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Linking spatial patterns of soil organic carbon to topography — A case study from south-eastern Spain

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ABSTRACT

A key uncertainty in our understanding of the global carbon cycle is the lateral movement of carbon through the terrestrial system. Soils are the major storage of carbon in the terrestrial biosphere and the inventory of soil organic carbon (SOC) is required for greenhouse gas inventories and carbon mitigation projects. The aim of this study is to characterize spatial patterns of the concentrations of topsoil total organic carbon (TOC) in a semi-arid Mediterranean area in south-eastern Spain and to assess their relationship to topography. We adopt a remote sensing based approach for the spectral determination and quantification of TOC with a complete coverage of bare soil surfaces. Digital terrain analysis and geostatistical techniques are applied to analyze the spatial patterns of TOC at different spatial scales. We show that accumulation of topsoil SOC is dependent on topographic position at the landscape scale with highest values found in valley bottoms. At the hill-slope scale, differences among terrain classes exist regarding the topographic controls on SOC. While positive correlation between the topographic wetness index (TWI) and TOC can be observed on steep slopes, that correlation is not significant on wide pediments. Small scale spatial variability is large on ridges, steep slopes and valley bottoms, while SOC distribution on pediments is relatively homogeneous. These differences are most likely governed by the presence of vegetation patches and variable runoff and sediment transport rates among the terrain classes. The successful application of hyperspectral remote sensing for the spatial estimation of SOC concentrations suggests that it is a promising technique to advance SOC inventories in semi-arid and arid regions.

1. Introduction

A key uncertainty in our understanding of the global carbon cycle is the lateral movement of carbon through the terrestrial system (Stallard, 1998; Kuhn et al., 2009). Soils account for the largest pool of actively cycling carbon in terrestrial ecosystems (WBGU, 1998; Jobbágy and Jackson, 2000; Janzen, 2004, and the inventory of soil organic matter (SOM) and the assessment of processes involving its transport are required for greenhouse gas inventories and carbon mitigation projects (Ravindranath and Ostwald, 2008). The uncertainties concerning the spatial variability of SOM can largely be attributed to two factors – (1) the multitude and complexity of processes affecting the spatial distribution of SOM (Smith et al., 2001) and (2) the difficulties in monitoring and spatially assessing SOM in soils (Harper and Gilkes, 2001; Kimble et al., 2001; Goidts et al., 2009).

SOM is a mixture of recognizable plant and animal parts and material that has been altered to the degree that it no longer possesses its original structural organization (Oades, 1989; Amundson, 2001). Soil organic carbon (SOC) is the main element present in SOM (48–60 wt.%) and is used as measurable basis for SOM estimation (Rossell et al., 2001). SOC enrichment in soils is primarily governed by net primary production of plants that enters soil upon senescence. Heterotrophic respiration bysoil microorganisms and fire return a large amount of SOC back to the atmosphere. At the same time, erosion and transport of soil derived material redistribute SOC laterally (Kimble et al., 2001; Smith et al., 2001; Quinton et al., 2006; Yoo et al., 2006; Alewell et al., 2009).

Lateral redistribution of SOC leads to SOC accumulation and burial at depositional sites (Burke et al., 1999; Belnap et al., 2005; Van Oost et al., 2007). The enrichment of SOC in the upper soil profile exerts a positive feedback mechanism on soil structure, water infiltration and nutrient availability, thus promoting plant growth and litter fall. SOC is particularly important in semi-arid areas since it sustains soil fertility, increases soil moisture storage and mitigates droughts (Tiessen et al., 1994). Erosional sites in contrast face SOC depletion and are placed under increased nutrient strain (Moorman et al., 2004; Quinton et al., 2010).

Earth surface is the template on which nutrient fluxes occur and its shape has been proposed as indicator for the processes governing the

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lateral distribution of SOC (Glatzel and Sommer, 2005; Yoo et al., 2006; Berhe et al., 2008; Hoffmann et al., 2009). Thus, digital terrain analysis has been successfully used to explain spatial patterns of SOC depletion or accumulation in temperate regions (Moorman et al., 2004). In arid and semi-arid areas, however, episodic rainfall events, highly variable infiltration rates and vegetation patches produce spatially discontinuous runoff patterns, generating erosional and depositional features independently of topography e.g. slope position (Cammeraat, 2002; Yair and Raz-Yassif, 2004). Thus, it is questionable if SOC storage patterns and their observed dependence on topographic parameters (Moorman et al., 2004; Yoo et al., 2006; Berhe et al., 2008) can be transferred to arid and semi-arid areas.

Soils are essential to ecosystems, human life and society and, thus, there is growing interest in soil degradation monitoring, particular in quantifying SOC stocks (Morvan et al., 2008; Goidts et al., 2009). Yet, the inventory and monitoring of SOC are challenging owing to its variability in three spatial dimensions and time, making region-wide spatial predictions challenging (Webster and Oliver, 2001; Cammeraat, 2002). As such, monitoring techniques are required that generate reliable, area-wide data of SOC distribution.

A relatively new technique to measure SOC is the application of hyperspectral remote sensing. Typically soil reflectance decreases with increasing SOC in the wavelength range 0.4–2.5 μm (Baumgardner et al., 1985) and different modelling techniques are used to predict SOC from continuous reflectance spectra or derivatives (Ben-Dor and Banin, 1994, 1995; Reeves et al., 2002; Udelhoven et al., 2003; van Waes et al., 2005; Brown et al., 2006; Viscarra Rossel et al., 2006). The transfer of prediction models to airborne or satellite remote sensing data has only rarely been conducted (Hill and Schütt, 2000; Gomez et al., 2008; Jarmer et al., 2010), although the approach has promise to obtain area-wide estimates of SOC distribution and support regional carbon inventories.

The aim of this study is to characterize spatial patterns of the topsoil (the uppermost layer of soil, ~2 cm depth) SOC concentrations in a semi-arid Mediterranean area in south-eastern Spain. We adopt and assess a remote sensing approach for the spectral determination of SOC of unvegetated soils. We then analyze the spatial patterns of SOC concentrations and their relation to topography using digital terrain analysis, explorative data analysis and geostatistical techniques. The patterns found are subsequently discussed in the context of the dominant hydrological and geomorphological process domain of the study area.

2. Study site

The study site (37.80–37.85°N, 1.81–1.86°W) is located in south-eastern Spain in the upper watershed of the Rio Guadalentin (Fig. 1). Mean annual rainfall in the lowlands of the Guadalentin basin totals 270 mm a^{-1} with a potential evapotranspiration of 880 mm a^{-1} (Navarro-Hervás, 1991; Cerdà, 1997). Three quarters of rainfall events are less than 4 mm and storm cells have limited extent. Hence, rainfall events usually generate runoff locally depending on areal distribution of infiltration and crusting properties and hardly reach the slope base (Puigdefabregas et al., 1998, 1999; Ruiz-Sinoga et al., 2010). In addition, in-channel sediments cause transmission losses and further reduce hydrological connectivity (Kirkby et al., 2005). Severe floodings originate from large rainfalls in relatively small areas (<10 km^2) with high hydrological connectivity owing to active channel incision and strong flow convergence (Kirkby et al., 2005).

The area is situated in the Subbetic zone of the Betic Cordillera and is characterized by rolling hills and wide pediments intermitted by mountainous terrain such as the 'Cigarrones' or the 'Sierra del Pinoso' in the south (Fig. 1). Bedrock is dominated by Eocene to Miocene limestone (ridges) and Cenomanian to Micoene marly strata, often covered with Quaternary slope and alluvial deposits (lower slope sections and valley bottoms). Wide pediments are attached to the rounded limestone hills. Following the FAO classification scheme, soils are mainly Lithosols and Calcaric Regosols. Soils under cultivation vary in thickness from 10 cm on convex slopes to > 1 m in valley floors, and are characterized by low organic matter contents, low aggregate stability and high stone content (Cammeraat and Imeson, 1998; Quine et al., 1999; van Wesemael et al., 2000).

Landuse is dominated by rainfed cultivation of cereals and tree crops (almonds and olives). Almond plantations have been expanded onto steeper slopes since 1970, facilitated by increasing mechanisation and supported by subsidies from the European Common Agricultural Policy (van Wesemael et al., 2000). Water supply to trees is achieved by removal of all potentially competing ground vegetation thus making soils susceptible to water and wind erosion (Garcá-Ruiz, 2010). Tillage erosion provoked by stronger mechanisation leads to high rates of soil translocation (Quine et al., 1999; van Wesemael et al., 2006). Traditional soil and water conservation structures such as terraces and check dams were often removed to enlarge field size or are left to degrade (Bellin et al., 2009).

Unfarmed areas mostly consist of tussock grassland and open shrubland, with *Stipa tenacissima* and *Rosmarinus officinalis* as dominant species. Pine forests (*Pinus halepensis*) with dense undergrowth of various bushes and grasses are mainly found at higher altitudes and north-exposed hillsides. Their occurrence on upper slopes mainly results from massive reforestation programmes during the 2nd half of the last century.

3. Methods

In the following text SOC refers to the substance while TOC (= total organic carbon) is used as quantitative variable that describes the SOC concentration in wt.% in the topsoil.

3.1. Field sampling and chemical analysis

Soil sampling was performed during dry weather conditions in September 2003. In order to assess the spatial variability of TOC in the topsoil 61 samples were taken along sampling transects (Fig. 7). At each sample position, an integrative sample was taken from the upper 2 cm of the soil profile representing an area of about 1 m^2. The sampling transects were arranged so that north- and south-facing ridges and valley bottoms were crossed.

After air-drying in the laboratory, soil samples were gently crushed in order to pass a 2 mm-sieve and carefully homogenized. TOC was measured using furnace ramping between 200 °C and 600 °C with a Leco-RC 412 analyzer. The precision of the measurements is specified to 1.5% of the detected amount, with a detection limit of 0.02% (Hill and Schütt, 2000).

3.2. Reflectance measurements

The bi-directional reflectance measurements of the soil samples were acquired in the laboratory with an ASD FieldSpec-II spectroradiometer (Analytical Spectral Devices). Spectral readings were taken at 1 nm steps between 350 and 2500 nm using a reflectance standard of known reflectivity (Spectralon©). The optical head of the spectroradiometer was mounted on a tripod in nadir position with a distance of 10 cm to the sample. A 1000 W quartz-halogen lamp was set in a distance of 30 cm and an illumination angle of 30° was used to illuminate reference panel and samples.

Absolute bi-directional reflectance spectra were calculated by multiplication of raw reflectance spectra by the certified reflectivity of the Spectralon panel. Subsequently, spectra were resampled to HyMap spectral resolution using linear interpolation.