Special Section: Digital Soil Mapping

Ulrike Werban*
Harm Bartholomeus
Peter Dietrich
Gilles Grandjean
Steffen Zacharias

Digital Soil Mapping: Approaches to Integrate Sensing Techniques to the Prediction of Key Soil Properties

The guest editors summarize the special section, Digital Soil Mapping, beginning with a look at the challenges that are pushing advances in soil mapping, and then introducing the contributors' efforts at improving current approaches.

U. Werban, P. Dietrich, and S. Zacharias, UFZ Helmholtz Centre for Environmental Research, Dep. Monitoring and Exploration Technologies, Permoserstr. 15, D-04318 Leipzig, Germany; H. Bartholomeus, Centre for Geo-Information, Wageningen University, 6708 PB Wageningen, The Netherlands; G. Grandjean, BRGM– Risk Division, Av C. Guillemin, 4506 Orléans, France. *Corresponding author (ulrike.werban@ufz.de).

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Knowledge about soil properties and their variation in space and time is a key challenge for understanding processes in the vadose zone. As we consider more complex models, applied to larger geographical regions, the demand for information on key soil parameters and thus input variables becomes harder to meet. In particular, classical soil maps and soil sampling has limitations in resolution, and information might be subjective. In the face of the new challenges in the context of climate and global change and the increasing need of multidisciplinarity, a more sophisticated use of soil information beyond the "classical" soil information is needed. Predictive soil mapping (Scull et al., 2003) or digital soil function mapping (Ugbemuna and Reuter, 2013) are promising ways to enhance the information content of soil maps. The application of pedometrical approaches, e.g., digital soil mapping (DSM) as one focus of pedometrics, provides the potential to overcome these issues. Today, DSM is well established in soil science, providing tools for improving, advancing, and increasing a more objective collection and spatial analysis of soil data. A broad variety of tools helping to improve the quality of diagnoses, to refine their resolution by using correlations between soil properties, sensor data, and environmental covariates is available and intensively discussed in the soil science community (Adamchuk and Viscarra Rossel, 2010; McBratney et al., 2003; Behrens and Scholten, 2006). However, Carré et al. (2007) asked the DSM community to be much more aware of end-user requirements and coined the term *digital soil assessment* for the quantitative modeling of soil attributes for assessing soil threats and soil functions. In addition, Grunwald (2009) identified a need for more sophisticated technologies to measure soil properties. Finke (2012) indicated the potential of integration of sensors in making maps and providing model input. Concerning soil moisture, Vereecken et al. (2008) described the need to develop strategies that combine hydrogeophysical measurement techniques with remote sensing methods and, moreover, the development of novel upscaling methods for predicting effective moisture fluxes and disaggregation schemes.

All studies mentioned above point towards an added value when amalgamating interdisciplinary communication about making and using maps. In our understanding the integration of sensing technologies for mapping and monitoring of soil properties will benefit from process-oriented and model-based identification of the required parameters. For DSM approaches we favor not only the empirical analysis and transfer of parameters but also a more process-oriented approach, which is promising though challenging. Lin (2010) summarized the scientific requirement of iterative feedback loops between monitoring, modeling, and mapping as the "3M-approach." Seen in this way, the tight integration of monitoring, modeling, and digital soil mapping is a precondition to address the new challenges of science. Digital soil mapping can support the extrapolation of point-scale information to larger areas, can support the validation of model result, and can provide guidance for proper site selection and improvement of monitoring concepts. On the other hand, models provide tools to transfer soil information gained by DSM into functional information. In this respect, and by combining pedological expertise with modern soil mapping techniques, DSM could significantly support integrated, hydropedological studies (see *Vadose Zone Journal* Special Section: Frontiers of Hydropedology in Vadose Zone Research, with an introduction by Vogel et al., 2013).

Abbreviations: DSM, digital soil mapping; DWI, dual-waveband indice; EMI, electromagnetic induction; PLSR, partial least square regression; PTF, pedotransfer function.

Just recently, Minasny et al. (2013) stated that pedometrics research in the vadose zone comprises studies of the spatial and temporal dynamics of soil properties as a scientific challenge to increase our understanding of the processes at the Earth's surface. They summarized three main topics for pedometrics in the vadose zone: (i) characterization of variability and prediction of variation of soil; (ii) sampling, measurement, and inferences of soil properties and processes; and (iii) dynamic spatiotemporal modeling. They identified a demand to incorporate process based knowledge, which adds the pedological and physical significance to the statistical robustness of predictions.

Digital soil mapping is a way to bridge the gap in scales between ground-based soil monitoring activities, which are normally limited to the point or small scales and modeling activities that cover larger areas. As such, the next step would be to combine remotely sensed soil-related information with proximally sensed and traditionally measured soil property data at larger spatial scales. Mulder et al. (2011) concluded that future studies will therefore focus on the improved integration of proximal and remote sensing using scaling based approaches to make optimal use of all data sources available. Estimating vadose zone properties by remote sensing is one major focus in a recent *Vadose Zone Journal* special section (Mohanty, 2013). However, we cannot neglect that sensing results are often limited to qualitative information and geophysical sensing results are ambiguous. Therefore, reliable quantification of sensing information is still a major challenge.

In this special section "Digital Soil Mapping: Approaches to Integrate Sensing Techniques to the Prediction of Key Soil Properties," we present nine contributions on studies of proximal and remote sensing technologies applied for mapping and monitoring of the pedosphere and unsaturated vadose zone. The foci of these papers range across the integration of covariates measured by geophysical or remote sensing techniques for soil and soil function mapping as well as modeling, application of remote sensing techniques to overcome scaling issues, discussion about parameter transfer, and finally commercial aspects of digital maps based on sensing techniques.

Integration of Geophysical Sensor Data

Sauer et al. (2013) and Schirrmann et al. (2013) present studies on producing fast and high resolution digital soil maps using geophysical sensor data, and both identify limitations when transferring results from plot scale to larger areas.

Assessing soil water content on a slow-moving hillslope located in Austria is presented by Sauer et al. (2013). For this purpose, time lapse mapping of bulk electrical conductivity using a geophysical electromagnetic induction (EMI) system, which is operated at low induction numbers. In addition, acquisitions of soil samples for gravimetric water content analysis are performed. Sample analysis reveals that the upper material is a spatially highly variable mixture of predominately sandy, silty, clayey, and organic materials. Classical approaches of mapping soil moisture on the basis of stationary mapping of electrical conductivity variations are not successful, due to this heterogeneity. Also, the time-lapse approach does not allow ruling out some of the ambiguity inherent to the quantitative linkage of bulk electrical conductivity to soil water content, except in some places. The relationship between the mean electrical conductivity averaged over a full vegetation period and an already available ecological moisture map produced by vegetation analysis is closely related to the relationship observed between gravimetric soil water content and electrical conductivity observed on sample collection, except for highly organic soils. These relationships are fully commented and discussed.

Schirmann et al. (2013) used a mobile near infrared soil scanner (1100–2300 nm) to map the properties of the topsoil of three fields "on-the-go." The spectral measurements were related to results from conventional laboratory analysis of soil P, K, Mg, soil organic matter, N, and pH. Maps and semivariograms of the principal component scores computed from the spectral information showed consistent spatial patterns, but the strength of the correlation between field spectra and soil chemical parameters was not consistent for the three fields. This made it difficult to develop cross-field calibration models. To improve relationships between soil spectra and soil attributes dual-waveband indices (DWIs) were used. Even though DWIs showed better model results when estimating soil properties within a single field, they did not improve cross field model calibration.

Parameter Transfer

Special attention is given to aspects of parameter transfer in the work of Wunderlich et al. (2013). Soil properties such as clay and water content were mapped using geophysical field surveys. Adequate geophysical pedotransfer functions are proposed, even if their choice remains an ambiguous question. To investigate the applicability of such functions to typical central European soils, laboratory measurements (conductivity, permittivity, water content, temperature) were performed on different samples. Relationship between permittivity and water content is explained by empirical, volumetric mixing, and effective media models. The volumetric mixing and the effective media models can fit the trend of the data points for sandy, but not for clayey soils. To improve these approaches a modified Hanai-Brueggeman model was studied. It yielded satisfying fits with respect to both data trends and RMS errors (0.3–1.5%). Validation processes showed that the temperature effects on electrical conductivity can be reliably corrected using existing empirical relationships.

Digital Soil Function Mapping and Parameters for Modeling Purposes

Krüger et al. (2013) combined results of geophysical sensor data for extraction of high resolution soil depth information to enhance accuracy of biomass modeling. They demonstrate a procedure to obtain detailed soil depth information on a small spatial scale using electromagnetic induction and ground penetrating radar. The study took place at a field site with highly heterogeneous soil depths where the available traditional soil survey does not provide adequate resolution. The resulting high resolution spatial data improved soil function modeling and reduced uncertainties of biomass results. Plant biomass production and soil water availability for plant growth was predicted. The presented findings could support management decisions for precision farming and environmental monitoring. The insights of their study could also be useful for the consideration of fertilization and of yield stabilization through adapted irrigation.

Ugbaje and Reuter (2013) present an approach to apply DSM procedures to predict available water capacity of soils in Nigeria using pedotransfer functions (PTFs). For the DSM prediction of soil texture, bulk density, pH, and organic carbon content in total 35 environmental covariates as potential predictors of soil properties including terrain attributes, land cover imagery, average annual temperature, and precipitation, Normalized Differenced Vegetation Index and Land Surface Temperature band were derived from digital elevation models, satellite imagery, and climate surfaces. The estimated soil properties are then used to predict water retention characteristics by means of the tested PTFs. In general, the presented approach provides promising results and the presented digital soil functional mapping is a promising way to map soil functions in extensive areas with a limited availability of qualitative soil information. However, field measurements are a mandatory requirement to validate and optimize the further use of the proposed methods. This is of particular importance for any functional soil mapping of larger areas, where the input data sets are of different quality.

Remote Sensing Techniques to Overcome Scaling Issues

Upscaling from field observations to more regional areas is not easy when no DSM model can be established. Some solutions nevertheless exist in the use of remote sensing data, provided that they are physically related to field measurements, that is, field spectroscopy and hyperspectral images. In that condition, some processing algorithms (correlations, statistics, regression) can be used to extrapolate field data to the scale of remote sensing ones. Of course, the performances of these techniques have to be evaluated for example by comparing the results with ground truth. In this special section, Martelet et al. (2013) predicted soil parameters at a regional scale, Lausch et al. (2013) presented a study on a grassland at a flood plain, and Casa et al. (2013) estimated soil properties at arable land.

Martelet et al. (2013) investigated, at a regional scale, whether various chemical, textural, or mineralogical parameters of a regolith could be related and quantitatively modeled vs. airborne gamma-spectrometric variables U, K, and Th. They predicted regolith parameter maps derived from the regression models that display consistent patterns with known geology geological sources of the gamma emission. Two main textural and mineral assemblages corresponding to weathering products and leached detrital materials were found to be the main gamma emitters. They used multiple linear regressions to establish statistical models relating around 20 regolith parameters where about 50% of the modeled regolith parameters were found to be predictable with an acceptable error. Furthermore, they added very simplified three-class geological information in the modeling process, which improved the resulting models. As a result they predicted regolith parameter maps derived from the regression models that display consistent patterns with known geology and show fairly good residuals during independent validation. In the geological context of their study, the gamma emitters appeared to be mostly weathering products and leached materials.

The main hypothesis of Lausch et al. (2013) is that biochemical and biophysical plant characteristics in combination with geophysical observations can be used to identify soil heterogeneity and provide additional information for identifying functional heterogeneity. Therefore, different imaging hyperspectral index types, single band reflectance, and spectral indices are related to the geophysical soil parameters using regression models. For EMI the elevation was the most predictive variable and integrating spectral indices into the elevation based model led to only small improvement in the predictive power for EMI. An improvement could be made to explain the variance of gamma-ray measurement signals by combining elevation and spectral information

The main objective of Casa et al. (2013) was to compare different methods allowing the joint exploitation of hyperspectral satellite data (vegetation and bare soil image) and geoelectrical data for estimating soil properties at the field scale. Therefore, they used a multiple jack-knifing approach to compare hybrid methods, allowing the fusion of remote sensing and geophysical data sources. Regression-kriging, partial least square regression (PLSR), and a combination of PLSR with geostatistics through kriging of the PLSR residuals were applied. For an arable field site their results show that high spectral resolution remote sensing data are less informative than geoelectrical data. In particular, the poor results obtained when using the vegetation image clearly indicated the difficulty of using crop vigor to infer soil properties. Bare soil image data are more useful as covariates; however, the authors stated that their value seems inferior to the geophysical data accessing deeper soil layers since image data are influenced only by the very surface of the soil.

Economic Value of Maps for End-Users

Diafas et al. (2013) estimated the economic value of soil information generated by a host of new proximal and in situ geophysical methods for the assessment of the following soil properties: carbon content, water content, clay content, bulk density, and soil depth. Therefore, they designed and applied a choice experiment as a technique in valuing soil information. Spatial resolution and map interpretation were also included as attributes, in addition to the soil properties. The survey reveals potential end-users and for what purpose they would want to use the offered maps. The authors were able to estimate the end-users' willingness to pay for individual features of the maps. One result is a particularly strong preference for maps of high resolution and accuracy that offer map interpretation in addition to a number of soil properties.

Summary

In summary, the papers published in this special section provide an overview about recent developments in the field of DSM that depict possible directions for better integration of sensing technologies in the prediction of soil parameters. Findings show progress and potential for applying sensing techniques. Readers of this special issue will find many aspects towards a process oriented and model based identification of required parameters resulting in digital soil maps relevant for research of the vadose zone.

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