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Soil organic carbon and particle sizes mapping using vis–NIR, EC and temperature mobile sensor platform

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ABSTRACT

Soil organic carbon (SOC) is an important parameter in the climate change mitigation strategies and it is crucial for the function of ecosystems and agriculture. Particle size fractions affect strongly the physical and chemical properties of soil and thus also SOC. Conventional analyses of SOC and particle sizes are costly limiting the detailed characterization of soil spatial variability and fine resolution mapping. Mobile sensors provide an alternative approach to soil analysis. They offer densely spaced georeferenced data in a cost-effective manner. In this study, two agricultural fields (Voulund1 and Voulund2) in Denmark were mapped with the Veris mobile sensor platform (MSP). MSP collected simultaneously visible near infrared spectra (vis–NIR; 350–2200 nm), electrical conductivity (EC: shallow; 0–30 cm, deep; 0–90 cm), and temperature measurements. Fuzzy k-means clustering was applied to the obtained spectra to partition the fields and to select representative samples for calibration purposes. Calibration samples were analyzed for SOC and particle sizes (clay, silt and sand) using conventional wet chemistry analysis. The objectives of this study were to determine whether it is the single sensors or the fusion of sensor data that provides the best predictive ability of the soil properties in question. Using partial least square regression (PLS) excellent calibration results were generated for all soil properties with a ratio of performance to deviation (RPD) values above 2. The best predictive ability for SOC was obtained using a fusion of sensor data. The calibration models based on vis–NIR spectra and temperature resulted in RMSECV = 0.14% and R^2 = 0.94 in Voulund1. In Voulund2, the combination of EC, temperature and spectral data generated a SOC model with RMSECV = 0.17% and R^2 = 0.93. The highest predictive ability for clay was obtained using spectral data only in Voulund1 (RMSECV = 0.34% and R^2 = 0.76). Whereas in Voulund2, improved results were obtained after combining spectral and temperature data RMSECV = 0.20% and R^2 = 0.92. The best predictions of silt and sand were obtained when using spectral data only and resulted in RMSECV = 0.35%, R^2 = 0.82 and RMSECV = 0.85%, R^2 = 0.81, respectively, in Voulund1 and RMSECV = 0.31%, R^2 = 0.86 and RMSECV = 0.74%, R^2 = 0.92, respectively, in Voulund2.

The best models were used to predict soil properties from the field spectra collected by the MSP. Maps of predicted soil properties were generated using ordinary kriging. Results from this study indicate that robust calibration models can be developed on the basis of the MSP and that high resolution field maps of soil properties can be compiled in a cost-effective manner.

1. Introduction

1.1. Soil organic carbon and particle sizes

Soil organic carbon (SOC) is an important parameter in the climate change mitigation strategies as it plays a key role in the global carbon cycle. Moreover, it is crucial for the function of ecosystems and agriculture. It affects soil biological, physical and chemical functions, having therefore a major influence on soil structure, ability to store water and form complexes with metal ions and to supply nutrients. Soil particular size distribution is

Abbreviations: A, absorbance (log 1/*R*, where *R* is reflectance); EC, electrical conductivity; EC-sh, shallow electrical conductivity; EC-dp, deep electrical Conductivity; MIR, mid-infrared; MSP, multi-sensor platform; MSEP, mean standard error of prediction (in kriging validation); MSC, multiplicative scatter correction; NIR, near infrared; NIRS, near infrared spectroscopy; OM, organic matter; PCA, principal component analysis; PLS, partial least squares regression; RMSECV, root mean square error of cross-validation; RPD, the ratio of standard error of prediction to standard deviation; SD, standard deviation; SOC, soil organic carbon; SNV, standard normal variate; VIS, visible.

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another important property of soil having both environmental and agricultural implications. It has effects on water holding capacity, nutrient retention and supply, drainage and nutrient leaching. Consequently, reliable techniques for measuring and mapping SOC and particle sizes are necessary in precision agriculture for decision-support systems and in sustainable land management practices. However, the conventional wet chemistry analyses of soil are costly what limits detailed characterization of spatial variability of soil and the possibility to create precise and fine resolution soil maps. Thus, alternative approaches are required.

1.2. Visible near infrared spectroscopy and electrical conductivity

Visible Near infrared (vis–NIR) spectroscopy is a rapid and cost-effective method which has been used for soil analysis since mid-1990s. Vis–NIR spectra carry information on organic and inorganic soil materials, particle size, color and water content. The technique employs measurements of photon energy in the wavelength range 350-2500 nm. Especially mobile vis–NIRS sensors for soil characterization are attracting increasing attention due to their potential for applications to e.g. precision agriculture or soil mapping in general. The first application of on-the-go spectroscopic sensors was reported by Shonk et al. (1991) followed by a study including a prototype portable vis–NIRS sensor developed by Hummel et al. (1996). Since then, prediction of a range of soil constituents has been tested using a variety of mobile sensors. The predictive abilities of mobile sensors vary significantly and depend on the type of data fused, soil spatial variability, the concentrations, and the ranges of the soil attributes (Stenberg and Viscarra Rossel, 2010). Unlike the well-controlled conditions imposed for laboratory measurements, many less controllable factors can affect the quality of in-situ acquired data such as soil particle size and aggregation, soil roughness, soil temperature, sensor-to-soil distance, vibrations, dust, plant residues, pebbles and stones but also confounding factors such as variation in soil mineralogy, moisture, organic matter and their interactions (Morgan et al., 2009; Shonk et al., 1991).

Soil electrical conductivity (EC) is another sensing technique and one of the most frequently used measurements for characterizing soil variability at field scale for precision agriculture because of its reliability, accuracy, high number of measurements and ease of collecting the data (Corwin and Lesch, 2003). It can be measured using electromagnetic induction or galvanic contact resistivity methods. EC is a function of the soil physical and chemical properties, soil salinity, saturation, water content and bulk density (Corwin and Lesch, 2003). It has been therefore widely used for mapping the variation in soil particle sizes, salinity, water content, bulk density, organic matter (OM) and temperature (Broge et al., 2004; Corwin and Lesch, 2005; Domsch and Giebel, 2004; Kochanowski et al., 1988; Lück et al., 2009; Lund et al., 1999; Moral et al., 2010; Sudduth et al., 2005). Moreover, it was found that EC increases 1.9% per 1 °C (Corwin and Lesch, 2005). Thus, soil temperature can be correlated to EC and easily used as additional variable in soil mapping.

1.3. Sensor data fusion

Mobile sensors such as vis–NIRS or EC sensors, can generate the densely spaced geo-referenced data in a cost-effective manner necessary for capturing soil spatial variability and are therefore, powerful tools for landscape-scale soil characterization (Malley et al., 2004). However, when using only one sensor it is not possible to measure all soil properties. Viscarra Rossel et al. (2011) listed a number of benefits from using a multi-sensor compared to a single-sensor system. The most important benefits were: robust operational performance, increased confidence of the acquired data due to different sensors measuring the same soil, extended attributes coverage, and increased dimensionality of the measurement space. Thus, for improved estimation of soil properties a fusion of conceptually different mobile sensors has been investigated in some studies. Knadel et al. (2011) reported on mobile soil sensor data fusion using the Veris mobile sensor platform (MSP) consisting of an optical shank-based vis–NIR (visible-near infrared) sensor and EC measurements to map soil organic carbon (SOC) within a partly highly variable field in Denmark. Improved SOC calibrations were obtained by fusing EC with spectral data. They generated a detailed map of SOC based on a significantly lower number of calibration soil samples than needed for conventional mapping based on grid sampling. In another study, Schirrmann et al. (2011) used the Veris mobile platform with additional pH meter for mapping macronutrients at two fields in Northern Germany. However, poor predictive abilities of the generated partial least square (PLS) regression models were reported. Further they concluded that the fusion of sensor data improved only the pH mapping results.

1.4. Soil analysis and mapping in Denmark

The existing information on soil properties in Denmark was obtained in the mid 70s during the Danish Soil Classification (Madsen et al., 1992). Not only is this information outdated but the data has also insufficient spatial resolution (1:50,000) for management on a field scale. Hence, new soil data must be collected and reflect the current soil properties on specific field, and at a specific location in this field. Detailed information of such soil properties as SOC and particle sizes can help Danish farmers to gain a better insight on the quality of their soil and support decision making to achieve higher yields. Moreover it can be used in the environmental regulation of agricultural production and will to a great extent help Denmark to fulfill the responsibilities of the Kyoto protocol from 1997.

To supplement the time-consuming and costly conventional approach to soil survey in Denmark, a method for SOC and particle sizes mapping employing the use of vis–NIR, EC and temperature sensors was investigated. Considering the advantages of NIRS and EC sensing techniques in combination with a mobile sensor platform for soil surveying the objective of this study was to test the feasibility of using the Veris MSP for simultaneous mapping of SOC, clay, silt and sand contents of two agricultural fields in Western Denmark. In search of robust calibrations we tested EC, temperature, and vis–NIR spectral data individually, and different combinations of these predictors for each soil property and field separately. As a final result prediction maps of soil properties were generated using ordinary kriging interpolation.

2. Materials and methods

2.1. Study site

The study sites are located in Western Denmark within Voulund farm (800 ha) (Fig. 1) which is producing mainly pigs, feed crops and maize. The two investigated sites (Voulund1–13.7 ha and Voulund2–12.7 ha) represent homogenous agricultural fields adjacent to each other with Voulund1 located north of Voulund2. The fields were planted with winter barley. The climate in this region is temperate-maritime with an average precipitation of 781 mm/year and mean annual temperature of 7.5 °C (Danish Meteorological Institute, verified August 2011). The soil type is a Spodosol located on the glaciofluvial sandy outwash plains of the most recent European glaciations (Schelde et al., 2011).