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Hyper-scale digital soil mapping and soil formation analysis

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ABSTRACT

Landscape characteristics show local, regional and supra-regional components. As a result pedogenesis and the spatial distribution of soil properties are both influenced by features emerging at multiple scales. To account for this effect in a predictive model, descriptors of the geomorphic signature are required at multiple scales. In this study, we present a new hyper-scale terrain analysis approach, referred to as Contextual Statistical Mapping (ConStat), which is based on statistical neighborhood measures derived for growing sparse circular neighborhoods. The statistical measures tested comprise basic descriptors such as the minimum, maximum, mean, standard deviation, and skewness, as well as statistical terrain attributes and directional components. We propose a data mining framework to determine the relevant statistical measures at the relevant scales to analyze and interpret the influence of these statistical measures and to map the geomorphic structures influencing soil formation and the regions where a statistical measure shows influence. We introduce ConStat on two landscape-scale DSM examples with different soil genesis regimes where the ConStat terrain features serve as proxies for multi-scale variations of climate and parent material conditions. The results show that ConStat provides high predictive power. The cross-validated R^2 values range from 0.63 for predicting topsoil clay content in the Piracicaba area (Brazil) to 0.68 for topsoil silt content in the Rhine-Hesse area (Germany). The results obtained from data mining analysis allow for interpretations beyond conventional concepts and approaches to explain soil formation. As such it overcomes the trade-off between accuracy and interpretability of soil property predictions.

1. Introduction

1.1. Landscape characteristics and digital soil mapping

Due to the economic and ecological pressure to estimate and handle the impacts of global climate change, population growth, food security, and bio energy, the demand for fine-resolution soil property data for large areas is strong and growing (Banwart, 2011; Hartemink, 2008). Hence, new and powerful approaches are needed to regionalize soil information as accurately as possible. This comprises the generation of new covariates covering all relevant landscape characteristics to describe soil formation (e.g., Behrens et al., 2010a; McBratney et al., 2003). Such new environmental covariates are needed because, in pedology, soilscapes are characterized by spatial and taxonomic relations between soils, as well as by the relation between landform and landscape characteristics and the soils (Gerrard, 1981; Hole, 1978). These landscape characteristics, as driving forces for soil formation, show local, regional and supra-regional components. As a result of these different components the soil forming factors influence pedogenesis at different scales. Therefore, the spatial distribution of soil properties can also vary at different scales and in different directions (Kerry and Oliver, 2011), a fact, which is not accounted for in traditional qualitative and quantitative state factor concepts so far but often described as relevant in pedological and pedometrical studies (e.g., Behrens et al., 2010a,b; Gerrard, 1981; Hole, 1978; Jenny, 1941, 1961; Kerry and Oliver, 2011; McBratney et al., 2003).

In most cases complex associations between soils and landscapes can only be described approximately because important data on landscape characteristics are too scarce and incomplete to provide accurate predictions of soils and their properties and because appropriate methods that allow for integrating over multiple scales are largely missing (Behrens et al., 2010a,b; Lagacherie, 2008; MacMillan, 2004). Such multi- or hyper-scale approaches of landscape description are rarely documented but can be regarded as the missing counterpart to the current data explosion we are facing due to new hyper-spectral remote sensing data (e.g. Hyperion) as well as traditional map sources (geology, terrain attributes, etc.) which are currently becoming digitally available for each point of a landscape.

What is required are operational methods that provide measures of the entire physical landscape. Pike (1988) calls these the 'geomorphic signature'. Terrain analysis generally provides a subset of the geomorphic signature — the 'geometric signature' (Pike, 1988). Pike (1988)

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also notes that a surveyor integrates a vast set of terrain features at different scales. However, local terrain attributes like slope are calculated on the basis of small neighborhoods. Regional terrain attributes, such as contributing area, comprise larger irregular surface areas. Hence, standard terrain analysis only covers the point and the catena scale and can thus primarily be used to describe soil variations caused by gravitational processes on a hillslope.

Terrain attributes can also be used as proxies for other environmental covariates, i.e., characterizing landforms by analysis of DEMs should reveal much about the topographic expression of geomorphic process (Pike, 1988). An obvious example is when slope and aspect are used as indicators for solar insolation (e.g., Jenny, 1941). Such proxy-phenomena might however also occur on larger scales where the original drivers are unknown or fine-resolution datasets about these drivers are not available and thus might allow for revealing (parts of) the geomorphic signature instead of the geometric signature only.

Using terrain as a proxy becomes even more complex when the influence of an unknown covariate is directional or should be related to specific geomorphic structures in terms of interpretation. Thus, common terrain analysis is limited in explanatory power when larger geomorphic arrangements at the regional and supra-regional scale influence the matter and energy fluxes resulting in a specific soil property condition at a specific point in a landscape. Such influences might occur due to modulations of other environmental covariates such as wind direction and speed, precipitation pattern, as well as shadowing effects. Additionally, differences of surface shape or roughness can be an indicator for changing parent material conditions.

One approach to solve such problems is to use a combination of local, regional and supra-regional geomorphic descriptions derived from a DEM as proxy information for the missing data on environmental conditions, since the environmental conditions during soil formation were influenced by the geomorphic settings, assuming the present land surface is relatively similar to the surface under which current soils developed. In the literature, few approaches are described to account for the influence of multiple scales in terrain analysis — all demonstrating that incorporating spatial context improves prediction accuracy (e.g., Behrens et al., 2010a; Gallant and Dowling, 2003; Smith et al., 2006). However, most approaches are limited in terms of the number of scales and/or the maximum scale, in terms of computational efficiency and/or are restricted to a limited subset of terrain attributes. To overcome these limitations and to efficiently integrate the local, regional and supra-regional landscape components Behrens et al. (2010b) introduced a digital terrain analysis framework developed for digital soil mapping, referred to as ConMap (Contextual Mapping).

ConMap is based on the differences in elevation from each pixel in a circular star-shaped neighborhood to the center pixel. The differences are calculated for every pixel of the study area and are directly used as features (independent variables; predictors) without any further mathematical or statistical processing in the learning approach. The major advantage is the ability to capture contextual information of very remote regions by simply extending the neighborhood for which the elevation differences are calculated. With regard to the concept of spatial hierarchy of land units for soil and land resource surveys as introduced by Gallant et al. (2008), ConMap allows integration of all levels of hierarchy – from the site to the broad physiography – in one approach, permitting accounting for interactions of environmental covariates across multiple scales and thus, in some cases, for much better prediction accuracies (Behrens et al., 2010b).

Even though the ConMap approach shows a high potential for DSM it also has some restrictions. The most notable reservation concerning the application of ConMap is that the DSM results cannot be easy interpreted in a common pedological sense. This is due to the fact that terrain attributes such as slope, aspect or contributing area are not used within the ConMap approach but only basic analytical indicators (i.e., elevation differences to the center pixel) all comprising a directional component.

In summary, it can be stated that existing approaches providing multi- or hyper-scale data for soil mapping have proven that prediction accuracy increases when including multiple scales. Hence, integrating across multiple scales must be regarded as an important tool for mapping soils as well as for understanding soil formation. However, the approaches described so far in literature are either restricted to a subset of terrain attributes, to a very restricted range of scales, are computationally too demanding and/or cannot be interpreted pedologically (cf. Behrens et al., 2010a,b). Hence, a new hyper-scale terrain analysis approach and a new theory and concept for interpretation, aiming to contextualize the state factor theory and the *scorpan* paradigm (McBratney et al., 2003) are required and, in particular, the space (n) component of scorpan.

1.2. Landscape characteristics and soil formation analysis

Due to the fact that the integration of multiple scales in a prediction approach for one specific scale or resolution is a new emerging field in pedometrical research (Behrens et al., 2005, 2010a,b; Grinand et al., 2008; Hengl et al., 2011; Mendonça-Santos et al., 2007; Smith et al., 2006; Zhu et al., 2008), concepts for interpreting multi- or hyper-scale landscape characteristics in terms of soil formation are largely missing. This is due to the fact, that regional and supra-regional morphometric landscape characteristics – opposed to common attributes (e.g., Böhner et al., 2002; Friedrich, 1996; Jenny, 1941; Moore et al., 1993) – have not been discussed widely in the pedological and pedometrics communities so far. In contrast to analyzing a classical terrain attribute like slope, which can easily be interpreted as an indicator for gravitational downslope movement of soil material, the analysis of regional and supra-regional landscape characteristics is not straightforward because their character is not as universal. Additionally, each landscape has a different geomorphic signature and shows specific interactions between morphometric, geologic and climate conditions — over time. Hence, if only information on morphometry is available, analysis becomes complex. This however is the typical case.

Soil formation analysis – taking regional and supra-regional landscape characteristics into account – therefore requires various new concepts of analyzing and describing landscapes. As part of a new concept it would be important to derive knowledge about:

(i) the strength of the influence which a specific regional or supra-regional morphometric landscape characteristic has on the spatial soil property distribution,
(ii) the direction/behavior of the influence a specific regional or supra-regional morphometric landscape characteristic has on the spatial distribution of soil properties,
(iii) the driving geomorphic settings and systems, and
(iv) the local strength of influence of the regional and supra-regional morphometric landscape characteristics on soil formation.

If such key pieces of information can be derived, comprehensive interpretation of soil formation in complex landscapes seems possible.

A key issue in interpreting soil formation is the explanatory power of the predictors used. Multiple linear regression models with a small set of features such as slope, aspect, curvature, local elevation or the compound topographic index are easy to interpret in terms of soil formation (e.g., Böhner and Selige, 2006). However, most natural phenomena are of high complexity and often show a high degree of feature interaction. Hence, classical approaches often return relatively low validation accuracies. In contrast the results obtained with approaches such as ConMap, especially in combination with non-linear regression or supervised classification approaches, might return much better prediction results (Behrens et al., 2010a,b).

The explanatory power of a feature itself seems to be a function of its level of aggregation. The features, which are most easy to interpret, originate from common digital terrain analysis. In contrast, the most analytical, non-aggregated and thus hardest to interpret features are the