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Mapping peat layer properties with multi-coil offset electromagnetic induction and laser scanning elevation data

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A B S T R A C T

Peatlands store large amounts of soil organic carbon (SOC). Depending on their present condition, they act as a source or sink of carbon dioxide. Therefore, peatlands are highly relevant for climate change investigations and there is considerable interest to assess spatial heterogeneity of peat soil properties in order to assess the total amount of stored carbon. However, reliable information about peat properties remains difficult to obtain at the field scale. A potential way to acquire this information is the indirect mapping of easily recordable physical variables that correlate with peat properties, such as the apparent electrical conductivity (EC_a). In this study, we aim to explore the potential of multi-coil offset electromagnetic induction (EMI) measurements to provide spatial estimates of SOC content, bulk density, and SOC stock for a highly variable and disturbed peatland relict (~35 ha) with a remaining peat layer thickness of less than 1 m. EMI measurements comprised six integral depths that varied from 0–0.25 to 0–1.80 m. In combination with ancillary laser-scanning elevation data, a multiple linear regression model was calibrated to reference data from 34 soil cores that were used to calculate integral properties of the upper 0.25, 0.5, and 1 m layer, as well as for the total peat layer. Leave-one-out cross-validation for the different depth ranges resulted in a root mean square error of prediction (RMSEP) between 1.36 and 5.16% for SOC content, between 0.108 and 0.183 g cm^{-3} for bulk density, and between 3.56 and 9.73 kg m^{-2} for SOC stocks, which corresponds to roughly 15%, 10%, and 20% of the total field variability, respectively. The selection of explanatory variables in the regression models showed that the EMI data were important for accurate model predictions, while the topography-based variables mainly acted as noise suppressors. The accuracy of the SOC content estimates roughly equalled the quality of SOC content predictions obtained in previous field applications of the visible-near infrared technique (vis-NIR). The spatial variation of the predicted peat layer properties showed similarities to the former land use distribution. Overall, it was concluded that EMI measurements offer a useful alternative to the established vis-NIR method for SOC content mapping in carbon-rich soils.

1. Introduction

Peatlands store large amounts of soil organic carbon (SOC). Whether a peatland still acts as a sink for carbon dioxide (CO_2) or has turned into a CO_2 source depends on its condition, i.e. its degree of disturbance due to changing environmental conditions or land use. In particular, decreasing water levels in peatland enhance decomposition by aerobic microbial activity, which makes the carbon stock in peatland highly vulnerable. Therefore, peatlands are of high relevance for future greenhouse gas emission and climate change predictions (Frolking et al., 2006; Drösler et al., 2008; Köchy et al., 2015). If decomposition of the aerated peat layer occurs, its physical and biogeochemical properties change, which often leads to a high spatial variability of peat properties in disturbed peatlands (Succow and Joosten, 2001; Holden, 2005).

There is considerable interest to assess spatial heterogeneity of peat soils and the amount of carbon stored in these ecosystems across various scales. For example, current efforts to mitigate greenhouse gas emissions from peatlands by rewetting formerly drained peatlands in the course of restoration projects benefit from spatial estimates of peat properties and remaining SOC stocks. Unfortunately, reliable information about peat properties at the field-scale remains difficult to obtain, since soil coring is laborious and only provides point information. A potential way to acquire more adequate field-scale information is provided by non-invasive mapping of easily recordable physical variables (proxies) that correlate with relevant soil properties, such as soil color, dielectric permittivity (ε), and bulk electrical conductivity (EC_b).

An established sensing method for soil color is the visible-near infrared technique (vis-NIR). It is based on the light absorbance of soil components in the vis-NIR range of the electromagnetic spectrum (Stoner and Baumgardner, 1981; Viscarra Rossel et al., 2006). In the past two decades, vis-NIR has been used for the assessment of several soil properties like nitrogen (Chang et al., 2001), potassium (Daniel et al., 2003),

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and clay content (Cozzolino and Moron, 2003). Various studies have also used vis-NIR for SOC content estimation and found that vis-NIR is a proper tool for in situ SOC content characterization (Walvoort and McBratney, 2001; Tian et al., 2013; Debaene et al., 2014). However, vis-NIR measurements using on-the-go sensors typically provide information at a single, and usually very shallow, measurement depth only. Acquiring information on deeper peat characteristics can only be achieved by soil probing, which impedes the mapping of large areas.

Geophysical methods like ground penetrating radar (GPR) and electromagnetic induction (EMI) are generally suitable to obtain information from deeper regions by non-invasively measuring ε and EC_b, respectively. Both variables depend on soil water content and porosity, and the EC_b is additionally influenced by the pore water electrical conductivity (σ_w) and the electrical conductivity along particle surfaces (surface conductivity). These dependencies are described by available petrophysical models (Archie, 1942; Waxman and Smits, 1968; Rhoades et al., 1976; Topp et al., 1980). GPR is a geophysical method that provides measurements of ε that can be used to estimate soil properties (Collins and Doolittle, 1987; Huisman et al., 2003; Neal, 2004). Several studies have shown the applicability of GPR in peatland since changes in ε of the different layers potentially allow the identification of peat thickness above a mineral basement (Slater and Revee, 2002; Kettridge et al., 2008; Proulx-McInnis et al., 2013; Comas et al., 2015).

EMI is a popular, non-invasive geophysical method to map EC_b of relatively large areas in comparably short times (e.g. Altdorff and Dietrich, 2012; Doolittle and Brevik, 2014). It provides integral apparent electrical conductivity (EC_a) values that constitute a non-linear average of EC_b over a specific depth range (McNeill, 1980). EMI has been used to characterize the spatial variation of soil texture (Corwin and Lesch, 2005), clay content (Weller et al., 2007), soil salinity (Rhoades, 1993), and soil water content (Robinson et al., 2009). Although well established, EMI has rarely been used to study peat layer properties. Slater and Revee (2002) supported their GPR study with EMI data of one depth integral (0–6 m). Recent advances in technology and interpretation make EMI even more attractive for characterization of peatland. Multi-coil offset EMI systems have become available that now allow the simultaneous recording of several integral depths (Delefortrie et al., 2014b; Doolittle and Brevik, 2014) and facilitate the accurate determination of EC_b for several layers using inversion (Monteiro Santos et al., 2011; von Hebel et al., 2014). In addition, readily available GPS technology now allows the rapid acquisition of georeferenced EC_a data with a high spatial resolution. Thus, multi-coil offset EMI systems offer the potential to resolve vertical and lateral heterogeneities (at a scale of <1 m) of peatland at the field scale and beyond (areas > 10 ha).

Most geophysical studies focused on intact peatlands with peat thicknesses of up to several meters. Disturbed and drained peatlands for which the peat properties strongly differ from the ones of natural peatlands due to degradation processes have rarely been investigated with geophysical methods (Walter et al., 2015). Due to the spatially often patchy land use history including peat cutting, the peat thickness and spatial pattern of such disturbed peatland typically shows a much higher lateral variability than intact peatlands (De Smedt et al., 2013). In addition, peat degradation is accompanied by changes of peat electrical properties, which may need to be considered in the interpretation of EMI survey results. For instance, the high specific surface area of peat soils is often associated with a high cation exchange capacity (CEC) (Bunt, 1988), which is expected to increase with progressing peat degradation (Puustjärvi, 1956). Since CEC is positively correlated with the amount of surface conductivity (de Lima and Niwas, 2000; Comas and Slater, 2004), EC_b is expected to increase with increasing peat degradation. Furthermore, Comas and Slater (2004) found that σ_w was positively correlated with CEC in peat, which is expected to further increase EC_b (Archie, 1942). Simultaneously, peat degradation leads to higher soil bulk density, lower saturated water contents, and modification of the water retention and hydraulic conductivity characteristics (Brevik and Fenton, 2004; Gnatowski et al., 2009; Dettmann et al., 2014; Islam et al., 2014), which all affect EC_b too. Walter et al. (2015) investigated various factors that influence EC_b in a comprehensive multi-site study and found that pore water electrical conductivity and CEC mainly controlled inter-site variability, whereas water content and CEC were most influential when a single site was considered. As water content and CEC are related to peat properties like bulk density, SOC content, and degree of decomposition, these results indicated that the mapping of horizontal and vertical peat variability may be possible with a site-specific calibration to EC_b (Walter et al., 2015). Nevertheless, the complexity of peatlands poses several challenges for mapping peat properties with EMI. Case studies are needed to investigate the capability of EMI to provide meaningful information about peat properties despite potentially complex peat internal layering with abrupt and gradual layer interfaces, sublayer anisotropy and dynamical pore water chemistry as well as the effect of various geological layers that can underlie a peatland.

In this study, we aim to explore the potential of multi-coil offset EMI measurements to quantify spatial variability of peat layer properties in a disturbed peatland relict that experienced drainage, peat cutting, and agricultural land use. Reference data from 34 cores and multiple linear regression (MLR) analysis is used to investigate whether EMI measurements of six integral depths between 0–0.25 and 0–1.80 m can be used to obtain information on the spatial variability of peat properties. Compared to previous geophysical studies in peatland, the SOC content and bulk density of the peat layer at our field site is spatially highly variable. Thus, knowing the spatial distribution of peat thickness is not sufficient to estimate SOC stock, which is the most relevant property for estimating potential climate change impacts. Given the spatial heterogeneity of peat properties at our field site, we decided to directly estimate SOC content, bulk density, and SOC stocks instead of peat thickness. Soil properties are known to correlate with topography-based variables like e.g. elevation, slope and curvature, and thus data from digital elevation models are often used as ancillary data in digital soil mapping (McBratney et al., 2003). Here, we want to evaluate the contribution of such data to the geophysical mapping of peat properties and included topographic information from laser scanning elevation data as ancillary variables in our MLR analysis.

2. Methods

2.1. Site description

The test site is a 35 ha part of the disturbed bog peat complex *Großes Moor* ('Great Peat Bog') in northern Germany (Gifhorn, N 52°34′54.22″, E 10°39′46.43″). The bog peat complex developed on glacial sand. During the 19th and 20th century, the bog was drained and used for peat cutting and intensive land use (Fig. 1). Due to this history, a peat layer of less than 1 m thickness remained from the originally up to six meters thick peat. From the peat cutting history, elongated peat shoulders and depressions remained. The elevation of the test site ranges from 58.01 to 60.05 m a.s.l. with a general trend of increasing elevation towards the north-east (Fig. 2).

In the period of arable land use, parts of the test site were plowed, which mixed peat with the underlying sand to various degrees. Currently, the test site is used as extensive grassland with a relatively shallow mean water table depth of about 10 to 40 cm below the soil surface. The vegetation varies from sedge (*Carex nigra*, *Carex leporina*) and grass (*Poa pratensis*, *Festuca ovina*, *Molinia caerulea*, *Eriophorum angustifolium*, *Juncus effusus*) to moss (*Sphagnum cuspidatum*, *Sphagnum fallax*) dominance as a function of spatial differences in water level. Sheep grazing occurs one to three times a year and the grass is mulched every autumn. Fertilizers are not applied (Leiber-Sauheitl et al., 2014). The spatial variation in greenhouse gas emissions at the test site was recently investigated by Leiber-Sauheitl et al. (2014).