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Soil organic carbon and influencing factors in different landscapes in an arid region of northwestern China

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ABSTRACT

Knowledge of the spatial pattern of soil organic carbon (SOC) and the factors influencing it in various landscapes is essential for understanding carbon cycles. An arid region with an area of 100 km^2 in northwestern China consisted of desert, cropland and wetland was investigated. The vertical patterns of SOC density in the three different landscapes and the horizontal distribution of SOC density in the study area were evaluated. The differences in SOC density among different landscapes and soil layers were analyzed, and the primary factors influencing SOC density were determined. The density of SOC was low and remained homogeneous in the profiles of desert soil. The vertical distributions of SOC density in cropland and wetland were well described by logarithmic functions ($R^2 = 0.97$ and 0.92, respectively, $P < 0.001$). Geostatistical analysis showed that SOC density presented moderate spatial variability and strong spatial dependence across all depths. Wetland and desert were easily recognized by the highest and lowest SOC densities in the study area, respectively. The densities of SOC in the 3-m profiles were 59.35, 149.6 and 174.4 Mg ha^{-1} for desert, cropland and wetland, respectively. The SOC in the 1–3 m layer represented 67.0, 52.7 and 58.0% of the total SOC stored in the 0–3 m profiles of desert, cropland and wetland, respectively. Clay and silt particles were the major determinant of SOC in the study area. The variability in SOC density explained by clay + silt content increased with depth ranging from 46.0 to 82.2% in desert and from 45.3 to 76.7% in cropland. The variability in SOC density accounted for by clay + silt content decreased from 52.2% in the 0–0.3 m layer to 43.3% in the 0–1 m layer of wetland. The remaining SOC density variability could be attributed to factors not included in this study, such as geography, vegetation and the degree of erosion. Errors in the measurement of SOC concentration and the distribution of soil-particle size, however, may introduce uncertainty in the determination of soil bulk density and thus the estimation of SOC density. The concentration of SOC in the 0–0.3 m layer increased by 196.3% after the reclamation of native desert less than 40 years ago and decreased by 5.3% after the cultivation of wetland as cropland for less than 30 years. Short-term cultivation is insufficient to significantly alter SOC concentration in the deeper layers of desert and wetland soils. The results of this study may be of further use in optimizing strategies for the protection of wetland, ecological restoration of desertified land and the sustainable management of cropland in arid regions of northwestern China.

1. Introduction

Soil is generally recognized as a major reservoir in global carbon cycling (Batjes, 1996; Lal, 2008). Much more organic carbon is sequestered in soils than in the atmosphere and vegetation combined (Grace, 2004). Changes in soil organic carbon (SOC) are responsible for variation in the physical, chemical and biological properties of soil and influence not only crop productivity and soil fertility (Maia et al., 2010), but also regional and/or global carbon cycles (Post and Kwon, 2000). The sequestration of SOC is therefore of great concern in research on carbon cycling. Understanding the spatial variability of SOC and the primary factors influencing it are essential for evaluating the functioning of soil and understanding the process of carbon sequestration in soil.

The SOC is controlled by various natural and anthropogenic factors. For example, climate change influences the mineralization of soil organic matter (SOM) and the flux of carbon from soil to the atmosphere (Rustad and Fernandez, 1998). Topographical factors (e.g. elevation, slope and aspect) determine the production and decomposition of plant litter by controlling the soil–water balance and thus impact SOM levels (Griffiths et al., 2009). The soil–water balance may be a critical factor in determining SOC content because it integrates climate, pedological properties, topographical features and management strategies (Grigal and Ohmann, 1992). Soil–water stress may decrease, and high temperatures enhance, the decomposition of SOM (Norton et al.,

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2008). Soil texture distinctly influences SOC because the silt and clay particles and micro-aggregates can protect SOM from decomposition (Zinn et al., 2005). Furthermore, the roles of clay and silt particles in the availability of water (Schimel and Parton, 1986) and in plant productivity (Hontoria et al., 1999) also impact SOM. Changes in land use strongly impact soil fertility and the variation in SOC storage (Karhu et al., 2011; Z. Wang et al., 2012), especially in arid and semiarid lands where pools of SOC are susceptible to changes in land use and climate (Su et al., 2009; West et al., 1994). Management strategies such as conservation tillage, crop rotation, residue return, balanced fertilization and elimination of bare fallow, can increase SOC concentration or stocks (Mishra et al., 2010; Yang et al., 2012). Soil erosion may represent a source or sink of carbon due to the spatial variability resulting from the translocation and burial of carbon (Lal, 2003; Quinton et al., 2010). In addition to the individual influences, the combined effects of environmental and anthropogenic factors on SOC have also been extensively evaluated. For example, increased air temperature and land use change in the Himalayan region of India resulted in a decline of SOC content by 0.3% from 1978 to 2004 (Martin et al., 2010). Elevation, slope, clay and water contents of soil jointly explained 70.3% of the variability in SOC in the upstream watershed of Miyun Reservoir, North China (S.F. Wang et al., 2012).

Accurately evaluating SOC is difficult due to the complexity of site properties. The SOC particularly varies in areas with complex landforms and frequent anthropogenic disturbances. The spatial distribution of SOC and the factors influencing it have usually been studied in small areas, e.g. tens of square meters or a few square kilometers (Don et al., 2007; Han et al., 2010; Rossi et al., 2009; Wang et al., 2011). Direct measurements at regional scales are usually made at shallow soil depths such as the top 0.3–1 m (Batjes, 2006; Zinn et al., 2005). Half of the carbon released in pastures after deforestation, however, is from layers below 1 m (Batjes and Sombroek, 1997). In comparison, Batjes (1996) reported that large amounts of organic carbon are stored in the 1–2 m layer, and much of the carbon at depth is stable and does not contribute much to CO_2 emission. Organic carbon within deeper soils in regions where soils are deep and where subsoils contain considerable amounts of organic carbon should be considered.

Even though arid regions have generally been regarded as potential carbon sinks (Grünzweig et al., 2003), little information is available on SOC in arid inland areas of northwestern China, where pools of SOC are susceptible to wind erosion and to changes in land use and management practices. In the middle reaches of the Heihe River, native desert has been transitioned to irrigated cropland in recent decades to meet the food and economic demands of increasing populations (Li et al., 2006). Excessive exploitation and unreasonable management have led to soil degradation, such as severe erosion and salinization. Ecological restoration has been implemented since 1975, and some desertified land in marginal oases has been reclaimed to irrigated cropland (Su et al., 2007). In the southern part of this region, economic demands have also driven the exploitation of meadow wetland for irrigated cropland. Cropland reclaimed from native desert has been cultivated for less than 40 years. Cropland in the old oases on the banks of the Heihe River and in the southern part of the study area has been continuously cultivated for more than 100 years. Cropland exploited from meadow wetland has been cultivated for less than 30 years. Information on the period of cultivation of croplands has been collected by reviewing the literature (Su et al., 2010) and by interviewing peasants and village elders. Changes in land use substantially affect the level of SOC, and may provide information for the role of landscapes in carbon cycles. The detailed objectives of this study were: (1) to investigate the vertical distribution of SOC density in three different landscapes and its horizontal distribution in the study area and (2) to analyze the differences in SOC density among different landscapes and soil layers and to determine the major factors influencing SOC in an arid region of northwestern China.

2. Materials and methods

2.1. Study area

This study was conducted in the vicinity of the Linze Inland River Basin Research Station, Chinese Ecosystem Research Network, located in Linze County, Gansu Province, China. The area has a continental arid climate. The mean annual precipitation is 117 mm, approximately 60% of the precipitation occurs from July to September. The mean annual temperature is 7.6 °C, and the mean annual potential evaporation is 2390 mm. The mean annual wind speed is 3.2 m s^{-1} and annual gale days (wind speed varies from 17.2 to 20.7 m s^{-1}) reach to 15 or more (Su et al., 2007), and the sand-drifting mainly occurs from March to May.

Our study covered an area of 100 km^2 (20 × 5 km), with the length from north to south and the width from east to west (39°12′30″–39°23′28″N, 100°05′32″–100°10′01″E, 1372–1417 m a.s.l.). The northern part of the study area includes the southern margin of the Badain Jaran Desert. The Heihe River flows across the area from east to west. Zonal soil in the northern marginal oasis is an Aridisol derived from diluvial–alluvial materials (Su et al., 2010). Entisols form after the long-term encroachment of drift sand from the Badain Jaran Desert and the deposition of aeolian sand. In the old oases in the central and southern parts of the study area, Siltigi-Orthic Anthrosols develop under long-term irrigation from sediment-rich water, fertilization and cultivation (Su et al., 2009). Inceptisols develop in meadow wetland in the southwestern part of the study area with severe salinization occurring at the soil surface. The desert vegetation consists of *Halaxylon ammodendron* (C. A. Mey.) Bunge, *Calligonum mongolicum* Turcz., *Tamarix chinensis* Lour., *Nitraria sphaerocarpa* Maxim and *Reaumuria soongorica* (Pall.) Maxim. The predominant species in wetland are Common Reed (*Phragmites australis* (Cav.) Trin. ex Steud.) and Common Leymus (*Leymus secalinus* (Georgi) Tzvel.), interspersed with *Achnatherum splendens* (Trin.) Nevski, *Kalidium foliatum* (Pall.) Moq. and *Nitraria tangutorum* Bobr. The main crops of the irrigated cropland are maize (*Zea mays* L.) for seeds, spring wheat (*Triticum aestivumLinn.*), tomatoes (*Solanum lycopersicum*) and sugar beets (*Beta vulgaris*). Fig. 1 presents the location of the study area in China, the land use and the sampling locations. The photographs of desert, cropland and wetland are representative of the landscapes analyzed in this study.

2.2. Field investigation and sampling design

A regular grid of 126 sampling locations 1 × 1 km in size was originally designed, but six locations could not be sampled due to the presence of the river channel, reservoirs, an elevated water table, roads or buildings. The remaining 120 locations (56, 43 and 21 locations for desert, cropland and wetland, respectively) were sampled to a depth of 1 m. Of the 120 locations, 112 (56, 42 and 14 for desert, cropland, and wetland, respectively) and 102 (52 for desert, 38 for cropland, and 12 for wetland) locations were sampled to depths of 2 and 3 m, respectively. The position of each sample location was recorded with a hand-held differential GPS receiver to an accuracy of 3–5 m. Disturbed soil samples were collected with a hand auger 5 cm in diameter every 10 cm from the 0–1 m layer and every 20 cm from the 1–3 m layer by pooling two 10-cm subsamples. Soil samples for the 0–10, 10–20 and 20–30 cm layers were taken with five subsamples randomly collected from a 5 × 5 m plot. A total of 2285 soil samples were collected and sealed in air-tight bags for measuring SOC concentration and the mechanical composition immediately after transport to the laboratory. Forty of the 120 locations in the study area were selected as typical representatives, 16 of which were from desert, 18 from cropland and six from wetland locations. These locations were in the centers of each landscape where the topography and vegetation were typical. Profile was dug to a depth of 1.2 m at each of the representative locations. Eleven undisturbed soil samples (10 for the 0–1 m layer and one for