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Original article

Changes in carbon and nitrogen storage along a restoration gradient in a semiarid sandy grassland

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ABSTRACT

Understanding carbon (C) and nitrogen (N) pools in degraded ecosystems is useful to predict future C and N sequestration potential during restoration. Here we examined the distribution of C and N pools in plant–soil system at four successional stages: mobile dune, semi-fixed dune, fixed dune and grassland. The four stages reflect the successional sequence during sandy grassland restoration in Horqin Sandy Land, Northern China. C and N storage in plant biomass, litter and soil increased significantly with advancing sandy grassland restoration. With the conversion from mobile dune to semi-fixed dune, fixed dune and grassland, total ecosystem C and N storage increased by 1.9, 4.8, 7.1 and 3.3, 15.7, 20.6 times, respectively. More than 80% of C and N storage were stored in soil in sandy grassland restoration. C or N storage in plant and root biomass, litter and soil was positively correlated to species richness. Soil C and N storage was positively correlated to the C and N in plant and root biomass. These results suggest that sandy grassland restoration has a high potential to sequester C and N in the soil. Increasing plant production and species diversity via restoration likely enhance the C and N sequestration in sandy grassland ecosystems.

1. Introduction

Arid and semi-arid regions cover approximately 45% of the earth's surface (Schimel, 2010), and store a substantial amount of carbon (C) and nitrogen (N) within the vegetation and the soil (Lal, 2004; Nosetto et al., 2006). Yet, most of these areas are prone to desertification, because of human activity and climate changes. With sandy desertification productivity sharply declines and a large amount of C and N is lost (Lal, 2004; Tschakert, 2004). These C and N losses due to desertification are a globally significant pool and contribute to the increase in atmospheric CO_2 (Lal, 2009). However, because desertified areas lost a large amount of C and N, ecosystem restoration not only increases productivity, but also sequesters a large amount of C and N.

Within the arid and semiarid regions of northern China, grasslands with sandy soils are highly vulnerable to wind erosion (Li et al., 2009). Sandy grasslands also contribute to a substantial proportion of the C flux in terrestrial ecosystems (Li et al., 2012; Peichl et al., 2012; Xie et al., 2005). Within sandy grasslands more than 90% of C and N is stored in the soil (Chen et al., 2012; Li et al., 2009). Several studies have shown that the identity of the dominant species during restoration can have a significant impact on C and N accumulation (Bardgett et al., 1999; Jiang et al., 2011). Many studies have also suggested that species richness increases plant biomass which can increase C and N accumulation in the soil (Dijkstra et al., 2005; Fornara and Tilman, 2008; Reich et al., 2001; Steinbeiss et al., 2008). Within sandy grasslands we have also found a positive relationship between species diversity and plant biomass (Zuo et al., 2012). Thus, to understand how sandy grassland restoration influences soil C and N accumulation, we need to consider plant biomass, the identity of the dominant species and the diversity of the plant community.

Horqin Sandy Land is located in the semi-arid area of southeast

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Inner Mongolia and is one of the most severely desertified regions of northern China (Li et al., 2009; Zhao et al., 2005). Since the 1970s, grazing exclusions had been implemented to stabilize dunes and restore the natural vegetation. Desertified sandy grasslands are characterized as mobile dunes, with more than 90% baer soil. Because Horqin Sandy Land has an annual precipitation of 350–500 mm and abundant seed sources remain (Li et al., 2012; Liu et al., 2009b), grazing exclusions allow pioneer plants to establish and survive and a succession from mobile dunes to semi-fixed and to fixed dunes occurs. To understand the restoration process, studies on vegetation (Qiao et al., 2012; Zuo et al., 2009), soils (Chen et al., 2012; Huang et al., 2012), soil macro faunal and microbial communities (Liu et al., 2009b; Wang et al., 2011) and vegetation-soil relationships (Zuo et al., 2014) have been carried out in recent years. However, potential changes in C and N sequestration after restoration remain to be evaluated.

The objective of this study was to examine how ecosystem C and N pools are distributed across a sandy grassland restoration sequence, and thus to evaluate the potential of C and N increases as sequestration restoration advances. We tested three hypotheses: 1) total ecosystem C and N storage increase with restoration; 2) soil stored the majority of C and N; and 3) species richness and biomass positively increase C and N sequestration.

2. Materials and methods

2.1. Site description

The study was conducted in a sandy grassland ecosystem in Horqin Sandy Land (42°55′ N, 120°42′ E; 360 m elevation), Inner Mongolia, Northern China. The area has a continental semi–arid climate, the annual mean temperature is around 6.4 °C, with a minimum monthly mean temperature of −13.1 °C in January and a maximum of 23.7 °C in July. Annual average precipitation is 360 mm, with 75% during the growing season of June to September. The annual mean wind velocity ranges from 3.2 to 4.1 m s^{-1}, and the prevailing wind direction is northwest.

This region is characterized by a mosaic of mobile dune, semi-fixed dune, fixed dune and grassland patches (Chen et al., 2012; Guo et al., 2008; Liu and Yan, 2010; Qiao et al., 2012). Soils are classified as sandy chestnut soils, vulnerable to wind erosion and plant distributions strongly respond to soil variability (Zuo et al., 2009). The dominant pioneer species on mobile sand dunes is *Agriophyllum squarrosum*. In semi-fixed dunes, the dominant species is *Artemisia halodendron*, an asexually-reproducing shrub adapted to slight sand burial. Fixed dunes are dominated by the forb *Artemisia scoparia*, and grasslands are dominated by the annual forb *A. scoparia* and the perennial grasses *Phragmites communis and Pennisetum centrasiaticum*.

2.2. Sampling design

All field sampling was conducted in August of 2013. We selected 24 sampling sites corresponding to the four typical successional habitats (6 replicate sites per habitat) along a restoration gradient of sandy grasslands, including mobile dune (MD) with less than 10% vegetation cover, semi-fixed dune (SFD) with 10–60% vegetation cover, and fixed dune (FD) with more than 60% vegetation cover and grassland (G) with more than 60% vegetation cover (Liu et al., 2009a; Zuo et al., 2012). These sites were located at 0.5–8 km distance from each other (Fig. 1). Semi-fixed dunes and fixed dunes were naturally restored from mobile dunes by fencing out livestock at some point between 1980 and 1995. Grassland sites were fenced to exclude livestock in 1996, thus grassland represents a relatively good vegetation type in this region.

At each site, we established one 20 × 20 m plot in an area with flat topography (slope < 5°). Five 1 × 1 m quadrats were set up at the four corners and the center in each plot to survey the vegetation and collect soil samples. The number of plant species and plant cover by species was recorded in each quadrat. Above-ground biomass was harvested and litter was collected within each quadrat.

After the litter layer was removed in each quadrat, roots were sampled at four depth layers (0–10, 10 to 20, 20 to 40 and 40–60 cm) using an 8 cm-diameter soil auger. Concurrently, three random soil samples were collected at each layer within each quadrat using a 3 cm-diameter soil auger, and pooled to form one composite sample for laboratory analysis. Soil samples were air-dried and hand-sieved through a 2-mm screen to remove roots and other debris. For soil bulk density, soil samples were collected in 5 cm increments using a soil auger equipped with a stainless-steel cylinder (5 cm in both diameter and height) and the bulk density was calculated as the average of two or four samples for each of the above mentioned four soil layers (Li et al., 2013).

Roots were washed and handpicked over a 1-mm screen to remove all soil, pebbles and debris. The aboveground biomass, litter and roots were dried at 60 °C for 48 h and were ground using a mill (Pulverisette 14, Germany). Soil samples for bulk density were dried at 105 °C for 24 h. Soil total C and total N concentrations were determined with an elemental analyzer (Vario Macro cube, Elementar, Germany). Data from different depths of five quadrats were averaged to calculate the root biomass, soil C and N content and bulk density at each depth in every plot.

Soil % C and % N were converted to g C and N m^{-2} with the corresponding soil bulk density. Plant and root % C and % N were converted to g C and N m^{-2} by considering the biomass sampled per area unit. Data from five quadrats were averaged to allow us to estimate the mass of C and N in aboveground plant, litter, root, soil, plant system (aboveground plant, litter and root) and total ecosystem (plant–soil system) at each plot.

2.3. Statistical analysis

All data were expressed as mean ± 1 SE (n = 6). Overall patterns in the aboveground biomass, C and N content in plant and litter and total C and N pools data in the different restoration stages was compared with a one-way analysis of variance (ANOVA). The effects of successional habitat and soil layer on soil variables, root biomass and its C and N content were analyzed by a two-way ANOVA. We used a least-significant-difference (LSD) test to compare different restoration stages, if a measured variable was significant ($P < 0.05$) in the ANOVA. All tests were performed with SPSS (version 16.0).

3. Results

3.1. Characteristic of biomass, C and N contents in plant systems

Aboveground plant biomass, litter mass and their C and N contents were significantly different among the four successional habitats (Table 1, $P < 0.01$). Plant biomass and litter mass increased with advancing sandy grassland restoration. Grassland had the highest aboveground plant C content and mobile dune had the highest aboveground plant N content. The litter C content in mobile dune and semi-fixed dune was higher than that of fixed dune and grassland, and semi-fixed and fixed dune had a lower litter N content, as compared to the mobile dune and grassland. Root biomass and C and N contents significantly differed between the 0–10 cm and 10–20 cm depth layers ($P < 0.01$). Root biomass also differed between the 20–40 cm and 40–60 cm depth layers ($P < 0.05$), but not for C and N content (Table 2).