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Multitemporal soil pattern analysis with multispectral remote sensing data at the field-scale

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ABSTRACT

This research proposes a new model for the generation of basic soil information maps for precision agriculture based on multitemporal remote sensing data analysis and GIS spatial data modelling. It demonstrates (i) the potential of multitemporal soil pattern analysis (ii) to generate functional soil maps at field scale based on soil reflectance patterns and related soil properties and (iii) how to improve these soil maps based on the identification of static homogenous soil patterns by excluding temporal influences from the developed prediction model. Principal components and per-pixel analyses are used for the separation of static soil pattern from temporal reflectance pattern, influenced by (vital and senescent) vegetation and land management practices. The potential of the proposed algorithm is investigated using multitemporal multispectral RapidEye satellite imagery at a demonstration field “Borrentin” field in Northeast Germany.

1. Introduction

Soil maps provide basic knowledge regarding soil–landform interactions and soil variability across diverse landscapes (Zhu et al., 2013). Qualitative and quantitative soil data at different scales (landscape- or field-scale) are increasingly desired for (1) general policy-making, land resource management and environmental monitoring and (2) more precise applications in precision agriculture, hydrological modelling and soil landscape studies (Franzen et al., 2002; Lin et al., 2005a,b; Robert, 1993).

The concept of precision agriculture is based on the presence of temporal and spatial within-field variability of soil and crop characteristics (Zhang et al., 2002). Precision agriculture responds to this variability with fine-scale information-based optimization of farm inputs (e.g., fertiliser, herbicides, and seeds) to increase farm profitability, crop productivity, environmental quality and sustainability (Ge et al., 2011; Mulla, 2013). The nucleus of site-specific management (SSM), a common precision agriculture practice, is the identification of (crop) management zones as “relatively homogenous sub-units of farm fields that can each be managed with a different, but uniform, customised management practice” (Mulla, 2013). Management zones usually reflect within-field variability at scales finer than soil mapping units in the form of soil pattern or vegetation pattern. Addressing site-specific variability requires more specific information regarding the soil properties (i.e., mapped on functional soil maps) than can be offered by traditional soil maps based on conceptual generalisation-models of remotely sensed data, direct field survey, and special knowledge of soil, terrain, geology, vegetation and human factors (Zhu et al., 2013).

In recent years, numerous quantitative soil mapping models and approaches for the determination of soil properties at the field-scale based on DEM, proximal and/or remote sensing data have been developed. Spatial and geostatistical techniques, such as inverse distance calculations, various kriging-procedures, fuzzy clustering algorithms (Birrell et al., 1996; Gotway et al., 1996; Guo et al., 2013; Liu et al., 2008; López-Granados et al., 2005; Sumfleth and Duttmann, 2008; Triantafilis et al., 2013; Yan et al., 2007; Zhu et al., 2013), can transfer punctual quantitative soil property data to fine-scale soil maps, depending on the sampling strategy and the accuracy of the extensive, time-consuming and costly field survey. Non-invasive proximal and remote sensors and their corresponding physical-based or empirical-based data analysis methods have been approved as potentially effective, rapid and cost efficient (Mulder et al., 2011) and provide continuous, direct or indirect data on physiochemical soil properties depending on spatial, temporal or spectral sensor resolution. Several studies have analysed the relationships between soil reflectance characteristics, such as soil colour and soil brightness/lightness, and soil properties (Hummel et al., 2001;

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Viscarra Rossel et al., 2006, 2009; Singh et al., 2004; Spielvogel et al., 2004).

Ge et al. (2011), Mulla (2013), Plant (2001), Panda et al. (2010) and Zhang et al. (2002) offer a research overview of proximal sensing systems (e.g., spectroscopy, soil electrical conductivity sensors, and NIR-sensors) and remote sensing systems (e.g., multi- and hyperspectral satellite sensors and LIDAR based DEMs), as well as their applications in agriculture and soil science, including crop yield, biomass, crop nutrients, water stress, infestations of weeds, insects and plant diseases, hail or wind damage and especially soil properties (e.g., organic matter, moisture, texture, pH, nitrogen, salinity, and cation exchange capacity).

Although quantitative information regarding soil properties could not be measured directly using qualitative multispectral data methods (e.g., colour composites, band ratios, indices, and transformations), there are several advantages to the use of multispectral (low-spectral-resolution) data for SSM applications: (1) very high return frequency, (2) spatial resolution, (3) existing data archives, (4) relatively low costs and (5) accessibility. The cause of high-temporal and high-spatial resolution multispectral imagery and time-series are suited for information extraction of qualitative determinations, delineation of management zones, deriving soil patterns and determining and mapping soil surface units (Ge et al., 2011; Mulder et al., 2011).

Sommer et al. (2003) remarked that in addition to technical and methodical progress, a deeper understanding of temporal–spatial variability and soil pattern properties as well as the underlying development processes is still highly demanded, especially for choosing best-SSM practices. McBratney et al. (2000, 2003) reviewed various hybrid approaches of quantitative soil pattern analysis.

For precision agriculture application in Germany, Lamp et al. (2001, 2002) presented the concept of "Digitale Hofbodenkarte" as a data fusion model based on field surveys, existing soil maps (e.g. Bodenschätzung 1:10.000), proximal sensors (EM38-sensor, NIR-sensor) and products of remote sensing (e.g., soil, phenology, yield maps). Because ECa is sensitive to numerous soil properties, such as texture (i.e., clay content), mineralogy, soil moisture and salinity (Corwin and Lesch, 2005), its use may be problematic in hilly to undulating young morainic soil landscapes composed of closely linked wet, boggy depressions and kettle holes with loamy, clayey peaks and plateaus, such as in north-eastern Germany (Lamp et al., 2004).

We present a model for functional soil mapping at the field-scale for precision farming based on multitemporal remote sensing data analysis and GIS spatial data modelling. The objectives are (i) to demonstrate the potential of multitemporal soil pattern analysis in comparison with monotemporal analysis, (ii) to generate functional soil maps based on identified soil reflectance patterns and related soil properties, and (iii) to improve these soil maps based on the detected static homogenous soil pattern. For data mining purposes, NDVI-thresholds and phenological data were used to select the most suitable RapidEye datasets out of 40. Because of the high spatial and temporal resolution of the multispectral imagery, the temporal–spatial static soil pattern could be derived using image-processing methods, such as standardised principal components analysis and per-pixel-algorithms. This allowed the production of a highly significant functional soil map with respect to organic matter for the field outside of Borrentin in Northeast Germany.

2. Materials and methods

2.1. Study area

The multitemporal soil pattern approach was tested on a 131-ha agrarian field (53°48′9″N, 12°58′13″E) directly south of the village of Borrentin and 12 km south of Demmin in the north-eastern lowlands of Germany. The "Borrentin" field is located in the intensively used agricultural state Mecklenburg-Western Pomerania, consisting of 80.3% farmland, 19.5% grassland/pastureland and 0.2% other agrarian land use. In 2012, the main crops were cereal crops (55.5%), feed crops (19.3%), oleaginous fruits (18.6%), root crops (3.6%), legume crops (0.4%) and others (2.6%) (Statistisches Landesamt Mecklenburg-Vorpommern, 2013).

Due to its geomorphological features, including (sandy-) loamy morainic parent material of the late Pleistocene, kettle holes and slightly undulated relief, the study site is characteristic of the young morainic soil-landscape of northern Germany (Bundesanstalt für Geowissenschaften und Rohstoffe, 2006). Stagnosols, Luvisols and their transitional types evolved from unconsolidated glacial till and colluvial soils from eroded loamy material or deposits over former bogs (Zentrales Geologisches Institut, 1942; Bundesanstalt für Geowissenschaften und Rohstoffe, 2006). The elevation ranges between 39.3 m and 52.1 m above sea level (mean: 42.4 m; std. dev.: 2.4 m), and slope angle between 0° and 7° (mean: 1.1°, std. dev.: 1.1) (Bundesamt für Kartographie und Geodäsie, 2014). At the field-scale, the "Borrentin" field has a low depression from southwest to northeast, with a high concentration of kettle holes and a more textured south-easterly adjacent area with relatively steep slopes and a few kettle holes concentrated in gullies (Fig. 1) (Bundesamt für Kartographie und Geodäsie, 2014).

Hydrologically, the Borrentin field drains subterraneously via a natural slope gradient from southwest to northeast, crossing the depression towards the creek "Galgenbach", which flows into the River Peene 3 km northeast of the 32-km^2 Kummerower Lake (Bundesamt für Kartographie und Geodäsie, 2012). The present climate is characterized by a long-term (1981–2010) mean temperature of 8.7 °C and mean precipitation of 584 mm/yr, measured at the Teterow weather station, 26 km west of Borrentin (DWD, 2014a,b).

In general, the study area is located at the test site of DEMMIN® (Durable Environmental Multidisciplinary Monitoring Information Network; upper left corner: 54°2′N, 12°52′E, lower right corner: 53°45′N, 13°27′E), which was installed in 1999 by the German Aerospace Centre (DLR) as a calibration and validation test site for national and international remote sensing missions. Since the installation of the TERENO north-eastern German Lowland Observatory (TERENO-NE) in 2011, managed by the German Research Centre for Geosciences Potsdam (GFZ), both institutions have cooperated in the region of Demmin. The primary objective of TERENO is long term monitoring (>15 years) and analysis of environmental change. Further specific goals of the TERENO remote sensing research group at GFZ are (1) supplying environmental data for algorithm development in remote sensing and environmental modelling, with a focus on soil moisture and evapotranspiration, and (2) practical tests of remote sensing data integration in agricultural land management practices.

2.2. Baseline data

For model generation and validation as well as data interpretation, comprehensive soil sampling and analysis were conducted. Table 1 shows all input data and their specific characteristics.

2.2.1. Remote sensing data

To analyse the complexity of the soil and vegetation reflectance patterns, a multispectral, state-of-the-art sensor with high spatial and temporal resolution was needed. Due to its 5.5 days return frequency (at nadir), 6.5 m spatial resolution and the accessibility of the existing data archives, the RapidEye satellite system was