasized. The third workshop was held in the year of 2008 at Logan, America, with the theme of "Digital Soil Mapping: Bridging Research, Production, and Environmental Application." The soil mapping research, environmental application, and operation were discussed. The fourth workshop was held in the year of 2010 at Roma, Italy, with the theme of "From Digital Soil Mapping to Digital Soil

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Assessment: Identifying key gaps from fields to continents." The issues of spatial scales were discussed. The theme of the fifth workshop was held in the year of 2012 at Sydney, Australia, with the theme of "Digital Soil Assessments and Beyond." Current and potential contributions of digital soil mapping to various assessments driven by stakeholders and global issues were emphasized. Then, it comes to the sixth global workshop on digital soil mapping. This event was organized by the Soil Science Society of China and the Institute of Soil Science, Chinese Academy of Sciences at Nanjing, China on November 9–11, 2014. Its theme was "Digital soil mapping across paradigms, scales, and boundaries." The advances in digital soil mapping paradigms, scales, and boundaries were emphasized in this workshop.

The state of the art of digital soil mapping has been reviewed several times mainly from different perspectives such as history, techniques, data production, and applications (McBratney et al. 2003; Lagacherie 2008; Grunwald 2010; Arrouays et al. 2014; Minasny and McBratney 2015). The objective of this paper is to present current status with respect to paradigms, scales, and boundaries and important issues on digital soil mapping that emerged more recently.

1.2 Soil Mapping Paradigms

A paradigm is a set of concepts or thought patterns, including theories, methods, and models. It provides solutions for a community of practitioners. In 1883, the Russian pedologist Dokuchaev put forward the famous theory on soil-forming factors, i.e., soil is formed over time as a consequence of climatic (CL), parent material (P), and biological processes (O), which he demonstrated that soils are products of soil-forming factors. Jenny (1941) further developed this into a soil-forming function, i.e., $S = f$ (clorpt…) by adding topographic relief as a factor. This equation suggests that, by looking for changes in these factors as the landscape is traversed, one can identify boundaries between different bodies of soils. The formulation has been used by a lot of soil investigators as a conceptual soil-forming model for understanding soil–landscape patterns within a region. Many studies have tried to quantitatively formalize the equation. Based on a review of various quantitative approaches to making digital soil maps, McBratney et al. (2003) proposed a quantitative framework suitable for digital mapping and modeling of soil classes and properties, i.e., the well-known SCORPAN model. It is an empirical model, and both factors and soil predictions are spatially and temporally explicit. To explicitly account for the role of anthropogenic factors in soil formation, Grunwald et al. (2011) and Thompson et al. (2012) proposed a new framework for soil mapping and modeling, i.e., the STEP-AWBH model. Water properties (e.g., surface runoff, infiltration rate) and human-induced forcings (e.g., contamination, greenhouse gas emissions) were added as new soil-forming factors. It is an enhanced quantitative framework for soil mapping and modeling. Its key features includes accounts for time-dependent variation of the factors and facilitates modeling of soil evolution and change.

1.3 Soil Mapping Scales

Soil varies over space and changes over time. At different spatial or temporal scales, soil can exhibit distinct processes and patterns. In order to meet the requirements of soil information for different levels of applications, digital soil mapping has been explored across various spatial or temporal scales. Temporal scales can span from hours to several decades and even one thousand years. Studies of digital soil mapping at specific temporal scale mainly focus on the changes of soil salinity, soil carbon, and soil thickness (Douaik et al. 2005; Follain et al. 2006; Lark et al. 2006; Sun et al. 2012; Ardekani 2013). Its purpose is to reveal the patterns of soil evolution. Spatial scales include global, continental, regional, catchment, landscape, and field. Digital soil mapping has been conducted at all these scales. The GlobalSoilMap.net Project launched in 2009 aims to produce a new digital soil map of the globe using digital soil mapping technologies. It will map most of the ice-free land surface of the world at a 90-m spatial resolution (Sanchez et al. 2009). The interpretation and functionality options will also be provided with the maps to support improved decisions for a range of global problems. However, limited attempts have been made at global scale especially for a high-resolution map. When there is no detailed map or soil samples are available in a region of interest, Mallavan et al. (2010) proposed a Homosoil method to extrapolate from other parts of the globe. In order to provide a consistent global soil data, Köchy et al. (2014) derived global distribution of soil organic carbon based on the Harmonized World Soil Database. Hengl et al. (2014) developed global 3D soil distribution data based on regression or regression-kriging methods. But due to some limitations, the prediction accuracies are relatively low. A few attempts have been made on the continental scale for all five continents (Henderson et al. 2001; Viscarra Rossel et al. 2011; Odgers et al. 2012; TÓth et al. 2013; Stevens et al. 2013; Dewitte et al. 2013; Láng et al. 2015). Scull and Okin (2007) discussed sampling challenges posed by continental-scale soil–landscape modeling and argued that the success of the sampling design in continental scale largely depend on the ability to anticipate the spatial variability of the variable being measured. Grunwald et al. (2011) incorporated anthropogenic forcings into a space-time modeling framework to provide a solution for soil mapping and modeling at continental scales. Some continental-scale mapping initiatives are also considered as national scale, because they cover the extent of a whole country, e.g., China, Australia, and the USA. A lot of studies have been made on the regional (Lacoste et al. 2011; Kerry et al. 2012; Wang et al. 2013; Heung et al. 2014; Guo et al. 2015), catchment (Zhu et al. 2001; Qin et al. 2011; Karunaratne et al. 2014; Wahren et al. 2015), landscape (Liu et al. 2013; Lacoste et al. 2014; Stockmann et al. 2015), and field scales (Ardekani 2013; Li et al. 2015; Bevington et al. 2016) due to the increasing requirements of soil information in agriculture and environmental management. Most digital soil mapping techniques have been developed for these scales.

1.4 Soil Mapping Boundaries

The soil-mapping boundaries can be the boundaries between different regions or nations and between soil science and other disciplines. First, if the soil-mapping area spans two or more countries, the soil data collected by different countries and different soil survey projects can be different in many aspects: data collection time (old vs. new soil survey data), data formats (profile points, polygon-based maps, and soil survey reports), sampling strategies (random, regular, or representative), sampling density (sparsely vs. densely distributed), sampling depth (topsoil vs. profile), laboratory analysis methods (e.g., laser diffraction techniques vs. pipette method for measuring soil texture), and soil classification systems (e.g., Canadian soil classification system vs. USDA soil taxonomy). Thus, soil data harmonization is necessary to get consistent soil data for digital soil mapping. Quite a few studies have explored the soil data harmonization techniques (Soon and Abboud 1991; Nemes et al. 2003; Pieri et al. 2006). The specifications of the GlobalSoilMap.net products (v2.3) have identified most of these problems and provide some regression equations for harmonizing multi-source soil data to a reference standard (Arrouays et al. 2014). Baruck et al. (2015) discussed the soil data harmonization issues for soil mapping across the eight Alps countries. The process of collecting soil data and mapping soils, as well as the soil classification systems used, significantly differs among the countries. The harmonization includes an upgrade of an existing international soil classification, e.g., the World Reference Base WRB (IUSS 2014). The harmonization is not only an international transborder problem. For example, in Italy within the Pedological Methods Program in the year 2000, criteria were established for making the soil map of Italy at a scale of 1:250,000. But in order to take into account local specificities, several regions developed their own soil survey manual. Second, the soil information products derived from digital soil mapping should not only meet the applications of soil science (e.g., agricultural production and management) itself but also those of other disciplines including hydrological, ecological, and climatic modeling and even pipeline network design. To what extent the products made by soil mappers can match the requirements of applications in other fields is still an issue to be addressed mainly due to the gaps between the disciplines.

1.5 Current Challenges

1.5.1 3D Digital Soil Mapping of Soil Properties

Most soil maps are continuous surface maps in two dimensions ignoring the fact that soil also varies with depth over a landscape. A few attempts have been made on 3D soil mapping (Liu et al. 2013; Minasny et al. 2013; Arrouays et al. 2014). Most considered it as multiple 2D soil-mapping operations at a set of predefined depth intervals. These 2D mapping results are represented as depth averages (for concentrations) or sums (for stocks). These averages can be reconstructed into a full 3D soil property map. Although multiple 2D mapping is simple to implement, it is a pseudo 3D mapping approach and has two drawbacks (Liu et al. 2015). One is that soil variation pattern in the vertical dimension is neglected when performing separate horizontal soil predictions for each depth interval. The other is that depth function fitting is often applied twice in the mapping process. Any errors in the fitting are thus repeated and may be magnified. In addition, most 3D soil-mapping studies only focus on soil organic carbon, mainly because the profile distribution of this property is relatively simple and thus can be easily fitted by an exponential decay function. But, other soil properties such as soil texture and bulk density, to a big extent, have been ignored by the 3D soil-mapping studies mainly due to their complex distribution patterns with depth. Thus, it is necessary to study how to generate accurate 3D maps of these demanded soil properties in the next years.

1.5.2 Soil Mapping in Areas with Intensive Human Activities

Human activities are an important soil-forming factor, which exhibit both deterministic patterns (e.g., land-use patterns) and highly randomness (e.g., agricultural practices such as irrigation and fertilization). There are two types of areas with intensive human activities. One is the urban areas experiencing intensive urbanization, and the other is the cultivated areas experiencing intensive land uses. Urban soils present a diversity of specific processes and features, such as soil pollution and compaction, zoning, fertilization, sewage release, and combustion. These processes may result in high patchiness and short-distance heterogeneity. Very high short-distance soil variability within such areas and long distances between settlements limit the use of traditional spatial interpolation methods. Similarly, agriculture soils also have high spatial heterogeneity because of irrigation and fertilization and specific practices. Thus, the digital soil mapping in these two types of areas is challenging. In both, much attention is needed for anthropogenic soil-forming factors. Vasenev et al. (2013, 2014) explored the soil organic carbon mapping in a highly urbanized area. In addition to traditional factors, urban-specific factors, including size and history of the settlements and functional zoning, were used as auxiliary information for mapping soil organic carbon stocks.

1.5.3 Multi-Source Data Integration for Soil Mapping

Soil data used for digital soil mapping can be collected from multiple sources: legacy soil data from conventional soil survey and new soil sampling data from recent soil survey projects. As mentioned above, data harmonization is needed before they are used for soil mapping. It includes the harmonization within a single soil data source and that between multiple sources. Both are challenging tasks. The soil-type cross-references from one soil classification system to another can only be performed at a coarse level (e.g., soil great group). It is usually difficult to convert clay, silt, or sand content from one soil texture classification standard to another. The conversion between different laboratory analysis methods is always empirical and dependent on the soil regions or types. In particular for the soil properties that are not steady over time (e.g., one or more decades), such as soil organic carbon and pH value, how to integrate legacy soil data with new soil sampling data for digital soil mapping remains a challenge. Sun et al. (2015) compared the changes of digital maps of soil organic matter generated from three sets of soil sampling data from three soil survey projects conducted at different periods. The proximal soil sensing and digital soil morphometrics are also important soil data sources which can provide a large amount of "soft" soil data for soil mapping. It is necessary to incorporate these data into existing soil sampling data for high-resolution digital soil mapping. But much work is still needed to be done. In addition to the data collected by specialists in soil science, Rossiter et al. (2015) argued that the citizen (non-specialists) can also assist digital soil mapping by providing soil samples or landscape knowledge. They proposed digital soil-mapping and citizen-science initiatives. The "citizen" can be farmers, land managers, civil engineers, gardeners, and participants in outdoor activities. They pointed out that a key issue for the citizen science is how to integrate observations from citizens and those from the professionals.

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