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Variation of soil carbon pools in *Pinus sylvestris* plantations of different ages in north China

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ABSTRACT

Plantations play an important role in absorbing atmospheric CO_2 and plantation soil can serve as an important carbon (C) sink. However, the stocks and dynamics of soil C in differently aged plantation forests in north China remain uncertain. In this study, we measured soil inorganic carbon (SIC), soil organic carbon (SOC) and total nitrogen content (STN), the light (LF) and heavy fractions (HF) of soil organic matter (SOM) to a depth of 1 m in 3 different ages (10-, 30-, 40-year-old) of *Pinus sylvestris* var. *mongolica* (Mongolia pine) plantations in 2011 and 2012. Soil pH, texture and moisture were also measured to explore the causes of SOC dynamics for different stand ages. Our results showed that no significant difference in SIC content was observed at different soil depths. As forest age increases, SIC content as well as the C and N content in SOM, LF and HF initially rose and then decreased, while the LF in SOC initially decreased and then increased. Although the C:N ratio of SOC and HF did not significantly change, the C:N ratio of LF increased with depth. SOC dynamics at different stand ages were significantly correlated with soil moisture and clay content. Soil pH and moisture explained 58.63% of the overall variation of SOC at different depths. Moreover, the SOC increased during the early stage of afforestation, mostly because of the increase in recalcitrant C; however, the decrease of SOC with increasing stand age was also mainly affected by C loss in the recalcitrant C pool.

1. Introduction

As the biggest carbon (C) pool in the world, the soil contains over 3300 Pg C [1], more than the total amount of C stored in the atmosphere and the plants. Soil C of forest ecosystems is an important part of the global C pool, holding 70–73% of all soil organic C (SOC) globally [2]. Therefore, even a slight change in the C pool of forest soil will generate significant impacts in the global C cycle, and will affect the balance of the ecosystem and global climate [3–4]. In recent years, human activities such as deforestation have damaged the previously existing balance of the global C cycle, and consequently cause increase of the concentration of CO_2 in the atmosphere [5–6]. Importantly, afforestation is believed to promote the capacity of soil to sequester C and to diminish the concentration of CO_2 in the atmosphere [5,7–8].

China has the world's highest afforestation rate. The implementation of a series of afforestation projects in China has expanded the growth of newly planted forest that enhances the C sink function of China's forests [9]. Huang et al. [10] reported that China's plantation forests reserve is 7.90 Pg C including 78.6% from the SOC, and afforestation activities will result in the fixation of 3.17 Pg C by 2050. Therefore, exploring the spatial-temporal change of soil C pool of Chinese plantation is of great significance to the research on the C cycle process of ecosystem, the management of anthropogenic C emissions, and the prediction how the forest C pool will change in the future.

However, great uncertainties exist in the role of different plantations and study sites in C fixation. For example, Jackson et al. [11] found that replacing grassland with woody plants would increase SOC content in arid regions, although this would decrease SOC in relatively humid regions. No consistent conclusions have been drawn related to changes and trend of the soil C pool after afforestation. The changes of the soil C pool in planted forest ecosystem are influenced by numerous factors, including soil texture, tree species, climate, human disturbance, land use history and so on [12–15]. The SOC pool may increase after afforestation [16–17]. Alternatively, it may remain stable [18–20], or initially decrease then increase [14]. Li et al. [21] collected the plantations data globally to conduct a meta-analysis, they found that the plantation type significantly influenced soil C storage. Therefore, specific research based on the specific conditions of different ecosystems should be conducted to make more accurate conclusions in the dynamics of C pool of plantations.

Soil C contains functional components that have different turnover times [22–25]. The soil density classification method is usually used to

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separate soil organic matter (SOM) into the light and heavy organic matter fractions. The former is not closely combined with mineral soil (the density is lower than 1.6 to 1.9 g cm^{-3}) and the latter has already formed organic-mineral compounds (the density is higher than 1.6 to 1.9 g cm^{-3}) [26]. The light organic matter fraction represents active organic matter that readily decomposes, holding great significance in organic matter dynamics, plant nutrition and other aspects of soil, while the heavy organic matter fraction represents the long-term and stable SOM [27]. The light and heavy organic matter fractions vary in several ways, including their decomposition rates, their physical and chemical properties [27–28], the amounts stored in planted forests of different ages [29–30], their speed of decomposition and recovery [19,31] and the vertical distribution of the fractions in different components of the soil [32–35]. Turner et al. [36] demonstrated that soil C in planted forest initially decreased after afforestation, with most soil C originating from losses of labile C; while the recovery of labile C pool resulted in the recovery of soil C storage. Similarly, George et al. [31] discovered that the labile SOM recovered faster than the heavy fraction after afforestation in regions with a Mediterranean climate. However, very few studies have addressed the dynamics in the light and heavy C fractions across different stages of development in planted forests [37].

Saihanba Forestry Center is the largest plantation base in China. According to the local historical records, this area was once covered with thick woods and intact vegetation. However, large-scale logging removed these historic forests completely. Therefore, we chose this plantation to study the soil C pool and its components of differently aged Mongolia pine forest in Saihanba. The aim of our study is to explore the stocks and dynamics of soil C in differently aged plantation. Our scientific questions include: (1) How does the amount of the soil C pool change during the different developmental stages of planted forests; (2) Will the variation of C and nitrogen (N) content in light and heavy fractions of soil in accordance with the total C and N pools, during the different stages of plantation development? Our scientific hypotheses are: (1) with increasing stand age, the total C pool of the soil will increase correspondingly because of the accumulation of litter fall; (2) with increasing stand age, the light and heavy fractions of SOC will accumulate, but given that the light organic matter fraction seems more sensitive to the environmental change, this fraction may decrease more rapidly during afforestation, while it may also recover faster.

2. Materials and methods

2.1. Site information

Beginning at the end of the 1950s, the Beijing-Tianjin area seriously suffered from increasing sandstorms. These sandstorms gave rise to an urgent need for the management of dust in these source areas. Thus, government agencies supported a large-scale afforestation action in Saihanba, Hebei Province, northwest of Beijing-Tianjin area. Saihanba Forestry Center was officially established in 1962. Land managers supervised the planting of forests, resulting in a 72,400 hm^2 plantation, with 77.5% covered with Mongolia pine as the dominant tree species. Our study site was located at the Saihanba Forestry Center (42°10′–2°50′N, 117°12′–17°30′E), covering major landforms of the Inner Mongolian Plateau in Bashang and the mountainous region in Baxia at elevations of 1010 to 1939 m. This study site supports abundant wild resources and various types of vegetation. It also covers a typical transition zone between cropping and nomadic areas that form the forest-grassland ecotone in temperate areas of China. The main forest types include cold-temperate coniferous forests and broadleaved deciduous forests.

The semi-arid and semi-humid climate of this high elevation region features long and cold winters, a short spring, and a relatively cool summer with an annual average temperature of −1.4 °C. The frost-free season lasts only 67 days, and daily temperatures range widely with high winds. The annual average precipitation is 450.1 mm, exhibiting an obvious southeast-to-northwest gradient. The soil was mainly sandy, with some meadow and marsh soils.

In our study, we selected 3 differently aged (10, 30, 40 years) Mongolia pine plantation forests, which were all covered by *Leymus chinensis* grasslands before the afforestation, and pure *P. sylvestris* forests were then planted in similar slope, direction and elevation. In addition, no treatments such as fertilization and irrigation were conducted after afforestation [41]. On the other hand, the sites selected cover 1.25 ha (age 10 years), 5 ha (30 years) and 10.14 ha (40 years), but are <10 km away from each other.

2.2. Experimental design

To study the effects of stand age on the soil C pool, we employed a space for time substitution approach in which the soil C stocks in stands of different ages are measured. The space-for-time substitution method has been used extensively for studying the rates of change in soil C stocks with time since afforestation under the assumption that only the time parameter changes [16–20,38–40]. Nevertheless, this approach is restricted by possible confounding site-related factors while at the same time it provides an integrated assessment of changes in soil C stock within a larger area. In our study, as is mentioned in the last paragraph of Section 2.1, the similar past and present as well as the short distance between the 3 sites reduce differences in climate and soil properties, which enable an ideal chronosequence for studying the effect of stand age on the soil C pool. Table 1 provides the details related to the experimental sites.

From July to August 2011 and 2012, each study unit was established as a 20 × 50 m^2 area. Five 10 × 10 m^2 sample quadrats were set up along a W-shaped route from each unit in the 3 plantation sites. In addition, 1-m-deep soil profile near the outside of each quadrat was measured. Soil bulk density was measured for 0–5, 5–10, 10–20, 20–30, 30–60, 60–100 cm deep soil layers using a cutting ring on the soil profile. As an exception, the 40-year site had hard rock in the 60–100 cm layer with little soil. We chose 25 sampling points in each quadrat (10 × 10 m^2), divided soil profiles into 6 layers, except for the 40-year site were only the upper 5 layers. At each site, every 5 sample points, numbered a–e in the unit of survey quadrats, are combined into 1 mixture sample (5 survey quadrats; Fig. 1). Soil samples of 6 layers were separated during the step of mixture. Large tree roots and gravel were removed and soil structure was kept as much as possible. After evenly blended, the weight of each fresh soil sample was no <350 g. Each was placed in the shade and transported to laboratory as soon as possible. Finally, 25 analytical samples had been collected for each layer at each site; the total samples of 1 site each year were: 25 groups of mixtures × 6 layers = 150 samples. We set aside about 100 g of fresh soil samples, dried other 250 g under room temperature. Then, dried samples were screened with a 2 mm sieve. All the steps were done uniformly, and the items that can be easily seen, such as gravel and plant roots, were removed.

2.3. Soil organic matter

We dried the soil pillars that had been collected with cutting rings to a constant weight at 105 °C and measured the soil bulk density [42]. An Eijkelkamp Calcimeter ART carbonate analyzer (Gelderland, Netherlands) was used to measure soil inorganic C content [43]. To separate the organic matter fractions in the soil, we weighed 5 g dry soil and put it into a 50 mL centrifuge tube, then added 25 mL 1.70 g mL^{-1} NaI solution into the tube. The mixture was oscillated for 1 h at 250 r min^{-1}. After oscillation, the liquid mixture was continuously centrifuged for 10 min at 3000 r min^{-1}. The supernatant were filtered through a 0.45 μm aperture and 7 cm diameter glass fiber filter. The light fraction (LF) was left on the filter and the supernatant were collected to recycle. Then the above steps were repeated for three times until there were no aerosols in the solution. We washed the supernatant twice with 50 mL deionized water, dried and weighed it (W_{HF}, g), giving

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