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Effects of plant restoration on soil microbial biomass in an arid desert in northern China

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ABSTRACT

Soil microbial biomass acts as both a source and sink of organic carbon and available nutrients, consequently affecting plant growth and production. However, our understanding regarding the effects of plant restoration practices on the patterns of soil microbial biomass remains limited. In this study, we established a 54-year chronosequence comprising moving sand dunes and adjacent sites that had been stabilized through different periods (10, 20, 29, 46, and 54 years) of plant restoration in the southeastern fringe of the Tengger Desert, China. Microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and their relationship with soil physicochemical properties were analyzed. The results showed that plant restoration significantly increased MBC and MBN in the arid desert. In all stabilized sites, MBC and MBN decreased with increasing soil depth, while they increased along the chronosequence with decreasing plant cover and successional biological soil crusts. MBC and MBN in moving dunes remained lower than those in stabilized sites and slightly increased from topsoil to subsoil. Both MBC and MBN were positively correlated with silt and clay contents, soil organic carbon (SOC), total nitrogen (TN), and MBC/SOC and MBN/TN ratios, whereas they were negatively correlated with sand content. Higher MBC and MBC/SOC were found in the later successional stages, suggesting a great potential for carbon sequestration and higher nutrient turnover for stand biomass. This study indicated that plant restoration plays an important part in the recovery of the biological functioning of soil in an arid desert.

1. Introduction

Arid and semi-arid lands contain 16% of the global soil carbon pool. Over two-thirds of lands in arid and semi-arid regions have been destroyed by desertification, leading to carbon loss (Lal, 2001). Many measures have been taken to prevent environmental deterioration and restore degraded soil in arid and semi-arid lands (Luna et al., 2016; Yang et al., 2014; Xiao et al., 2016a). The availability of basic information on ecological processes that occur during the course of ecosystem recovery is critical for proper planning and management of rehabilitation programs in disturbed ecosystems (Liu et al., 2015; Garris et al., 2016).

Soil organic carbon (SOC) is a key factor in soil fertility and an important destination of atmospheric CO_2 fixed by plants (Lal, 2001). Evaluating the SOC can contribute to our understanding and prediction of the effects of changes in soil quality and management practices on soil biological conditions and the carbon cycle. Reasonable and efficient plant restoration measures have been reported to increase SOC stocks and improve soil quality in desert regions (Yu et al., 2016; Huang et al., 2012; Yang et al., 2014). However, restoration of degraded land through planting vegetation does not contribute more SOC than native forests, as shown by a meta-analysis of various factors such as plant species, site preparation, and study region on the basis of limited studies (Liao et al., 2010). Currently, the role of plant restoration on SOC remains unclear under different conditions. This emphasizes the necessity for more experimental studies on ecosystem carbon cycle for plantations.

Soil microbial biomass (SMB), the living component of soil organic matter, acts as the source and sink of carbon and available nutrients (Singh et al., 1989). SMB regulates biogeochemical

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processes in terrestrial ecosystems (Paul and Clark, 1989; Killham, 1994); meanwhile, it contributes to soil aggregation and plant nutrient uptake, growth, and productivity (Smith and Paul, 1990; Hannam et al., 2006). Although microbial biomass carbon (MBC) constitutes a small fraction of SOC (Miralles et al., 2012), it can respond much more quickly to changes in soil quality and management practices than the SOC and TN contents as well as other soil physicochemical properties (Smith and Paul, 1990; Jacinthe and Lal, 2008; Junior et al., 2016). Thus, SMB is increasingly being used as a sensitive indicator for evaluating the soil biological properties (Carter, 1986; Wieder et al., 2013; Lan et al., 2013).

Plant restoration may induce diverse changes in SMB, including increases (Luna et al., 2016), decreases (Zhang and Chu, 2011) and no clear trend (Mackay et al., 2016) due to differences in soil physicochemical properties, nutrient availability, plant species, and management practices. Investigations on SMB have been conducted mainly in forestry (Hannam et al., 2006; Feng et al., 2009) and agricultural ecosystems (Jacinthe and Lal, 2008; Van Groenigen et al., 2010), or anthropogenic disturbances (Hu et al., 2010; Zhang and Chu, 2011; Liu et al., 2012). Despite efforts to investigate the ecological effects of plant restoration in desert lands regarding changes in plant species composition, biological soil crusts (BSCs), nutrient levels, and labile carbon content (Li et al., 2012; Miralles et al., 2013; Liu et al., 2015; Yu et al., 2016), its effects on SMB is limited in desert regions.

To protect the Baotou–Lanzhou Railway from being buried in the sand, artificial vegetation parallel to the railway was established at the edge of the Tengger Desert in northern China in 1956, 1964, 1981, 1990, and 2000 (Li et al., 2012, 2014; Yang et al., 2014). Studies in this region found that soil physicochemical properties and plant community structure have markedly changed in a 54-year stabilized chronosequence. Specifically, plant restoration reduces soil temperature changes, increases soil moisture of topsoil, and enhances soil enzyme activities including oxidases and hydrolases (Zhang et al., 2012, 2013a,b; Li et al., 2014). Vegetation cover decreases over time due to succession from shrubs to herbaceous plants (Xiao et al., 2004; Yang et al., 2014; Li et al., 2014). Under harsh conditions, the low cover of vascular plants on stabilized sand surfaces allows BSCs to develop gradually from cyanobacteria-dominated to lichen-moss dominated crusts in the interspaces of sparse plants. The cover of lichen-moss dominated crusts on surface dunes can reach more than 95% after 50 years of stabilization (Li et al., 2007). In this successional process, SMB might change with shifts in plant species composition and BSC type.

In present study, we evaluated the effect of plant restoration by natural succession (enclosure management) and plantation on SMB in a 54-year chronosequence at the edge of the Tengger Desert. The successional changes of SMB in the stabilized chronosequence were explored by measuring soil MBC and microbial biomass nitrogen (MBN) contents in stabilized sites and adjacent moving dunes. The mechanism of SMB changes was revealed by analyzing the relationship between SMB and soil physicochemical properties. This study will provide useful data for a better understanding of the function of SMB in plant restoration in arid deserts.

2. Materials and methods

2.1. Site description

The study area is located in the Shapotou region of Zhongwei County in the Ningxia Hui Autonomous Region in China. This region lies at the southeastern edge of Tengger Desert (37°27′N, 104°57′E) (Fig. 1), with an elevation of 1500 m. The mean annual temperature in this region is 9.6 °C and the absolute maximum and minimum temperatures are 38.1 and −25.1 °C, respectively. The mean annual precipitation is 181.6 mm, and the annual potential evaporation is 3000 mm (Li, 1991). There are huge, dense reticulate dunes (Fig. 2a) with loose soil and impoverished moving sand. The natural vegetation cover is approximately 1–2%.

In 1956, an artificial vegetation protection system was established in the study area (Li et al., 2014). At the forepart of the protection system, sand barrier fences were established with woven willow branches or bamboo to reduce wind erosion. Wheat or rice straw checkerboards (1 m × 1 m in area and 0.15–0.20 m high (Fig. 2b) were built behind the sand barriers to protect the planted xerophytic shrubs from wind erosion. These straw checkerboards increased the roughness of the sand surface 400–600-fold and reduced wind velocity by 10 and 20–40% at heights of 2 and 0.5 m, respectively (Zou et al., 1981). Xerophytic shrub seedlings were planted within the checkerboards and grew without irrigation (Li et al., 2014). These shrubs included *Artemisia ordosica* Krasch, *Caragana korshinskii* Kom., *C. microphylla* Lam., *Calligonum mongolicum* Turc'z, *Atraphaxis bracteata* A. Los, *A. pungens* Jaub. et Spach., *Elaeagnus angustifolia* L., *Salix gordejevii* Y.L. Chang, and *Hedysarum scoparium* Fisch. The stabilized area was further expanded in 1964, 1981, 1990, and 2000 using the same methods on the moving dunes (Li et al., 2014).

Over the past 54 years, artificial vegetation has been established on moving dunes without irrigation, while the original desert landscape (Fig. 2a) has changed into a complex artificial-natural desert ecosystem (Fig. 2c). The plant community structure has gradually shifted from single shrub communities at the initial stage into a complex community structure dominated by annual herbs at the later stages, such as *Agriophyllum squarrosum* (L.) Moq., *Eragrostis poaeoides* Beauv., and *Bassia dasyphylla* O. Kuntze (Table 1). The vegetation cover varies between 20 and 40%, with an annual litter amount of 43.6 g m^{-2} (Yang et al., 2014; Li et al., 2014). Soil crusts have been formed on sand dunes in three stages: first, surface crusts were formed on aeolian accumulation after the sand dunes had been stabilized by vegetation; then, these surfaces were colonized by blue-green algae to form BSCs (Fig. 2d); moss species became common in the stabilized sites 29 years after stabilization (Li et al., 2002) (Fig. 2e), whereas lichen (only *Collema tenax*) occurred on sand dunes after 46 years of stabilization (Li et al., 2004). Changes in the surface habitat have had a significant impact on the characteristics of plant community and BSCs (Table 1) (Li et al., 2011, 2014; Yang et al., 2014).

2.2. Sample collection and handling

In July 2010, soil samples were collected using the synchronic sampling method. With this method, the simultaneous sampling of different chronosequence sites is equivalent to the re-sampling of the same site through time via a space-for-time substitution procedure (Walker et al., 2010). Sites stabilized in 1956, 1964, 1981, 1990, and 2000 were chosen to obtain a 54-year chronosequence. Adjacent moving dunes were used as controls. Each of the sites had the same initial conditions as the parent material (i.e., aeolian sandy soil) and followed the same sequence of changes (Li et al., 2014).

Four plots per site were chosen as four replicates, which shared the same geomorphological, climatic, and soil characteristics. A random sampling method was used to integrate the effect of factors such as BSCs and shrubs. In each plot (10 m × 10 m), soil cores (2.5 cm in diameter) were collected from 12 random locations at different depths (0–5 cm, 5–10 cm, and 10–20 cm) and pooled together from the same depth. The quarter method was used to separate composite samples (Agriculture Chemistry Specialty Council, 1983).