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Reflectance anisotropy for measuring soil surface roughness of multiple soil types

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A B S T R A C T

Information on soil surface roughness at the centimetre scale is needed for inclusion in a range of physical and functional algorithms including heat budgets, runoff and sediment transfer models, and can also be used to understand soil degradation processes. Previous work has shown that such information can be obtained from multiple view angle measurements of hyperspectral Hemispherical Conical Reflectance Factors (HCRFs), but the issue of whether this technique works on soils of different biochemical composition has not yet been demonstrated. The objective of this work was therefore to determine the capability of these approaches for discriminating soil surface roughness conditions when different soil types are considered. Five soil types with varying biochemical properties were subjected to artificial rainfall, producing a sequence of soil states of progressively declining soil surface roughness. Point laser data (2 mm sample spacing) were geostatistically analysed to give a spatially-distributed measure of surface roughness. HCRFs from the soil states were measured using a ground-based hyperspectral spectroradiometer for a range of viewing zenith angles in the solar principal plane from the extreme forwardscatter (−60°) to the extreme backscatter (+60°) at 10° sampling resolution in the solar principal plane. A directional index (Anisotropy Measure; AM) was determined, using a ratio between extreme forward-scattered and backscattered HCRFs. Regression analysis of AM against a geostatistically-derived value of soil surface roughness (sill variance) was used to test the ability of the AM for description of surface roughness for all soil types. The results show that use of a directional AM index dramatically improved the relationship with sill variance compared to the use of a single viewing angle ($R^2=0.68$ at $\theta_r=40°$; $R^2=0.88$ (AM)), demonstrating the great potential of this approach for compensating for spectral differences between different soil types. The results provide an empirical and theoretical basis for the future retrieval of spatially-distributed assessments of soil surface structure across larger spatial extents.

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1. Introduction

Information on soil surface roughness (SSR) at the centimetre scale is required for a wide range of applications, including modelling land–atmosphere gaseous exchange (Morner and Etiope, 2002; Mosier, 1998) and calculating heat budgets (Bastiaanssen et al., 1998). It is a key parameter in erosion and hydrological models (Jetten et al., 1999; King et al., 2005) and temporal changes in SSR and soil crusting also indicate physical soil degradation (Lal, 2001). Deriving a quantitative measure of SSR is also important in research aiming to distinguish SSR from other variables, such as soil moisture content and soil organic matter (Anderson and Croft, 2009). Remote sensing offers a means of measuring and monitoring changes in SSR over spatially extensive areas and has the potential to provide data at a fine temporal resolution. This has particular significance due to the study of soil condition, because of the spatial and temporal variability in SSR (Le Bissonnais et al., 2005). Much of the work into quantifying SSR through remote sensing approaches has been focused on RADAR techniques. However, RADAR only gives a coarse classification of roughness levels (i.e. smooth, moderately rough and rough) (Baghdadi et al., 2008) and unlike optical wavelengths does not provide complementary information on soil biochemical properties.

There is now a growing recognition for off-nadir measurements of reflected solar radiation in providing surface structural information (Diner et al., 2005). Fuelled by this, a new generation of Earth observation sensors with multiple view angle capabilities are in operation (MISR, POLDER II, MODIS). Data from these systems now require validation support from ground-based studies, to both investigate the impact of biophysical parameters on Hemispherical Conical Reflectance Factors (HCRFs) and to develop models for retrieving structural information from the data (Chappell et al., 2006). Previous papers have demonstrated that HCRFs relate to soil surface roughness for a single soil type (Anderson and Kuhn, 2008; Croft et al., 2009), due to differential self-shadowing by soil aggregates (Cierniewski and Verbrugghe, 1997). However, the influence of different soil types with varying biochemical properties on this relationship has not yet been considered.

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Soil reflectance across the spectral region of 400–2500 nm carries biochemical information as a result of its mineral composition, water and SOM content and texture, as a function of wavelength (Irons et al., 1989). These spectral variations present a challenge for the extraction of a geometric signature when different soil types are considered. This is because optical properties of soils may differentially affect HCRFs, where the contrast between shaded and sunlit areas is reduced in darker soils (Kimes, 1983). In addition, the presence of different absorption features associated with distinct biochemical functional groups in the different soil types may cause a wavelength-dependent change in the relationship. Consequently, to accurately quantify SSR through HCRFs for multiple soil types, it may be necessary to limit the influence of optical effects on HCRFs. The potential of this multiple view angle approach has previously been shown in vegetation studies for acquiring canopy structural information (Chen et al., 2003), however it has yet to be tested on soil surfaces.

This work tests a dual-directional reflectance anisotropy index (Anisotropy Measure; AM) which uses a ratio of forward scatted and backscattered reflectance factors (see Croft et al., 2009, for further details) against an independent measure of SSR (derived from laser data). This approach is to statistically assess if soil-type specific spectral properties can be filtered out; leading to a more accurate quantification of SSR for a range of soil types.

The specific aims of this work were to:

1. investigate the influence of different soil types and spectral signatures on the relationship between sill variance and HCRFs by creating comparable levels of surface roughness between crusting states of different soil types;
2. test a directional reflectance anisotropy index (AM, Croft et al., 2009) in order to reduce the impact of soil biochemical variations and more accurately retrieve SSR across different soil types.

2. Methods

2.1. Soil sampling and preparation

Soil aggregates were sampled from the surface layer of freshly tilled agricultural fields for four soil types (silty clay, clay loam, silt loam and silt). In addition, a peat soil from an ombrotrophic raised bog was included in the experiment to assess the impacts of higher soil carbon contents on HCRFs (Table 1). The five soil types were selected to represent a range of soil characteristics with varying particle size composition, soil organic matter (SOM) and iron (Fe) content, and consequently different reflectance spectra.

The silt (St) and silt loam (SL) soils were sampled from two agricultural fields in Möhlin, located approximately 15 km east of Basel, Switzerland. The region supports intensive agriculture, with loess rich and well-drained soils, which are prone to erosion (Schaub et al., 1997). The clay loam (CL) soil was a well-drained, shallow calcareous brown earth, overlying coarse-grained fragmented limestone with surface textures of silty clay loam or clay loam (Courtney and Webster, 1973) from Bradford Abbas, near Sherborne, Dorset. The Silty clay (SC) soil, from Oborne, near Sherborne, Dorset, contains a thin Silty Clay A horizon, with fewer calcareous stones present than the CL soil. The peat (Pt) soil was sampled from a bare surface cutover layer of an ombrotrophic lowland bog at Wedholme Flow, Cumbria.

2.2. Producing a soil surface roughness gradient

Each soil was oven dried at 40 °C for 48 h to remove any trace of moisture and to ensure uniformity in soil moisture, as seal formation and aggregate breakdown are influenced by antecedent conditions (Levy et al., 1997). Soils were sieved to produce aggregates between 1 mm and 16 mm in size, and poured evenly into separate sample trays (25×20×2 cm). For each soil type, five different SSR states were generated using artificial rainfall at a rainfall intensity of 45 mm h^{-1} with an average drop size of 3.1 mm and a kinetic energy of 390 J/h/m² (see Croft et al., 2009). The different durations of rainfall selected (Table 2), ensured that the SSR states across the different soil types were comparable in terms of their thematic stages of structural breakdown. After rainfall, the soils were dried slowly at 30 °C for 36 h to remove soil moisture and preserve surface structure.

The shorter time steps for SL and St are due to the lower SOM and clay content (Table 1), with silty soils typically being more susceptible to crust formation (Le Bissonnais et al., 1989). Of the agricultural soils, SC took the longest to break down because of its higher SOM content (Table 1), which stabilises soil aggregates through chemical binding between organic polymers and mineral substrates and physical protection by roots and fungi (Chaney and Swift, 1984; Tisdall and Oades, 1982). In addition, SOM decreases the 'wettability' of soil aggregates, reducing the likelihood of slaking (Chenu et al., 2000). The peat soil was resistant to breaking down under rainfall and displayed little structural or hydrological change even after 120 min. Consequently only three states were used, representing the control state (no rainfall), an intermediary rainfall stage (40 min) and the maximum duration of rainfall (120 min).

2.3. Soil surface spatial characterisation

A calibrated laser-profiling instrument was used to characterise surface roughness, following the method outlined in Anderson and Kuhn (2008) and Croft et al. (2009). A 10 cm×10 cm plot in the centre of each soil tray was measured at a sample spacing of 2 mm to capture fine-scale processes associated with changes in soil structure, such as raindrop detachment and aggregate breakdown. The laser data were analysed using 2-dimensional semi-variogram analysis, in order to give a three-dimensional spatially-distributed value of surface roughness (i.e. the dissimilarity of surface height elevations). Spherical models were fitted to the sample variograms for each soil state using the Gstat package (Pebesma, 2001; Eq. (1)), where γ is semivariance for a given lag distance (h). Spherical models were chosen due to their suitability for use with datasets that exhibit higher short-range variability (Corwin et al., 2006). The total sill variance (c_T) is the sum of the nugget (c_0) and structured sill variance (c_1) values; if $h \le a$. $c_T = c_0 + c_1$ where $\gamma(h) = c_T$ if $h > a$ (Deutsch and Journel, 1998; Eq. (2)).

$$\gamma(h) = c_1\left[1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3\right] + c_0 \quad \text{for } 0 < h \le a \tag{1}$$

Table 1
Soil properties of the five soil types used.

Soil type	Code	Grid ref (lat/long)	Sand (%)[a]	Silt (%)[a]	Clay (%)[a]	C (%)[a]	N (%)[a]	C/N[a]	Fe content (g/kg)	Soil colour (Munsell)	Soil series
Silt loam	SL	47.55 °N 7.83 °E	12.93	79.06	8.01	1.44	0.17	8.24	0.552	2.5Y 4/2	Luvisol
Silt	St	47.55 °N 7.84 °E	10.20	81.38	8.42	1.37	0.17	8.28	0.768	2.5Y 4/6	Luvisol
Clay loam	CL	50.93 °N 2.59 °E	30.22	35.95	33.83	3.43	0.28	12.26	3.805	10YR 4/3	Cambisol
Silty clay	SC	50.97 °N 2.49 °E	11.21	46.88	41.92	6.70	0.57	11.88	6.164	10YR 5/4	Cambisol
Peat	Pt	54.87 °N 3.23 °E	45.59	51.62	2.79	45.28	1.91	37.59	1.106	5YR 3/2	Histosol

[a] n = 10.

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