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Soil stoichiometry and carbon storage in long-term afforestation soil affected by understory vegetation diversity

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ABSTRACT

The afforestation of abandoned land could offer opportunities to sequester soil organic carbon (SOC), promote nutriment elements cycling, improve plant diversity in the plantation understory and provide ecosystem services. The objectives of this study were to identify plant diversity in the plantation understory, quantify the changes in SOC and total nitrogen (TN) storage in deep soil, assess the SOC, TN, and total phosphorus (TP) stoichiometries, and investigate their relationships in the Loess Plateau Region (LPR) undergoing long-term afforestation. Soil samples were collected at a soil depth of 0–200 cm under 30-yr old *Robinia pseudoacacia* L. and adjacent abandoned sites, and SOC, TN and TP were determined in different soil depth. Additionally, plant composition and diversity in the plantation understory were evaluated. The results showed that land subjected to long-term afforestation had greater plant coverage, plant density, richness index (R) and Shannon–Wiener diversity (H) compared to abandoned land communities ($P < 0.05$). SOC, TN and TP contents in afforested sites were significantly increased in surface soil (0–30 cm) as well as in the underlying soil (100 cm) compared to the corresponding abandoned land sites ($P < 0.05$) in most cases. Meanwhile, SOC, TN, and TP stoichiometry in afforested areas were higher than those of abandoned lands and significantly related to understory vegetation diversity ($P < 0.05$). In addition, lands subjected to long-term afforestation effectively increased SOC and TN storages compared to abandoned land at soil depths of 0–30 cm and 100–200 cm and were also significantly related to understory vegetation diversity ($P < 0.05$). These findings demonstrating that afforestation not only affects SOC and TN stocks in surface soil, but also strongly influences that in deep soil. And it is also indicating that long-term afforestation could greatly affect soil R_{CN}, R_{CP}, and R_{NP} ratios.

1. Introduction

Afforestation areas, which occupy approximately 0.20 billion ha worldwide, could effectively help mitigate increasing atmospheric CO_2 (Zhong et al., 2013). Afforestation also affects the establishment of natural vegetation and understorey ecology via resource competition (i.e. Bremer and Farley, 2010), allelopathy (i.e. Zhang et al., 2010). In addition, plant diversity in the plantation understory plays important roles in improving stimulating the soil nutrient cycling and maintaining soil quality after afforestation (Halpern 1995; Wang et al., 2011). Brockerhoff et al. (2003) reported that wider tree spacing during plantation establishment supports better maintenance of understorey vegetation. Zhang et al. (2014) found that the first four years after the establishment of afforestation are associated with lower plant diversity, however, plant diversity was improved after long-term afforestation. Meanwhile, understanding plant diversity in the plantation understory is critical to investigate the ecological functions of plantations and improve their management, especially after long-term afforestation.

Following afforestation, changes inevitably occur in soil physical and chemical elements, particularly in the three main elements: carbon, nitrogen and phosphorus (Adams et al., 2001; Wei et al., 2009). Many studies (i.e. Walker and Adams, 1958; Post et al., 1982; Melillo et al., 2003; Zhong et al., 2013) have indicated that soil carbon, nitrogen, and phosphorus are often closely related. Cleveland and Liptzin (2007) found a well constrained C:N:P ratio of microbial biomass in 0–10 cm

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organic-rich soil globally. Tian et al. (2010) documented that soil C:N, C:P, and N:P ratios in organic-rich topsoil could be good indicators of soil nutrient status during soil development. Zhang et al. (2014) also demonstrated that vegetation cover, plant communities, geomorphology, and seawall all affected C, N, and P stoichiometry in soils. Despite progress made in terrestrial ecosystem restoration methods and analyses (Han et al., 2005; Manzoni et al., 2010) the stoichiometrical characteristics of C, N, and P in soils have yet to be fully described (Swift et al., 1998; Manzoni and Porporato, 2009), especially in the Loess Plateau Region (LPR) of China.

Approximately 75% of total terrestrial C is stored in the world's soils (Henderson 1995), and forest soils hold approximately 40% of C belowground (Dixon et al., 1994). Therefore, even if afforestation only slightly affects soil C stocks at the local level, it could have a significant effect on the global C budget (Paul et al., 2002). Sean et al. (2012) illustrated that changes in soil organic carbon (SOC) due to afforestation are negatively related to mean annual precipitation and positively correlated with plantation age. Nave et al. (2012) also demonstrated that afforestation has significant positive effects on SOC sequestration in the United States, although these effects require decades to manifest and primarily occur in the uppermost portion of the mineral soil profile. Thus, long-term afforestation is a better management option for increasing terrestrial C sequestration.

It has been reported that more than 50% of total SOC is stored in the subsoil (at a depth below 50 cm) (Amundson, 2001), and at least 61% of the total soil C is stored below a depth of 30 cm depth in the northern circumpolar permafrost region (Guo and Gifford, 2002). In recent decades, many studies have illustrated that subsoil C may be even more important than topsoil C as a source or sink for CO_2 than topsoil C (VandenBygaart et al., 2010; Rumpel and Kögel-Knabner, 2011). Thus, considering the potential role of SOC as an atmospheric CO2 sink it is important to understand whether the long-term afforestation affects large amounts of SOC in the subsoil or deep soil. However, the C and N storages in deep soil layers are not fully understood in LPR of China to date.

The LPR is an important geological region that influences the global carbon cycle (Wang et al., 2010a,b). Vegetation coverage in the LPR is relatively low due to its harsh environment (Wei et al., 2012). Soil erosion and desertification in LPR reduced net primary productivity by 12 kg C ha^{-1} $year^{-1}$ (Bai and Dent, 2009). Since the 1950s, the Chinese government has made great efforts to control soil erosion and restore ecosystems (Fu et al., 2002). More than 9.27 million ha of abandoned farmland (investment of more than 28.8 billion USD and with the involvement of 0.12 billion farmers) have been afforested in this region through the "Grain to Green Program" (GTGP), which has implemented large-scale ecological rehabilitation since 1999 (Lü et al., 2012). However, few studies have reported the plant diversity, soil C:N:P stoichiometry, carbon storage in deep soil and their relationships after long-term afforestation in this region until recently. Thus, this study aimed to: (a) analyze the plant diversity in the understory after long-term afforestation; (b) illustrate the soil C:N:P stoichiometry and assess SOC and N storage in different soil depths; and (c) evaluate the relationship between plant diversity, soil C:N:P stoichiometry, and soil C and N storages after long-term afforestation.

2. Methods and materials

2.1. Research area

The study was conducted in the Wuliwan catchment (36°46′42″–36°46′28″N, 109°13′46″–109°16′03″E), which is located in Ansai county in the central region of LPR (see Fig. 1). Ansai is a typical county characterized by a semi-arid climate and a hilly loess landscape in the Loess Plateau. it has an annual average temperature of 8.8 °C, and an average annual precipitation of 505 mm. 60% of the precipitation which occurs between July and September (~300 mm in dry years while >700 mm in wet years). Accumulated temperatures above 0 °C and 10 °C are 3733 °C and 3283 °C, respectively. On average, there are approximately 157 frost-free days and 2415 h of sunshine each year. Arable farming mostly occurs on sloping lands without irrigation. The loess parent material at the site has an average thickness of approximately 50–80 m and the soil in this region is Calciustepts soil (Gong et al., 1999). Sand (2–0.05 mm) and silt (0.05–0.002 mm) account for approximately 29.22% and 63.56% of the material at a soil depth of 0–20 cm, respectively. The soil is highly erodible, with an erosion modulus of 10,000–12,000 Mg km^{-2} $year^{-1}$ before the restoration efforts began in this region (Liu, 1999). After 30 years of vegetation restoration the area of forested lands, the area of the area of forestland increased significantly from 5% to 40% (Xue et al., 2009).

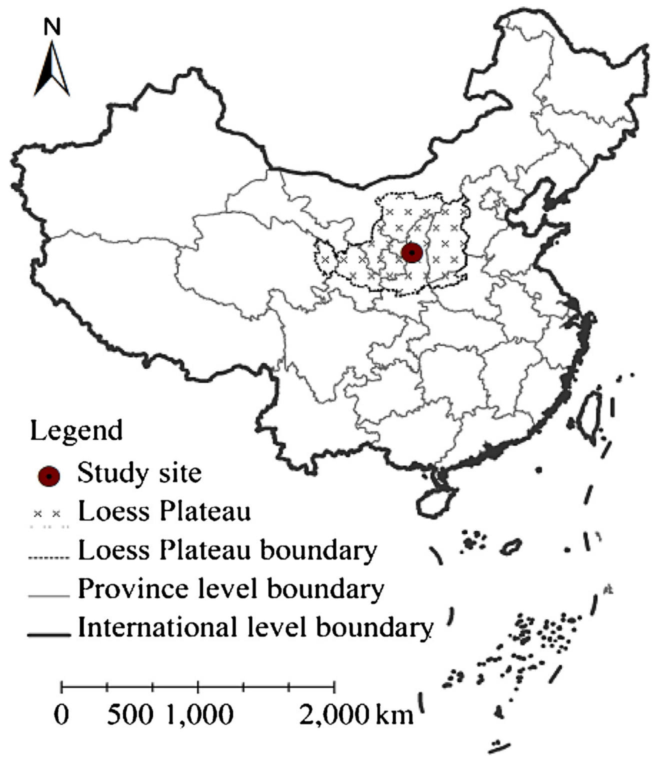

Fig. 1. Location of the Loess Plateau and the study site.

The Wuliwan catchment is one of the experimental sites of the Institute of Soil and Water Conservation, Chinese Academy of Science (CAS). The major agricultural land use type in the LPR is slope cropland. Agricultural management in this region, including the major crop types grown, has not been changed significantly since the 1970s. After more than 30 years of comprehensive management, the ecological environment of the catchment has been significantly improved (Zhang et al., 2007). Beginning in late 1970s, slope cropland was replanted with forest, mainly *Robinia pseudoacacia* L. to control soil erosion. Abandoned cropland was also generated during this period due to its extremely low productivity and long distance from farmers' residences (Li et al., 2004). Despite that wild grasslands and shrub lands were usually found on steep slopes, they were often used for firewood collection resulting in reduced vegetation to barrenness for long periods (80 year).