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Soil carbon storage along a 46-year revegetation chronosequence in a desert area of northern China

Yong-Le Chen[a,b], Zhi-Shan Zhang[a,*], Yang Zhao[a], Yi-Gang Hu[a], Ding-Hai Zhang[c]

[a] Shapotou Desert Research and Experimental Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China
[b] College of Life Sciences and Oceanography, Shenzhen University, Shenzhen 518060, People's Republic of China
[c] College of Natural Sciences, Gansu Agricultural University, Lanzhou 730070, People's Republic of China

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ABSTRACT

Soil contains the majority of terrestrial carbon; however, most studies only focus on soil organic carbon (SOC) in the first meter or even shallower layers, and soil inorganic carbon (SIC) and root-derived carbon (RDC) are often overlooked. Here, we investigated the distribution of soil carbon at a depth of 0–3.0 m over a 46-year revegetation chronosequence on moving sand dunes and evaluated the potential influence of soil water content on soil carbon. The SOC density increased significantly along the 0–3.0 m profile, and showed a faster increasing rate in shallow layer (0–0.4 m) than that of the deep layers below 0.4 m. Although the SIC density did not increase significantly, it accounted for > 65% of the total soil carbon in shallow layer and at least 82% in deep layer. The live and dead RDC increased significantly over the chronosequence in both shallow and deep layers. The RDC accounted for a small amount of the total soil carbon at an average of 3.19%. The SOC was closely linked with live RDC in both the shallow and deep layers. The soil water content was only positively correlated with the SOC in the shallow layer. The SOC storage in the shallow layer required 57.4 years to reach the level at the natural vegetation site, whereas the storage in the deep layers required > 100 years. Our results indicated that soil carbon accumulation is a slow process in both shallow and deep layers after revegetation, and the most notable increase in soil carbon was accounted by SOC. We suggest that SOC, SIC and RDC should be considered when assessing the effects of revegetation on soil carbon in water-limited ecosystems.

1. Introduction

Soil represents an important and effective carbon reservoir in terrestrial ecosystems, and it is expected to have a more substantial sink capacity than the associated vegetation; thus, soil has a considerable ability to sequester carbon for the mitigation of elevated atmospheric CO_2 (Schlesinger, 1990; Batjes, 1996; Lal, 2004a, 2004b; Schmidt et al., 2011). Soil in water-limited ecosystems, which account for 47.2% of the global terrestrial surface, is estimated to contain approximately 241 Pg soil organic carbon (SOC) in the top one meter and an even larger soil inorganic carbon (SIC) pool (Eswaran et al., 2000). Therefore, the soil carbon storage in these ecosystems must be quantified and its potential response to environmental changes, e.g. vegetation and soil changes, should be determined.

Complete assessments of the SOC, SIC, and RDC pool are particularly lacking, especially in water-limited ecosystems. Due to the faster sequestration rate of SOC, most studies have focused on SOC, only a few studies have documented the distribution and dynamics of SIC (Diaz-Hernandez et al., 2003; Hirmas et al., 2010; Chang et al., 2012). However, SIC is a main constituent of soil carbon in these ecosystems, and recent studies have suggested that SIC sequestration through both biological and non-biological processes may be underestimated (Wohlfahrt et al., 2008; Lal, 2009; Li et al., 2015). Root system is also a frequently neglected carbon reservoir. Actually, the cumulative contribution of RDC is comparatively larger and the residence time of root tissues in soil is longer than other plant tissues (Rasse et al., 2005; Pierret et al., 2016). Considering the high belowground production of root systems, which are normally large and deep in water-limited ecosystems (Chapin et al., 1993), RDC should not be overlooked when assessing soil carbon.

Most individual studies and large-scale investigations only focused on the first meter of soil (Batjes, 1996), or at even shallower depths, generally due to difficulties and costs associated with deeper sampling. However, many previous studies have detected larger amounts of soil carbon in deeper soil profiles in water-limited ecosystems (Harrison et al., 2011; Rumpel and Kogel-Knabner, 2011; Harper and Tibbett,

* Corresponding author.
E-mail address: zszhang@lzb.ac.cn (Z.-S. Zhang).

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2013); thus, deeper sampling is necessary. Furthermore, carbon turnover in deep soils is commonly slow, implying deep organic carbon has a longer residence time (Pierret et al., 2016). In water-limited environments, soil water is a key factor that controls the soil carbon stock and dynamics via its effects on plant carbon allocation, microbial activities, and soil aggregate formation (Jobbágy and Jackson, 2000; Rey et al., 2005; Moyano et al., 2013). In general, increased soil water will stimulate plant production in both aboveground and belowground parts, thereby benefiting SOC accumulation. Thus, soil water is involved in contributing new carbon to the SOC pool, as well as retaining the available SOC (Norton et al., 2012; Zhou et al., 2012; Mi et al., 2014; Verburg et al., 2014). Soil water is also a necessary participant in the deposition, dissolution and leaching of SIC (Lal, 2009). Former studies have investigated the relationships between soil water and SOC (Wynn et al., 2006; Yang et al., 2008), but few studies have mentioned SIC and considered the different soil carbon components simultaneously in deep soil.

In this study, we took advantage of a 46-year-old revegetation chronosequence on sand dunes of the Tengger Desert to quantify the distribution and dynamics of different soil carbon components (SOC, SIC and RDC). Long-term studies conducted in this area have documented improvements in the topsoil conditions, such as increases in fine soil particles and soil nutrient availability (Duan et al., 2004; Li et al., 2007a), and enhanced biogeochemical processes in the topsoil (Wang et al., 2006). The revegetated soil system changes occurred along with a significant decrease in the soil water content in the deep layer over the 46-year succession (Li et al., 2014). However, the effects of decreased soil water content on the soil carbon storage via alterations to the revegetated soil system remained unclear. To enhance our knowledge-base on this topic, this study aimed to (1) investigate the temporal changes of carbon in soil along 0–3.0 m profile over a 46-year-old revegetation chronosequence; (2) analyze the relationships between SOC, SIC, RDC, and soil water content; (3) evaluate the revegetation success based on the rate of soil carbon sequestration. To achieve these issues, we collected soil samples from three revegetation sites (with ages of 20, 29, and 46 years) and compared the results with those from a moving sand dune and a naturally vegetated site.

2. Materials and methods

2.1. Study sites

The study was conducted along the southeastern fringe of the Tengger Desert in northwestern China. This area is characterized as a transitional zone from sandy desert to steppe. Because of the considerable groundwater depth (> 80 m), it is not available to vegetation; therefore, precipitation is the sole source of soil water in the study area (Li et al., 2004). Along the transitional zone, five study sites were set up from east to west (Fig. 1).

Shapotou (37°32′ N, 105°02′ E, at an elevation of 1300 m AMSL) is a typical temperate desert region. The annual mean temperature is 10 °C, and the mean January and July temperatures are −6.9 and 24.3 °C, respectively. The annual mean wind velocity is 2.9 m s^{-1}, and the annual mean precipitation is 186 mm, of which 80% falls between May and September. Large and dense reticulated barchans sand dune chains are typical of the landscape, and an aeolian sandy soil is the main soil type. Moving sand dunes are dominated by *Hedysarum scoparium* Fisch. & C. A. Mey. and *Agriophyllum squarrosum* (L.) Moq., which provide cover of < 1%. Since the 1950s, a 16 km long, 500 m wide rain-fed revegetation protective system was established along both sides of the Baotou-Lanzhou Railway in this region to stabilize the moving sand dunes and prevent desert encroachment. Xerophytic shrubs were planted following the establishment of the sand barrier. Subsequently, revegetation was further developed in 1964, 1981, and 1990. After long-term revegetation efforts, a diversified ecosystem composed of planted xerophytic shrubs (mainly *Artemisia ordosica* Krasch., *Caragana*

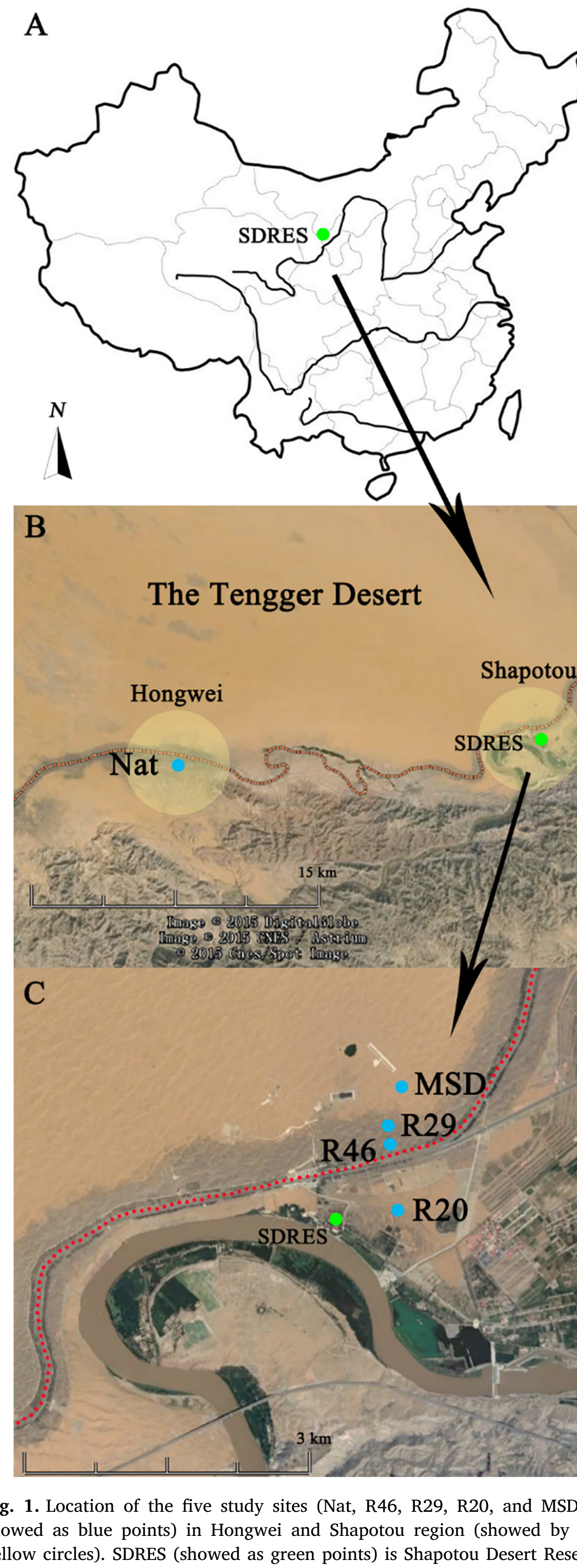

Fig. 1. Location of the five study sites (Nat, R46, R29, R20, and MSD site showed as blue points) in Hongwei and Shapotou region (showed by light yellow circles). SDRES (showed as green points) is Shapotou Desert Research and Experimental Station. Red dashed line is the Baotou-Lanzhou railway. A: Location of SDRES on the map of China. B: Location of Hongwei and Shapotou region along the Tengger Desert. C: Location of four sand dunes sites in Shapotou region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)