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Towards on-the-go field assessment of soil organic carbon using Vis–NIR diffuse reflectance spectroscopy: Developing and testing a novel tractor-driven measuring chamber

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ABSTRACT

Proximal sensing of soil organic carbon (SOC) in the field using diffuse reflectance spectroscopy is still difficult under variable weather conditions. Here, we introduce a tractor-driven measuring chamber for on-the-go visible and near-infrared diffuse reflectance spectroscopy (Vis–NIRS) meeting experimental and precision agriculture demands. A commercial full-range spectrometer operates in a closed dark chamber with artificial light. Sensor view angle, distance to soil, and illumination conditions were optimized. The mobile chamber was placed on drum rollers to flatten the ploughed and tilled soil surface and to minimize disturbances in Vis–NIR spectra by surface roughness. Prior to on-the-go spectra acquisition under field conditions, SOC prediction models for the soils under study were independently calibrated under variable moisture and roughness conditions. Driving at a tractor velocity of 3 km h^{-1} resulted in measuring spots of approximately 8 cm length and 3 cm width at 0.6 m distance to one another in the direction of movement, delivering geo-referenced SOC concentrations at a sub-m spatial resolution. Gravel on the soil surface resulted in erratic extremes of predicted SOC concentrations, but these could be eliminated as outliers. The system was tested under field conditions on two long-term experiments at two different sites which revealed each a large span of SOC concentrations. On-the-go predicted SOC concentrations and those obtained from conventional plot-wise lab analyses were correlated with coefficients of determination of R^2 = 0.65 and a standard error of 1.22 g SOC kg^{-1}. Further improvements, particularly in data processing, will enable a reliable proximal sensing on-the-go for precision agriculture purposes in the near future.

1. Introduction

Visible and near-infrared diffuse reflectance spectroscopy (Vis–NIRS) is being increasingly used for the ground-based estimation of soil properties ("Proximal Soil Sensing"; Viscarra Rossel et al., 2011). Various soil properties such as soil organic carbon (SOC; Bellon-Maurel and McBratney, 2011; Ladoni et al., 2010), nutrients (Maleki et al., 2007), soil moisture (Minasny et al., 2011; Nocita et al., 2013), mineral composition, and texture (Viscarra Rossel et al., 2009) have been successfully detected. Different approaches and various sensors with different wavelength ranges have been tested under field conditions (Adamchuk, 2011). Spectra acquisition in the field is generally disturbed by various factors like variable soil moisture, surface roughness, or sunlight (Minasny et al., 2011; Stenberg et al., 2010). Hence, sensor probes have been mounted to chisel systems to minimize disturbances from variable surface properties (Christy, 2008; Mouazen et al., 2005). Nevertheless, spectra collected that way still suffer from variations in soil contact and measuring geometry (Adamchuk, 2011; Mouazen et al., 2009). Geometrical variations of the sensor head with the integrated illumination unit and the resulting noise could be corrected by adjusting the tractor three-point linkage system, leveling the contact probe, and by spectra pre-transformation procedures (Mouazen et al., 2005, 2009). The sapphire window, which protects the contact probe, seems to be rather resistant (Christy, 2008), but its optical quality is potentially impacted by dirt and scratches.

In view of a desirable spectra acquisition on-the-go, several studies have aimed at solving problems from spectral interferences by variable moisture (Christy, 2008; Mouazen et al., 2005;

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Nocita et al., 2013) or soil surface roughness (Fontán et al., 2010; Rodionov et al., 2014; Wu et al., 2009). Variations in soil moisture impact the brightness of the sample and spectral features related to water, while a rough soil surface in the field may induce baseline shift or scattering as reviewed by Stenberg et al. (2010). Yet the difficulties in predicting soil properties on-the-go are still challenging, particularly when selecting only certain spectral regions for parameter estimation (Bellon-Maurel et al., 2010; Bellon-Maurel and McBratney, 2011). Rodionov et al. (2014) recently published an approach to predict SOC from full range spectra which considers roughness and moisture effects in the same calibration dataset. This approach offers a new option to assess SOC on-the-go, because the full range spectra taken on-the-go bear information on these formerly disturbing factors.

The objective of this study was to develop a robust procedure for the Vis–NIRS based SOC prediction in the field. The procedure was designed for an evaluation of soil properties in small scale field trial plots such as in breeding experiments, but beyond this, an application in precision agriculture was envisaged. The new system should (i) be rather independent of weather conditions, at least with respect to illumination conditions, (ii) allow a faster data acquisition than common backpacker systems, and (iii) deliver full-range spectra to derive as much information as possible. For this purpose, we constructed a novel mobile measuring chamber mounted on a tractor, allowing on-the-go measurements in the field with a commercial full-range Vis–NIR spectrometer, but under standardized measuring conditions. Quantity and quality of incident light, geometrical positioning of the sensor head, and surface properties were optimized. Finally, the second objective of the study was to test the chamber for the estimation of SOC concentrations in the field. This test should include a recently published multivariate calibration model that had been adapted to varying moisture and surface roughness conditions (Rodionov et al., 2014) which regularly occur under field conditions.

2. Material and methods

2.1. Construction of a novel measuring chamber

The measuring chamber to be developed should allow Vis–NIR spectra acquisitions on-the-go under field conditions, but in a controlled measuring environment. Therefore, a tractor-mounted system seemed preferable, permitting a constant power supply for illumination and a robust and heavy construction resistant to field conditions. The measuring chamber as finally utilized for the field tests is shown in Fig. 1.

The device is mounted to a tractor via the three-point linkage. It is designed to be operated on the bare, tilled soil, for example during seedbed preparation. Rough surfaces are flattened during operation, because two drum rollers of ca. 1 m width and ca. 0.27 m diameter running before and behind the lamp and sensor holder carry the chamber with its weight of approx. 250 kg. The contact pressure of the measuring chamber can be roughly estimated at 25 kN m^{-2}. The dark measuring chamber keeps out natural sunlight and dust, because steel sheets mounted to the lateral frame superficially cut into the soil. The chamber can be easily opened for adjusting purposes, sampling, etc. Illumination of the soil surface at defined wavelengths and intensity is performed by six 12V-halogen lamps, which are arranged around a circular head plate at a height of 35 cm above the targeted soil surface; the lamps are adjusted to a 45° incidence angle of the light beam. The resulting beam distance between the lamp and the sample surface is approx. 50 cm. In preliminary studies, several robust and inexpensive halogen lamps were tested (Section 2.3). Supply of a constant current for the illumination and the spectrometer is ensured by a standard generator (14 V, 90 A h; Valeo, Créteil, France), driven by the tractor's power take-off shaft at 1000 min^{-1}, and a standard car battery (12 V, 55 A h).

2.2. Vis–NIR spectrometer

The commercially available ASD AgriSpec Vis–NIR spectrometer with 350 to 2500 nm range (Analytical Spectral Devices Inc.; Boulder, CO, USA) was used for field measurements as well as for comparative laboratory studies. The sensor had 3 nm spectral resolution at around 700 nm and 10 nm spectral resolution at around 1400 and 2100 nm. Spectral discontinuities occurred at 1000 nm and 1830 nm which are the transition wavelengths of the different spectrometer components. The sensor head with a 25° view angle was adjusted at 5 cm height above the soil surface, resulting in a measuring spot of 2.2 cm diameter (i.e., approx. 3.8 cm^2). The sensor head was connected to the spectrometer with a 1.5 m fiber optic cable (1.7 mm external fiber optic cable diameter; Analytical Spectral Devices Inc.; Boulder, CO, USA).

At the beginning of each analytical session, the base line was corrected and the instrument was optimized on a dark current followed by white standard reference measurements (Spectralon II; Labsphere, North Sutton, NH, USA). During the whole measurements, the power supply (12 V) was continuously monitored by the spectrometer software. The standard reference spectra were acquired to control reliable sampling at time intervals of 15 min.

Spectra collection was conducted with the RS3 software (ver. 5.5.6, Analytical Spectral Devices Inc.; Boulder, CO, USA). In order to exclude noisy ranges of the Vis–NIR spectra, the spectral range from 410 to 2300 nm was evaluated for all further investigations. Geo-referencing for each spectrum was continuously performed using a GPS receiver (NL-302U; Navilock, Berlin, Germany), automatically embedded in the RS3 application software. Maps of SOC concentrations were created using ArcGIS 9.3 (ESRI, Redlands, CA, USA).

2.3. Testing the performance of the mobile measuring chamber

Several tests of the mobile chamber had to be conducted to ensure a reliable spectra acquisition and on-the-go SOC prediction in the field. We tested (i) the illumination conditions, (ii) the exclusion of dust and ambient light, and (iii) the quality of SOC prediction in the mobile chamber and in the lab using identical soil samples.

Prior to the field tests, alternative lamp types were tested under laboratory conditions against the calibrated standard ASD Pro lamps (Analytical Spectral Devices Inc.; Boulder, CO, USA) which are recommended by the manufacturer of the sensor. Finally, the lamp type Reflecto MR16 (12 V 50 W, fixed 24° beam angle; Ushio America Inc., Cypress, CA, USA) was selected because it (i) possesses nominal spectral features which are comparable with the standard lamps, (ii) is encapsulated and (iii) is much cheaper than the standard lamp. For this comparative study, SOC prediction was evaluated for 250 ground soil samples as derived from spectra acquired with the different lamp types. The soil samples were placed in petri dishes. For the Ushio lamps, the lamp geometry was identical to the conditions in the mobile measuring chamber (lamp holder with six lamps). In contrast, only three ASD lamps were used as in the standard lab procedure. First, the base line was corrected and the instrument was optimized on a dark current followed by white standard reference measurements (Spectralon II; Labsphere, North Sutton, NH, USA). For the acquisition of a single Vis–NIR spectrum, 50 scans were recorded. For both lamp types, three replicate spectra per sample were taken. For each spectrum, the scanned spot was slightly modified by rotating and moving the petri dish. Finally, one mean spectrum per