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REVIEW

Recent progress and future prospect of digital soil mapping: A review

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Abstract

To deal with the global and regional issues including food security, climate change, land degradation, biodiversity loss, water resource management, and ecosystem health, detailed accurate spatial soil information is urgently needed. This drives the worldwide development of digital soil mapping. In recent years, significant progresses have been made in different aspects of digital soil mapping. The main purpose of this paper is to provide a review for the major progresses of digital soil mapping in the last decade. First, we briefly described the rise of digital soil mapping and outlined important milestones and their influence, and main paradigms in digital soil mapping. Then, we reviewed the progresses in legacy soil data, environmental covariates, soil sampling, predictive models and the applications of digital soil mapping products. Finally, we summarized the main trends and future prospect as revealed by studies up to now. We concluded that although the digital soil mapping is now moving towards mature to meet various demands of soil information, challenges including new theories, methodologies and applications of digital soil mapping, especially for highly heterogeneous and human-affected environments, still exist and need to be addressed in the future.

Keywords: digital soil mapping, soil-landscape model, predictive models, soil functions, spatial variation

1. Introduction

Humankind is facing tremendous challenges including food security, climate change, land degradation, biodiversity loss, water resource shortage and ecosystem sustainability (FAO and ITPS 2015). These global and regional issues are closely related to soil functions that linking with biomass production, environmental buffering, water purification and climate mitigation (McBratney *et al*. 2014). To address the above-mentioned issues, spatially accurate soil information is urgently needed.

Unfortunately, the existing soil maps, produced by conventional soil survey and mapping techniques, are often coarse in scale and lack details, not to say inaccurate in spatial boundaries and attribute data (McBratney *et al.* 2003; Zhang *et al.* 2004; Arrouays *et al.* 2014). These maps also can not reflect current status of soil conditions, and are incompatible to grid-based geospatial data in many land surface process models and applications. The main reason for this gap is that conventional soil survey is very laborious, time-consuming, and expensive (Bouma 1989; Grunwald *et al.* 2011). The advancement of computation power and geo-information technology has created a great potential for improvement in soil mapping techniques. In

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this background, digital soil mapping (DSM), also termed predictive soil mapping, had emerged (Scull *et al.* 2003; Minasny and McBratney 2016; Pásztor *et al.* 2016). DSM can be defined as the creation and population of spatial soil information systems by numerical models inferring the spatial and temporal variations of soil types and soil properties from soil observation and knowledge from related environmental variables (Lagacherie and McBratney 2007).

Previous overviews of DSM were provided by McBratney *et al.* (2003), Scull *et al.* (2003), Zhang *et al.* (2004) and Grunwald (2006). Discussions of soil mapping applications at geographic settings and model resolutions were provided by Lagacherie *et al.* (2007) and Hartemink *et al.* (2008). In the last decade, major progresses have been made in different aspects of digital soil mapping. DSM is becoming more and more mature and operable than ever before. Therefore, the objective of this paper is to review the major progresses of DSM in the last decade. The rise of digital soil mapping, especially important events or milestones, the development of the paradigms of digital soil mapping, recent progresses in various aspects of the field are summarized and discussed. In the last section, we also attempt to look into the future of the DSM and provide opinions on its development directions.

2. The rise of digital soil mapping

In the 1990s, quantitative techniques for soil survey and mapping were developed based on an analysis of relationships between soil properties and soil formation factors (environmental variables). This can be seen as the beginning of digital soil mapping. A range of techniques were used in this stage: linear regression, generalised linear models, classification and regression trees, neural networks, fuzzy systems and geostatistics (McBratney *et al.* 2003). For example, Moore *et al.* (1993) used linear regression to model soil properties (soil organic matter content, pH, soil texture) and terrain attributes (slope, aspect, and topographic wetness index (TWI)). McKenzie and Austin (1993) used linear regression to model the relationships between soil properties (clay content, cation exchange capacity, pH, and bulk density) and landscape attributes (slope gradient, relief and slope position). The models explained most of variation of these soil properties. Gessler *et al.* (1995) modeled the relationship between the A-horizon thickness and terrain attributes and found that plan curvature and TWI could explain 63% spatial variation of A-horizon thickness.

There are three milestones for the development of digital soil mapping. The first milestone is the international workshop on digital soil mapping which was held in Montpellier, France, 2004. It provided an opportunity to put in common a wide range of skills and tools that have a role to play in DSM: soil surveying, soil information systems, expert systems, GIS, pedometric techniques, data mining techniques and remote sensing procedures. The second milestone is the setting up of the working group on digital soil mapping under International Union of Soil Science (IUSS) in 2005. This working group organized such global workshops regularly (every two years). Table 1 lists the host cities and themes of the workshops. The workshops, combined with the Pedometrics meetings which holds every two years since 1997, ensure that every year can have an opportunity to bring together soil mapping scientists to communicate the progresses of soil mapping researches. The third milestone is the official launch of the GlobalSoilMap.net Project at University of Columbia, USA in 2009. Eight nodes across the world were set up for the project. The establishment of the GlobalSoilMap.net Consortium (GSC 2015), putting together the major players in digital soil mapping in the world, has initiated a process that will deliver a new digital soil map of the world at fine resolution (Sanchez *et al.* 2009). This project aims to predict and map most of the ice-free land surface of the globe over the next decade at a grid resolution of 90 by 90 meters using state-of-the-art and emerging technologies.

3. Digital soil mapping paradigms

A paradigm is a set of concepts or thought patterns. The theory of soil forming factors first created by Dokuchaev (1967) in the late 19th century, and further elaborated by Jenny (1941), i.e., $S=f(cl, o, r, p, t, \ldots)$ is the most famous soil science paradigm. The equation suggests soil is the product of its forming factors, climate, organism, relief, parent materials and time and it would be possible to identify

Table 1 Global workshops on digital soil mapping organized by the International Union of Soil Sciences (IUSS) Working Group

No.	Year	Location	Theme
1	2004	Montpellier, France	Digital soil mapping: An introductory perspective
2	2006	Rio de Janeiro, Brazil	Digital soil mapping for regions and countries with sparse soil data infrastructures
3	2008	Logan, USA	Digital soil mapping: Bridging research, production, and environmental application
4	2010	Rome, Italy	From digital soil mapping to digital soil assessment: Identifying key gaps from fields to continents
5	2012	Sydney, Australia	Digital soil assessments and beyond
6	2014	Nanjing, China	Digital soil mapping across paradigms, scales, and boundaries
7	2016	Aarhus, Denmark	Digital soil maps for everyone