Catena 160 (2018) 222–232

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Topographic metric predictions of soil redistribution and organic carbon in Iowa cropland fields

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ARTICLE INFO

Keywords:
Topographic wetness index
Topographic relief
SOC distribution
Principal component
Topography-based model

ABSTRACT

Topography is one of the key factors affecting soil organic carbon (SOC) distribution and soil redistribution (erosion or deposition) because it influences the gravity-driven movement of soil by water flow and tillage operations. In this study, we examined impacts of sixteen topographic metrics derived from Light Detection and Ranging (LiDAR) data on SOC distribution in agricultural fields. We adopted the fallout radionuclide ^{137}Cesium (^{137}Cs) to estimate soil redistribution rates and patterns of SOC distribution across 560 sampling locations at two field sites and a larger scale for the Walnut Creek watershed in Iowa. Then, using stepwise ordinary least square regression (SOLSR) and stepwise principal component regression (SPCR), topography-based models were developed to simulate spatial patterns of SOC density and soil redistribution rates. Results suggested that erosion and deposition of topsoil were regulated by topography with soil gain in lowland areas and soil loss in sloping areas. Topographic wetness index (TWI) and relief were the most influential variables controlling SOC density and soil redistribution rates, respectively, and were of primary importance in SOLSR models. All topography-based models developed through SPCR and SOLSR demonstrated good simulation performances, explaining > 62% variability in SOC density and soil redistribution rates across two field sites with intensive samplings. However, the SOLSR models showed lower reliability than the SPCR models in predicting soil properties at a watershed scale. Results of this study highlighted the topography-based SPCR model as an effective and a promising tool allowing for scaling of in situ SOC density and soil redistribution rates at crop sites to a large-scale watershed, and provided valuable insight into the spatial patterns of SOC distribution.

1. Introduction

Soil redistribution (erosion and deposition) has significant impacts on soil physical and chemical properties in agroecosystems (Fullen and Brandsma, 1995; Du and Walling, 2011; Quijano et al., 2016). Erosion in excess of soil production leads to losses of soil fertility and then affects distribution of soil organic carbon (SOC). As an important soil property and a key factor affecting soil quality, SOC is lost from locations in a landscape by multiple processes, including soil aggregate disruption, carbon transport, and SOC mineralization with potential for deposition at other locations (Lal, 2003; Hemelryck et al., 2010; Wang et al., 2014; Fissore et al., 2017). Light and small particles following disaggregation could be easily mobilized by erosion caused by water, wind, or tillage operations, resulting in SOC depletion in eroded areas and subsequent deposition at depressional sites (Harden et al., 1999; McCarty and Ritchie, 2002). Preferential removal of fine and nutrient-enriched soil particles through erosion has significant impacts on agricultural lands. Globally, SOC transported by erosion processes in croplands ranges from 0.47 to 0.61 Pg C year^{-1} (Van Oost et al., 2007). SOC loss may deteriorate soil structure, decrease crop productivity, and increase erosion-induced carbon dioxide (CO_2) emissions. A better understanding of soil redistribution and erosion-induced SOC distribution is critical for elucidating the contribution of erosion to SOC dynamics, and thus provides valuable insights into effective soil management at the landscape scale.

Soil redistribution can be traced by the fallout radionuclide Cesium − 137 (^{137}Cs) (Ritchie et al., 1974). As an anthropogenic radio-isotope, ^{137}Cs was introduced to the Earth's surface through nuclear weapon testing in the 1950s and 1960s. Because of the non-exchangeability of ^{137}Cs, this isotope has been used as a tracer for quantifying soil erosion rates in recent decades (VandenBygaart, 2001; Martinez et al., 2010). A number of studies have applied ^{137}Cs to investigate soil erosion and deposition in agricultural fields and significant correlations between ^{137}Cs inventory and soil redistribution and SOC content have been

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http://dx.doi.org/10.1016/j.catena.2017.09.026
Received 4 May 2017; Received in revised form 19 September 2017; Accepted 26 September 2017

identified across multiple sites (Zhang et al., 2006; Ritchie et al., 2007; Mabit et al., 2008; Martinez et al., 2010; Li et al., 2014; Young et al., 2014; Quijano et al., 2016).

Topography is an important factor regulating soil erosion since it affects surface runoff, soil texture, and vegetation (Martz and De Jong, 1987; VandenBygaart, 2001; Rezaei and Gilkes, 2005; Liu et al., 2006; Afshar et al., 2010). Landscape topography is a description of the shape and features of landforms, and topographic information can be generated from digital elevation models (DEMs) derived from remotely sensed data (Glenn et al., 2006; Doneus, 2013). The remotely sensed data are useful in assessing land condition and the effects and effectiveness of land management, and improving the mapping and characterization of agricultural lands (Baessler and Klotz, 2006; Fitzpatrick et al., 2007; Li et al., 2016b). Application of Light Detection and Ranging (LiDAR)-derived DEMs for geomorphometry is drawing increasing attention because LiDAR data have high resolutions (100 cm horizontal resolution and 10 cm vertical resolution) in characterizing land surfaces (Lang et al., 2013). Several studies investigating soil erosion highlighted topography as an effective factor in predicting soil redistribution and investigating SOC distribution in agricultural fields (Theocharopoulos et al., 2003; Polyakov and Lal, 2008). Van der Perk et al. (2002) reported that up to 43% of the soil redistribution variability could be explained by DEM-derived topographic attributes.

Impacts of topography on SOC distribution have been considered in extrapolating field observations to analyze soil erosion and spatial patterns of SOC (Amore et al., 2004; Shen et al., 2009; Lieskovský and Kenderessy, 2014; De Vente et al., 2013; Fissore et al., 2017). However, feasibility of applying topography-based statistical models to predict soil erosion and deposition has not been evaluated. Compared to previous empirically- or process-based models that employed discrete data based on field samplings, development of a topography-based model based on LiDAR-derived topographic metrics will benefit investigations with limited observations and can generate continuous SOC maps. Application of such a topography-based SOC model can also provide scientific support for soil erosion control and management of agricultural lands and their impacts on SOC fate.

In this study, we explored topographic controls on soil movement and SOC dynamics and developed topography-based models using stepwise principal component regression (SPCR) and stepwise ordinary least square regression (SOLSR). Model performance was evaluated across spatial distribution of SOC in agricultural fields within the Walnut Creek watershed in Iowa. Soil measurements including SOC density, Cesium-137(^{137}Cs) inventory and an estimate of soil redistribution rate based on the ^{137}Cs measurement were selected as dependent variables in model development. LiDAR-derived DEMs were used to generate set of 16 parameters including local, nonlocal and combined topographic metrics which are commonly used to characterize water movement and distribution on landforms. To remove collinearity among topographic metrics, we applied SPCR to develop independent variable combinations used for model construction. Objectives of this study were to: 1) investigate relationships between landscape topography and soil redistribution and SOC distribution in agricultural fields; 2) develop topography-based models to simulate SOC density and soil redistribution rates in the agricultural fields and apply to a watershed scale.

2. Materials and methods

2.1. Study areas

The Walnut Creek watershed (WCW) is located in Boone and Story counties (41°55′–42°00′N; 93°32′–93°45′W) and its outlet is south of Ames with an area of 5130 ha (Fig. 1a). The landforms under study are part of the Des Moines lobe which was glaciated up until about 12,000 years ago. This region currently has a humid continental climate with warm summers and cold winters. Mean annual temperature is 8 °C with an average high of 22 °C in July and an average low of − 6 °C in January (Ritchie et al., 2007). Mean annual precipitation is 818 mm, with relatively short and intense rainfalls during May and August (Hatfield et al., 1999). Croplands in the WCW have a relatively flat topographic relief (2.03 ± 1.62 m), but are still subject to considerable soil erosion with a mean water erosion rate about 8 t ha^{-1} (Coiner et al., 2001). Soils in the watershed are classified as the Clarion (mesic Typic Hapludolls) – Nicollet (mesic Aquic Hapludolls) – Webster (mesic Typic Hapludolls) soil association. Well–drained Clarion soils are typically located in upland areas or on slopes, while poorly drained Webster and Canisteo soils are mainly located in lowland areas. Okoboji and Harps soils are very poorly drained and are the dominant soil types at depressional sites. > 86% of the watershed is farmed with a corn and soybean rotation being the dominant cropping system since 1957. Detailed information of climate, soils, and farming practices can be found in Hatfield et al. (1999). In this study, only a rough boundary of the Walnut Creek watershed was delineated.

In addition to the watershed-scale investigation, two field sites with intensive samplings were selected in this study. The total area for each site is approximately 15 ha. The first site (Site 1) is located in the WCW, and the second site (Site 2) is outside the watershed located between Boone and Ames and within 10 km of the closest watershed boundary (Fig. 1a). Topographic relief generated from a maximum elevation per 90 m radius map ranges from − 1.3 m to 3.3 m at field Site 1 (Fig. 1b) and 0.0 m to 4.5 m at field Site 2 (Fig. 1c). Field Site 2 also adopts a corn-soybean rotation as that of WCW. The principal tillage practices across the sites are moldboard plowing followed by two disking, and harrowing operations in spring (Schumacher et al., 2005; Young et al., 2014). Tillage practices at Sites 1 and 2 were along the north-south direction, while tillage directions in the watershed varied roughly equally between north-south and east-west directions as influenced by different management practices and field configurations.

2.2. Field sampling and analysis

A total of 460 crop field locations were randomly selected in the WCW and 230 locations were selected at each of Sites 1 and 2 using ArcGIS 10.2.2 (ESRI, Redlands, CA; Fig. 1). Topographic information of the 460 locations was collected from LiDAR-derived DEMs to reflect the terrain characteristics of the watershed (Fig. 1a). One hundred out of the 460 locations were chosen for field experiments estimating SOC density and ^{137}Cs inventory in the WCW, including two 300-m transects (each have 9 sampling locations) with an average slope of 2.2° and 82 randomly selected samples in crop fields. For Sites 1 and 2 with more intensive sampling, a 25 m × 25 m grid was created and the 230 samples were taken at grid nodes at each site (Fig. 1b and c).

Three samples were collected from the 0 to 30 cm soil layer within a 1 m × 1 m quadrat at each sample site using a push probe (3.2 cm diameter) in May 2003 for Sites 1 and 2. The same sampling method was conducted at the 100 locations in the WCW in Oct. 2006. For sampling locations that had obvious sediment deposition, samples were collected from the 30 to 50 cm soil layer to assess the potential for a significant ^{137}Cs inventory below 30 cm. Each soil sample was weighted after dried at 90 °C for 48 h. Bulk density of the volumetric samples was calculated using the weight. The three samples collected at one location were mixed together for SOC content and ^{137}Cs concentration measurement. Geographic coordinate information of sampling plots was recorded using a Trimble RTK 4700 global positioning system (GPS). Baseline ^{137}Cs was estimated from reference soil samples collected from areas where no apparent soil redistribution had occurred since the mid-1950s. For measurement of baseline ^{137}Cs in 2003 and 2006, four composite samples involving 3 soil cores (0 to 30 cm) were collected from a local cemetery in the southern part of WCW. Soils in the reference areas were Nicollet loam under grass cover.

The composite samples were sieved through a 2 mm screen. A subsample was taken and further ground to a very fine powder with a