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Spatial distribution of soil organic carbon in the ecologically fragile Horqin Grassland of northeastern China

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ABSTRACT

The spatial distribution of soil organic carbon (SOC) and its storage in the topmost 100 cm of the soil were investigated in the Horqin Grassland of northeastern China. Soil samples were collected at 1465 sites, covering $12.03 \times 10^4\,km^2$. The region had a mean SOC density of $6.84\,kg\,C\,m^{-3}$, which is lower than China's mean ($9.60\,kg\,C\,m^{-3}$) and the world's mean ($10.40\,kg\,C\,m^{-3}$). The mean SOC density was much higher in the northern part of the study area ($8.85\,kg\,C\,m^{-3}$) than in the southern part ($4.84\,kg\,C\,m^{-3}$). The total SOC storage in the Horqin Grassland was 862.74 Tg. SOC storage decreased with increasing soil sampling depth. The SOC stored in the top 10, 20, 40, and 60 cm accounted for 17.7, 31.7, 53.8, and 71.3%, respectively, of the total amount in the top 100 cm. The region's extensive desertification appears to be one of the most important factors that led to the relatively low SOC content and the difference between the northern and southern parts of the Horqin Grassland. Our results provide an important baseline for evaluating past losses of SOC due to desertification, and for projecting the potential increase in SOC from the restoration of desertified land and how SOC will respond to climate change.

1. Introduction

A large quantity of organic carbon is stored in the soil of the world's terrestrial ecosystems. The soil organic carbon (SOC) pool in the top 100 cm totals about 1550 Pg, which is about twice the size of the atmospheric pool and three times the size of the biotic pool (Lal, 2004a). Against the background of global warming, the relatively large size and long residence time of the SOC pool make it an important sink for carbon released into the atmosphere by anthropogenic activities (Post et al., 1982). Changes in SOC storage are now taken into account in international negotiations regarding climate change (Martín et al., 2011). SOC and its potential to mitigate the build-up of atmospheric carbon dioxide (CO_2) through soil carbon sequestration have attracted considerable scientific attention (Jobbágy and Jackson, 2000; Lal, 2004b; Smith et al., 2008; Schrumpf et al., 2011; Grüneberg et al., 2014; O'Rourke et al., 2015; Deng and Shangguan, 2017).

Accurate estimates of SOC storage and its changes are necessary to support improved carbon management and climate change mitigation, as well as to help parameterize the carbon cycle models that are being used to guide climate policy (Schrumpf et al., 2011; Scharlemann et al., 2014). Many studies have estimated SOC storage at regional (Yang et al., 2009; Wiesmeier et al., 2015), national (Kern, 1994; Yu et al., 2007; Martín et al., 2011), and global (Post et al., 1982; Mitra et al., 2005; Scharlemann et al., 2014) scales. However, high uncertainty is associated with the estimates, especially for global SOC storage, because of inconsistent methods and limited data for many regions. Most studies have estimated global SOC at roughly 1500 Pg in the topmost 100 cm of the soil, but estimates range from 504 to 3000 Pg (Scharlemann et al., 2014). The estimates of SOC storage for the contiguous United States range from 62.1 to 99.3 Pg (Kern, 1994), whereas estimates for China's terrestrial ecosystems range from 50 to 180 Pg (Yu et al., 2007) and estimates for global wetlands range from 202 to 535 Pg (Mitra et al., 2005).

The inconsistencies among studies highlight the need for more detailed regional-level measurements of SOC storage and its spatial distribution through *in situ* sampling. SOC levels depend on local climatic conditions and other site-specific conditions, as well as on the type of land-use and land management (Yu et al., 2007). Thus, spatially explicit databases obtained from *in situ* measurements are important to help researchers establish the relationships between the geographical

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distribution of SOC and the climate, vegetation, human development, and other factors that affect this distribution; such data provides the basis for assessing the influence of changes in any of these factors on the carbon cycle (Post et al., 1982). However, despite a great deal of research on SOC, there currently remains substantial uncertainty on the size of the SOC storage, its spatial distribution, and carbon emissions from soils (Scharlemann et al., 2014).

The Horqin Grassland is one of the largest grasslands in China. However, this region has undergone serious aeolian desertification in recent decades. The area of desertified land accounted for 77.6% of the total area in the late 1980s (Liu et al., 1996). There is a strong link between desertification and the emission of CO_2 from the soil and vegetation (Lal, 2001). Arid and semi-arid regions have been regarded as having high potential as carbon sinks due to the large global extent and widespread desertification of these regions (Nosetto et al., 2006). Therefore, more and more researchers have studied carbon sequestration in severely desertified areas through strategies such as afforestation (Cao et al., 2008; Li et al., 2013, 2017) and grazing exclusion (Li et al., 2012), as well as carbon and nitrogen losses due to desertification (Zhou et al., 2008) and carbon and nitrogen storage in various land uses (Li et al., 2014) in the Horqin Grassland. However, these studies were only conducted in limited areas and none investigated, in detail, the spatial distribution of SOC and its storage throughout this area.

In this paper, we present the results of the largest field study to date in the Horqin Grassland to obtain details of the spatial distribution of SOC and estimate its storage. We tested the following hypotheses: (1) that the Horqin Grassland would have a relatively low SOC density, primarily due to widespread desertification in the region; and (2) that the SOC distribution would be affected by climatic and topographic factors. The results from this study can provide a baseline for evaluating future changes in SOC storage in the Horqin Grassland and data for the parameterization of regional models that can be used to predict the SOC dynamics induced by climate change and changes in the land-use and cover type.

2. Materials and methods

2.1. Study area

The Horqin Grassland (also called the Horqin Sandy Grassland or the Horqin Sandy Land) is located in the western part of northeastern China. The present study area, which covers 13 counties of China's Inner Mongolia autonomous region, has an area of 12.03×10^4 km^2. It ranges between 41°40′38″N and 46°3′25″N and between 117°52′12″E and 123°42′48″ E (Fig. 1). The Xiliao River crosses this region from west to east and separates it into two parts: the northern part is characterized by alluvial flood plains and sloping piedmont plains, whereas the southern part is characterized by sand dunes that alternate with gently undulating interdunal lowlands (Li et al., 2017). The study area is a typical temperate grassland of the Central Asian Steppe ecosystem, with a continental semiarid monsoon temperate climate. Elevation ranges from 90 to 1625 m above sea level. Mean annual air temperature is 3 to 7 °C. Mean monthly temperatures vary from a minimum of −12.6 to −16.8 °C in January to a maximum of 20.3 to 23.5 °C in July. The annual frost-free period is approximately 140 to 160 days. The mean annual precipitation is 350 to 500 mm, with the highest values in the summer from June to August (Duan et al., 2014).

The zonal soils are classified as Kastanozems, Chernozems, and Luvisols based on the Food and Agriculture Organization of the United Nations soil classification system (FAO, 2006), but the current dominant soils are Arenosols as a result of desertification. The native vegetation mainly consists of mesoxerophytes characterized by palatable grass species along with sparsely scattered woody species (Li et al., 2017). However, the vegetation has been degraded seriously during the past century by extensive desertification, which has been caused by a combination of climate change and unsustainable land use. As a result, the area has become dominated by xerophytes and psammophytes (Liu et al., 1996).

2.2. Soil sampling and measurement methods

Soil samples were manually collected from five layers (0 to 10, 10 to 20, 20 to 40, 40 to 60, and 60 to 100 cm) using a 2.5-cm-diameter soil auger. Because of the huge study area, sampling was very expensive and very labor- and time-consuming. Therefore, soil samples were collected over a 7-year period from 2011 to 2017. Soil sampling in Naiman County was conducted from July to August 2011, whereas the other 12 counties were sampled from April to August from 2014 to 2017.

We originally intended to collect soil samples from each 10 km × 10 km cell in the study area. However, soil samples were collected at intervals of < 10 km for some sites with high spatial heterogeneity and at intervals of > 10 km for some sites with large areas of mountains and sand dunes. In the end, we selected a total of 1465 locations (733 in the northern part and 732 in the southern part) for soil sampling within the study area. The mean sampling interval was 6.65 km. One 10 m × 10 m plot was established at each of the 1465 locations. The soil samples were collected randomly at 15 sampling points within each plot and bulked to prepare a composite sample for each layer. Therefore, we obtained five composite samples (one per depth range) to a depth of 100 cm within each plot, yielding a total of 7325 composite samples.

Three additional sampling points (replicates) in each plot were selected to determine the soil bulk density, using a soil auger equipped with a stainless steel cylinder (100 cm^3 in volume) to sample intact soil cores at 10-cm intervals. This work is more arduous than the work to collect composite soil samples. Because of high variation in the soil texture and water conditions, it was difficult to collect intact soil cores to a depth of 100 cm using this method. Therefore, a single soil bulk density value was calculated for a combined layer down to 100 cm depth at a given location, which represents the average of 5 to 10 soil cores at each point.

In the laboratory, soil samples for determination of the SOC concentration were air-dried, hand-sieved (through a 2-mm mesh), hand-picked to remove fine roots and other debris, and then ground to pass through a 0.25-mm mesh. Where it was not possible to insert the soil sampler into the soil, or where the sampler encountered an obstacle (*e.g.*, a stone) larger than the sampler's diameter (2.5 cm), it would have been prohibitively difficult to collect a full sample at that location, so we reposition the sampler to a nearby location. Where coarse fragments smaller than the sampler diameter were included in the sample, we accounted for their volumetric percentage of the sample in our calculations. This affected a total of only 4.1% of our samples. We used the Walkley-Black dichromate oxidation procedure (Nelson and Sommers, 1982) to determine the SOC concentration.

2.3. Data acquisition for factors that influenced SOC

The land-use type, geographical coordinates, and elevation were recorded for each of the 1465 sample locations using a GPS receiver. We created a dataset that included the slope, slope aspect, aridity index (evaporation/precipitation), Thornthwaite's moisture index, mean annual precipitation, and mean annual air temperature, averaged from 1980 to 2015, and values of the normalized-difference vegetation index (NDVI) in 2015 for each sampling location, as well as the areas of the different land-use types in 2015 for each county. Data were obtained from the Resources and Environmental Sciences Data Center, Chinese Academy of Sciences (RESDC, 2017).

2.4. Estimation of SOC density and storage

For each county, SOC density (SOCD, in $kg\,C\,m^{-3}$) was estimated using Eq. (1) and SOC storage (SOCS, in Tg) was estimated using Eq.