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Organic carbon in soil physical fractions under different-aged plantations of Mongolian pine in semi-arid region of Northeast China

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ABSTRACT

In order to understand the changes of surface soil carbon (C) storage following the afforestation of sandy grasslands, we used physical fractionation procedures to quantify C concentrations and sucrase enzyme activity in bulk soil and different particle fractions along two replicate chronosequences of Mongolian pine (*Pinus sylvestris* var. *mongolica* Litv.) plantations in the southeastern Keerqin Sand Lands, Northeast China. Carbon concentration in bulk topsoil (0–15 cm) initially decreased following afforestation of grassland and subsequently increased as the forest matured. In general, this pattern of C concentration changes was associated with all particle-size fractions (except clays) and both macro- and microaggregates. The patterns of topsoil C were also influenced by wind erosion and deposition, with marked increases in the relative mass of silt and fine sand fractions occurring during forest development. The loss of aggregates immediately following afforestation was counteracted by formation of aggregates as the forests developed, contributing to the stabilization of carbon. To enhance soil C storage during afforestation of sandy soils in such semi-arid regions it is recommended to minimize disruption of grassland vegetation during the planting stage.

1. Introduction

Land use and land cover changes have been shown to have significant impacts on soil physical structure that often result in changes in soil organic carbon (C) storage and turnover (Jastrow, 1996; Six et al., 2002). The restoration of degraded arid and semi-arid lands by the introduction of woody species has become a worldwide method for protecting soils, combating desertification, supplying timber, and increasing C sequestration (Kumar et al., 2001; Grünzweig et al., 2003; Maestre and Cortina, 2004; Nosetto et al., 2006; Lal, 2009). Although it is certain that afforestation will contribute to C sequestration in forest biomass, the impact that forest planting will have on soil C storage is much less certain, and may vary with other factors such as precipitation, soil texture, stand age, and forest type (Archer et al., 2001; Davis and Condron, 2002; Guo and Gifford, 2002; Paul et al., 2002). Soil C sequestration may be limited if rates of C mineralization increase during afforestation; this effect can be facilitated by coarse soil texture and low-activity clay mineralogy (Richter et al., 1999; Paul et al., 2002). Knowledge of the changes in soil organic C following grassland afforestation is incomplete, and more data are needed (Nilsson et al., 1995; Jackson et al., 2002; Grünzweig et al., 2003; Nosetto et al., 2006), particularly for the extensive semi-arid sandy soils of northern China (Hu et al., 2008).

In recent decades, afforestation has become an increasingly important method of land-cover change in the arid and semi-arid regions of northern China, including extensive sandy areas (1.53×10^6 km^2). These plantations have been established in the interest of desertification control and timber production in sandy areas (Chen et al., 2006; Zeng et al., 2009). The Mongolian pine (*Pinus sylvestris* var. *mongolica* Litv.) is one of the most commonly planted trees. By 1998, the area of Mongolian pine plantations had reached 1.78 million ha in Inner Mongolia (State Forestry Administration of China, 2000). The planting of Mongolian pine began in the 1950s in Zhanggutai, Zhangwu County, Liaoning Province, located in the southeastern Keerqin Sand Lands (Fig. 1). It seems likely that this extensive change in land use could profoundly affect soil C dynamics, yet little is known about the effects of this afforestation activity on soil C stocks (Hu et al., 2008).

Several processes could influence net C storage following afforestation of the Sand Lands with pine. First, increased rates of C mineralization or decreased *in situ* supply of detrital C could reduce soil C storage immediately following afforestation (Richter et al.,

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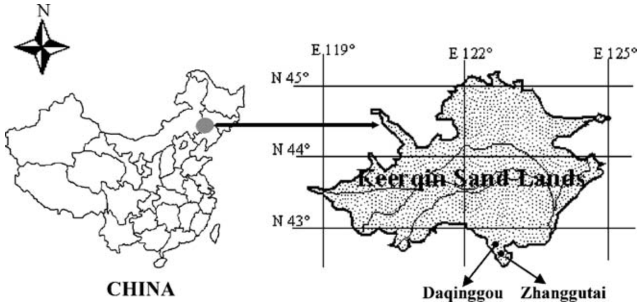

Fig. 1. Map of research region (southeastern Keerqin Sand Lands), and two Mongolian pine afforestation chronosequences (Zhanggutai and Daqinggou) in Northeast China.

1999; Guo and Gifford, 2002). Second, as the forest develops net C accumulation could occur as a result of increased detrital production and protection of soil organic matter by physical or biotic mechanisms (Kuzyakov et al., 2000). In particular, soil organic matter dynamics have been linked to changes in soil physical structure, especially aggregate formation (Six et al., 2000, 2002; Allison and Jastrow, 2006).

The objective of the present study was to evaluate the response of soil C pools in topsoil to afforestation of degraded grassland, with pine in the Keerqin Sand Lands, Northeast China. We conducted a study on two replicate chronosequences of pine plantation in this region. Based in part on previous studies of stand development on other sites in this region (Zhao et al., 2007; Hu et al., 2008; Chen et al., 2009), we hypothesized that topsoil C storage would decline initially following plantation establishment, as a result of reduced detrital inputs and possibly accelerated losses by mineralization and wind erosion. Thereafter, we expected accumulation of C in topsoil accompanied by increasing protection of C in micro- and macroaggregates.

2. Method

2.1. Study area

The study area is located in the southeast of the Keerqin Sand Lands (Fig. 1), a sub-humid arid area in the temperate climatic zone. It has average annual precipitation of 450 mm, with more than 60% occurring in June–August; annual potential evaporation of 1300–1800 mm; and average annual temperature of 6.3 °C, with the lowest monthly mean temperature occurring in January (−12.5 °C) and the highest in July (23.8 °C). The mean annual frost-free period is 145–150 days. The native vegetation in the study area is grassland (dominated by *Artemisia scoparia*, *Pennisetum flaccidum*, *Erodium stephanianum*, and *Phragmites communis*), and grass-elm savanna (*Ulmus pumila*). The soil is an aeolian sand (Typic Ustipsamment), developed from sandy parent material through the action of wind, with low organic C, nitrogen, phosphorus contents (Chen et al., 2002) and 10–12% water holding capacity.

2.2. Study plots

Two chronosequences of pine afforestation were established in the study area, one in Zhanggutai Town of Zhangwu County, Liaoning Province (42°43′N, 122°22′E) and another in Daqinggou National Nature Reserve (42°45′N–42°48′N, 122°13′E–122°15′E). Both areas have a long history of livestock grazing, but grazing intensity has been lower in the latter area where it was eliminated on establishment of the reserve in the mid-1990s. Each chronosequence consisted of a young (12–14 years), mid-aged (20–25 years) and old (32–40 years) pine plantation as well as adjacent grassland. Each of the plantations was established by planting nursery-raised seedlings in pits of 40 cm × 40 cm × 40 cm size, with a spacing of 3 m × 1 m or 2 m × 2 m. Pruning of about 25% of the crown was conducted after 15–17 years of afforestation (Hu et al., 2008).

All the chosen forest and grassland stands have southerly aspects, and are on slopes of <5°. All stands are characterized by similar soil and climatic conditions. We established study plots of 20 m by 20 m in each of the two study areas. The basic stand characteristics of the experimental plots were measured in July 2007 by taking the diameter at breast height of each tree and estimating canopy height with a clinometer (Table 1).

2.3. Sample collection

Each plot was further divided into four subplots (10 m × 10 m). In each subplot, we removed surface litter and randomly collected five soil cores in the 0–15 cm layer with an auger (inner diameter of 5 cm), and then the five soil cores were composited into one sample. Therefore, we obtained four samples for each plot. Soils were transported on ice to the laboratory and stored at 4 °C.

Field-moist soils were processed within 3 days of collection by gently breaking apart cores along natural break points, then passing the soil through an 8-mm sieve. Root pieces and organic debris (not incorporated into aggregates and longer than 8 mm) that passed through the sieve were removed. After thorough mixing, a subsample was air-dried for soil organic C analysis of each bulk sample. Another subsample of the bulk soil was frozen at −20 °C for enzyme analysis. The remaining soil was stored at 4 °C until it was needed in one of three separate fractionation procedures (below) within another 20 days. Like the bulk soil, part of soil fractions after fractionation were air-dried for soil organic C analysis, and part of these were frozen at −20 °C for enzyme analysis.

2.4. Soil fractionation procedure

Particle-size distributions of soil samples were determined by wet sieving following a modified version of the Cambardella and Elliott (1993) procedure. Particle fractions were retained for measurement of C concentration and sucrase activity.

Table 1
Vegetation characteristics in two Mongolian pine afforestation chronosequences in the Keerqin Sand Lands, Northeast China measured in July 2007.

Stand symbol	Ecosystem type	Stages	Age (years)	Density (trees ha^{-1})	Basal area of trees ($m^2 ha^{-1}$)	Height (m)	Location
G1	Grass	Grassland	0	0	0	0	Daqinggou
P1	Mongolian pine	Young	12	1000	5.02	4	Daqinggou
P3	Mongolian pine	Middle-aged	20	1000	11.30	6	Daqinggou
P5	Mongolian pine	Old	32	850	26.69	12	Daqinggou
G2	Grass	Grassland	0	0	0	0	Zhanggutai
P2	Mongolian pine	Young	14	825	4.15	4	Zhanggutai
P4	Mongolian pine	Middle-aged	25	1000	25.43	10	Zhanggutai
P6	Mongolian pine	Old	40	750	36.80	16	Zhanggutai

Mean ± 1 SE (n = 4).