Qualitative and quantitative mapping of biochar in a soil profile using hyperspectral imaging

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ABSTRACT

NIR (near infrared) hyperspectral reflectance imaging has been carried out with the aim of identifying biochar particles and mapping biochar concentrations in a soil monolith (12 cm × 12 cm × 30 cm), which was extracted from the top 30 cm of an agricultural field amended with biochar. Hyperspectral images were obtained directly on one vertical side of the soil monolith and also on ground soil samples extracted from the same side after scanning. Median spectra from the ground samples were used to calibrate a PLS regression model of the C content in the samples and this model was applied to predict the distribution of the biochar in the soil profile. Spectral angle mapper (SAM) was also applied as a comparative technique to predict the biochar distribution, using reference spectra from pure unground biochar. The analysis of the hyperspectral measurements was validated by conducting chemical analysis of the total C and ^{13}C signature on the ground samples extracted from the scanned side of the monolith. The results indicate that biochar can be qualitatively identified in soil profiles using hyperspectral NIR images. Quantifying the amount of biochar, however, is challenging on the pixel level due to the rough surface of the soil profile, non-homogenous distribution of the biochar and varying moisture conditions.

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1. Introduction

Soil organic carbon (SOC) dynamics are a central component of the terrestrial C cycle, and has a large influence on the Earth's climate (Davidson and Janssens, 2006). Measures to maintain and further increase C stocks in the world's soils are crucial for reaching the climate goal scenarios set by the International Panel On Climate Change (IPCC, Chapter 3, 2014). Biochar technology is one of the most promising methods for stabilizing biomass C in soils, with a maximum mitigation potential of 1.8 Pg CO_2–C equivalent per year (Woolf et al., 2010). Implementation of mitigation strategies based on increasing SOC stocks will require precise monitoring of indigenous SOC and added C forms, and forecasting of their long-term fate.

The conventional method for measuring SOC stocks is based on dry combustion analyses, where small quantities of finely ground soil samples are fully oxidized so that all present C can be detected and quantified as CO_2 (Nelson and Sommers, 1996). If the soil sample is suspected to contain carbonates, those must be removed before the dry combustion analysis is conducted (Nelson and Sommers, 1996). Although this method is precise, it suffers from several drawbacks and limitations. The method is time consuming, as samples need to be collected in the field, air dried, finely ground, potentially de-carbonated, precisely weighed and finally analyzed. This is actually a severe limitation of the method as SOC monitoring requires analysis of very many samples, due to the high spatial variability of SOC and the low signal to noise ratio of SOC changes relative to stocks. Clearly, methods requiring fewer steps would be greatly advantageous.

A second drawback of dry combustion as a monitoring method for soil C is that it provides only an average value over a given depth, which for agricultural soils is often the Ap horizon. Conducting routine assessment of C-depth distribution by the dry combustion method quickly becomes both time-consuming and expensive due to the many samples required. However, depth distribution is actually quite crucial for properly estimating SOC stocks. One reason is that changes in soil organic matter (SOM) concentrations are generally accompanied by changes in soil bulk

density, resulting in changes of SOC distribution with depth (Gifford and Roderick, 2003). To solve this problem, equivalent soil mass corrections need to be implemented (Ellert and Bettany, 1995). Such corrections require precise sampling depth considerations and assumptions about the uniformity of SOC concentrations throughout the soil layers (Barré et al., 2010). Knowledge of SOC depth distribution is even more crucial for evaluating the fate of applied biochar products in the upper soil. In our field experiments, we have observed that ploughed-in biochar tends to accumulate at the bottom of the plough layer, potentially creating a strong bias over small variation of sampling depth for dry combustion (unpublished data). Also, biochar products can be partially eluviated down the soil profile, notably in a colloid form (Zhang et al., 2010). These examples underscore the need for rapid methods for mapping the vertical distribution of indigenous SOC and added biochar along the depth of the soil profile.

Recently spectral and hyperspectral methods have been tested for rapid and cost-efficient determination of SOC concentrations on large numbers of samples. In these methods, SOC is measured by means of reflectance spectroscopy at visible (VIS, 400–700 nm) and near-infrared (NIR, 700–2500 nm) wavelengths, both in the laboratory (Sørensen and Dalsgaard, 2005; Xie et al., 2011) and in the field (Stevens et al., 2008; Morgan et al., 2009). In the laboratory, IR-based methods have proven time saving and cost efficient as compared to dry combustion analyses because the ground soil samples are directly, rapidly and non-destructively scanned on the IR spectrometer. The method is efficient and quite precise when calibration on a subset of dry combustion analyses is performed. Another application is airborne mapping of surface soil SOM concentrations. Airborne SOC mapping is limited by unstable illumination, vegetation cover and varying moisture conditions at the field scale, the latter having a substantial effect on IR signals (Nocita et al., 2013). More recently, Buddenbaum and Steffens (2011),Steffens and Buddenbaum (2013), and Steffens et al. (2014) have analysed the chemical and physical characteristics of soil cores using hyperspectral imaging. They showed that this technique can be used to evaluate at high resolution the spatial variability of SOM qualities (i.e., the SOM chemical nature) and other soil properties within small profiles. Hyperspectral imaging has the advantage of capturing both the spatial and spectral information of a sample at macro size levels. Relative to laboratory IR methods, hyperspectral soil C mapping of undisturbed soil cores has the advantage that the high-resolution depth distribution of C forms can rapidly be determined with reduced sample preparation time. The present study is specifically aimed at testing hyperspectral imaging as a tool to map the 2D biochar distribution in ploughed soil profiles.

2. Material and methods

2.1. Study site and soil sampling

Biochar produced from *Miscanthus giganteus* chaff (Fig. 1) was applied at 25 t of C per ha in the autumn of 2010 to the surface of a cropland and immediately incorporated in the topsoil by mouldboard ploughing at 30 cm. The biochar was produced in Germany by Pyreg GmbH in a continuous slow pyrolysis machine of light industrial scale (www.pyreg.de). The highest heating point was estimated to be between 500 and 750 °C. *Miscanthus* was selected as a feedstock for our experiments because it is a C4-photosynthesis plant and therefore displays a ^{13}C signature distinctive from that of SOM in temperate soils formed under C3-photosynthesis vegetation.

The field experiment was located on the Norwegian University of Life Sciences field station in Ås, Norway (59°39′51″N, 10°45′40″E). The soil is an Albeluvisol (IUSS Working Group

Fig. 1. Pieces of coarse miscantus biochar, as ploughed into the field. The particle size ranges from a few millimetres to one centimetre.

WRB, 2006) with a sandy clay loam texture free of carbonates. Mouldboard ploughing resulted in the biochar being distributed in concentrated diagonal seams in the Ap horizon in 2011. Further ploughing and seedbed preparation in 2012 and 2013 progressively resulted in a more even distribution throughout the Ap, although inhomogeneity persisted. Mapping of the evenness of biochar distribution after 4 years of soil tillage provided an ideal case study for the present research. In March 2014, a soil monolith 12 cm × 12 cm × 30 cm was extracted with a stainless steel box from the top 30 cm of a biochar amended field plot.

2.2. Imaging setup

Soil monolith scanning was conducted in a laboratory setup (Fig. 2) with a pushbroom-type hyperspectral camera (Specim,
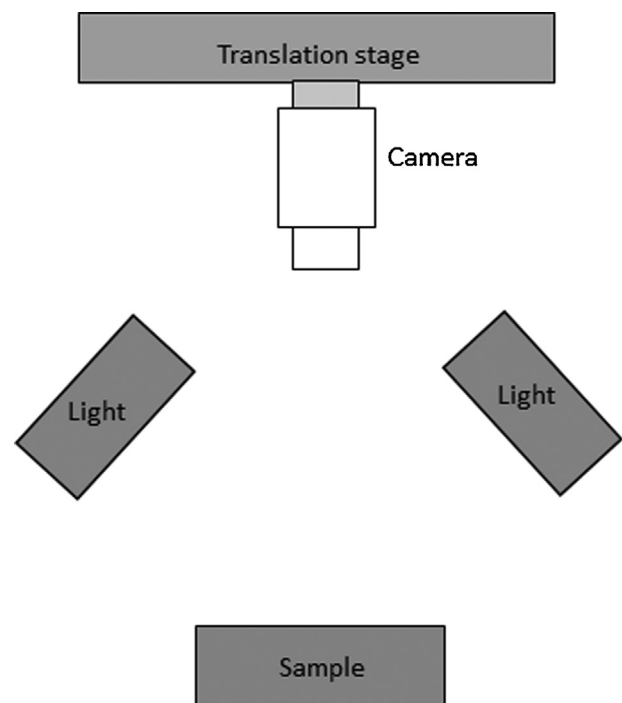

Fig. 2. The experimental setup.