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Soil organic carbon assessment by field and airborne spectrometry in bare croplands: accounting for soil surface roughness

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ABSTRACT

Visible, Near and Short Wave Infrared (VNSWIR) diffuse reflectance spectroscopy (350 nm to 2500 nm) has been proven to be an efficient tool to determine the Soil Organic Carbon (SOC) content. SOC assessment (SOCa) is usually done by using calibration samples and multivariate models. However one of the major constraints of this technique, when used in field conditions is the spatial variation in surface soil properties (soil water content, roughness, vegetation residue) which induces a spectral variability not directly related to SOC and hence reduces the SOCa accuracy. This study focuses on the impact of soil roughness on SOCa by outdoor VIS-NIR-SWIR spectroscopy and is based on the assumption that soil roughness effect can be approximated by its related shadowing effect.

A new method for identifying and correcting the effect of soil shadow on reflectance spectra measured with an Analytical Spectral Devices (ASD) spectroradiometer and an Airborne Hyperspectral Sensor (AHS-160) on freshly tilled fields in the Grand Duchy of Luxembourg was elaborated and tested. This method is based on the shooting of soil vertical photographs in the visible spectrum and the derivation of a shadow correction factor resulting from the comparison of "reflectance" of shadowed and illuminated soil areas.

Moreover, the study of laboratory ASD reflectance of shadowed soil samples showed that the influence of shadow on reflectance varies according to wavelength. Consequently a correction factor in the entire [350–2500 nm] spectral range was computed to translate this differential influence.

Our results showed that SOCa was improved by 27% for field spectral data and by 25% for airborne spectral data by correcting the effect of soil relative shadow. However, compared to simple mathematical treatment of the spectra (first derivative, etc.) able to remove variation in soil albedo due to roughness, the proposed method, leads only to slightly more accurate SOCa.

1. Introduction

The monitoring of soil attributes and their evolution over time as well as the development of pedological models rely on the availability of accurate and extensive soil data. The high spatial variability of soils arising from both local and global factors of soil formation requires generally collecting soil information from a very dense network of sites. Diffuse reflectance spectroscopic techniques, and in particular Visible, Near and Short Wave Infra Red (VNSWIR) spectroscopy (350 nm to 2500 nm), allows rapid sampling and instantaneous determination of many soil properties, at field and regional levels (in remote sensing mode). This technique can provide in a cost effective way the large quantity of spatial data required in soil monitoring or modelling studies like the monitoring of decline of soil organic matter in the topsoil.

Spectral libraries and multivariate modelling are often used to predict soil attributes of unknown samples. In the laboratory, such approach has proven to provide accurate determinations of SOC (Viscarra Rossel et al., 2006). When using the same approach, field spectroscopy and hyperspectral remote sensing, however, may fail to produce reliable and robust determinations due to uncontrolled measuring conditions and spatial variation in surface soil properties. According to Atzberger (2000), the main factors affecting the soil reflectance are soil water content, vegetation residues and surface roughness.

For the purpose of this study, field spectroscopic measurements were taken over bare and dry soils. Hence soil roughness remained the main disturbing factor and other influences have not been taken into consideration.

The effect of roughness on soil reflectance has been addressed in several studies. Arnfield (1975) showed that, for a relatively rough soil surface, soil albedo is generally lower than for a corresponding smooth surface due to self shadows. Atzberger (2000) simulated the influence

Abbreviations: VNSWIR, Visible, Near and Short Wave Infrared; SOCa, Soil Organic Carbon assessment; ASD, Analytical Spectral Devices; AHS, Airborne Hyperspectral Sensor; soil RS, soil Relative Shadow; SZA, Solar Zenith Angle.

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of soil roughness on reflectance by using the SOILSPEC model. He found that, when the soil becomes smoother, due to decreasing micro-shadow effects, soil reflectance increases throughout the visible range.

Geometrical models have been developed to simulate bidirectional reflectance of light from rough soil surface based on the assumption that reflection is strongly correlated with the area of shadowed soil as well as on illumination and viewing geometry. Even though these models have been validated (Cierniewski, 1987; Cierniewski and Verbrugghe, 1997) their application in field conditions is not trivial, since many input parameters have to be considered which are quite difficult to assess in practical cases.

Several geometrical models (Cierniewski and Verbrugghe, 1994; Cooper and Smith, 1985; Irons et al., 1992; Norman et al., 1985) predict soil reflectance based on the assumption that shadowing of soil aggregates or clods has a greater influence than the scattering properties of a soil (Cierniewski and Verbrugghe, 1997). This study is also based on this principle and therefore the influence of roughness on soil reflectance is estimated by assessing its shadowing effects. This approach has been recently validated by (García Moreno et al., 2008).

The purpose of this study is to propose a new method to identify and reduce the effect of soil Relative Shadow (RS, the percentage of shadowed soil of the studied surface) on the assessment of SOC content from VNSWIR hyperspectral (350–2500 nm) field and airborne spectroscopic data.

First a method to measure RS and to correct its impact on field reflectance, measured with an Analytical Spectral Devices (ASD) spectroradiometer and the Airborne Hyperspectral Sensor (AHS), is proposed. Secondly the impact of RS on reflectance and SOCa accuracy is studied under laboratory conditions. Then SOC content is predicted by using uncorrected and corrected field reflectance values to evaluate the improvement in SOCa accuracy achieved with this method. The proposed method is finally compared with well-known mathematical pre-processings that intend to enhance SOCa accuracy.

2. Data collection

2.1. Field data collection

2.1.1. Study area

The study area consisted of a north-south transect of ~7 km width and ~60 km length (NW corner: 50°03′N 6°03′E; SE corner: 49°33′N 6°12′E), crossing 4 of the 5 agro-geological regions of the Grand Duchy of Luxembourg.

The Grand Duchy of Luxembourg is characterised by a large variability of soils on a relatively small area (2586 km^2). The four agro-geological regions in the study area are:

- The North, called Ardennes or Oesling, is a relatively homogeneous area consisting of plateaus and dissected valley lying on a Devonian slate substrate. The Oesling presents soils that tend to accumulate organic matter with an average SOC content of 26 g C kg^{-1} (Lioy et al., 2007). The predominant soil types are Leptosols or dystric Cambisols according to the World Reference Base classification (FAO, 1998) with a sandy or sandy-loam texture.
- The South of Luxembourg, called Gutland, is characterised by a very diverse pedological context with several types of soils and a large SOC variability. The average SOC content in Gutland is 17 g C kg^{-1} (Lioy et al., 2007). This region can be further subdivided into three agro-geological zones:
  - Minette, in the south-western part presents relatively homogeneous soil conditions. Soils in this region are heavy with high clay content (clay or loam–clay texture) and with a predominance of Gleyic Luvisols and Vertisols.
  - The predominant geologic substrate of the Middle of land is Luxembourg sandstone. The texture of the soils in this area is nevertheless not only sandy, but also sometimes clay rich. The most common soils in this area are Arenosols and Cambisols.
  - Redange region, lying between the central part of Luxembourg and the Oesling, is characterised by a very heterogeneous geology. Within this area, red sandstone, limestone, loess, gypsum-keuper and others substrates are found. Texture is also variable but loam soils are predominant. Major soil types limited to the investigated area are Luvisols.

2.1.2. Field campaign

The field campaign took place on the 5th–6th October 2007. This time period was selected to ensure a high proportion of bare soils after harvest and ploughing of mainly maize fields. The weather conditions were lightly cloudy sky on the 5th October 2007 and perfect clear sky on the 6th of October 2007.

A total of 165 sampling plots were delimited in 22 bare fields (6 to 23 plots per field) evenly distributed in the four aforementioned agro-geological regions (5–6 fields by agro-geological region). Each sampling plot consisted of a 7.5 m wide square centred on a geographical position recorded by a GPS receiver in differential mode (localisation accuracy <0.5 m).

For each plot, vertical digital photographs of the soil were taken for soil shadow analysis and several soil samples were collected for analysis of SOC content, soil moisture and soil surface spectral characteristics. Bulk soil samples (200 g) were collected from the soil surface of each plot for further spectral analysis in the laboratory (Cf. Section 2.2).

2.1.3. Soil Organic Carbon (SOC)

Each soil samples used for SOC analyses was composed of 10 sub-samples collected to a depth from 0 to 5 cm with an auger at random locations within the sampling plot. Soil organic carbon of air-dried and sieved (2 mm) samples was analysed by dry-combustion with a LECO CN analyser. Samples with carbonates (detected using effervescence to 1 M HCl) were removed from the dataset. SOC contents varied from 7 to 40 g C kg^{-1} and differed markedly between soil types and agrogeological regions.

2.1.4. Soil moisture

The total amount of rainfall during the previous 7-day period before the over flight was 23.2 mm at an average air temperature of 10.3 °C (Luxembourg City). Last rainfall events occurred 3 days before the field campaign. Gravimetric soil surface moisture was determined for 159 arbitrarily-selected soil samples taken the day of the over flight within the sampling plots in the very first millimetres of the soil surface (up to 1 cm) as presented in Stevens et al. (2010). Soil moisture content was relatively low and varied greatly according to soil type (median: 5.9%, range: 0.9–19.1%). This enabled to consider the soil surface as dry during the field campaign and, consequently, soil moisture was not considered as a factor affecting the soil reflectance in this study.

2.1.5. Soil shadow

Soil Relative Shadow (RS, the percentage of shadowed soil of the studied surface) was measured for each sampling plot from digital photographs of the soil surface taken vertically at nadir position and at 1.50 m high, during the day before the flight (05/10/2007) and the day of the flight, mainly with a Canon Power Shot A620® digital camera but also with a Canon DIGITAL IXUS 500® and a NIKON D50®. Each photograph was recorded as a composition of the three Red, Green and Blue (RGB) spectral bands. 3 photographs were taken within each sampling plot, with the sun in front of the operator and before other measurements (SOC, water content) in order to capture a non-disturbed soil surface (neither operator's shadow nor footprint). Around 500 vertical soil photographs were taken on the 5th and 6th October (250/250). Photographs were taken simultaneously (in a time interval of maximum 10 min) with field ASD spectroradiometer measurements in order to have same illumination and consequently the same shadow conditions for both measures.