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Short communication

Carbon–nitrogen interactions during afforestation in central China

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ABSTRACT

We conducted a field study in Danjiangkou Reservoir region of central China to evaluate soil C and N dynamics following afforestation by comparing soil organic C and N (SOC and SON), soil net N mineralization and nitrification, and inorganic N concentrations in the plant rhizosphere and open areas in the forest, shrubland and adjacent cropland. Afforestation increased SOC but did not significantly affect SON in the plant rhizosphere. Due to large quantity of low-quality litter (with high C:N ratios) inputs, afforestation enhanced soil C recalcitrant indexes (RIC) but decreased soil N recalcitrance indexes (RIN) in the plant rhizosphere. Both SON and RIN significantly decreased following afforestation in the open areas. Afforestation decreased inorganic N concentrations and net N mineralization. Soil net N mineralization were negatively correlated with soil C:N ratios across land use types. These results suggest that afforestation could increase SOC stocks resulting from large low-quality litter input, but over the long-term, this increase was likely limited due to decreased soil N availability.

Afforestation has been proposed as an effective method for reducing the atmospheric CO_2 concentration because of the ability to sequester C in vegetation and soil (IPCC, 2007). Despite numerous studies have been conducted to investigate the contribution of afforestation to C sequestration on both regional and global scales (Richter et al., 1999; Paul et al., 2002; Powers et al., 2011; D.J. Li et al., 2012; M. Li et al., 2012), effect of afforestation on soil C accumulation remains a widely debated topic (Smal and Olszewska, 2008; Mao and Zeng, 2010; Hernandez-Ramirez et al., 2011). For instance, Hernandez-Ramirez et al. (2011) demonstrated that afforestation caused increases in soil C due primarily to large litter production. In contrast, Smal and Olszewska (2008) reported that soil C decreased during afforestation when litter input is low with uneven spatial distribution. Vesterdal et al. (2002) inferred that soil C would increase following subsequent rooting and canopy closure during afforestation. Among those inconsistent controversies, increased nitrogen (N) availability and soil C recalcitrance index (RIC, the ratio of unhydrolyzable C to total soil organic C) due to large litter input have been considered to be two major mechanisms for determining C accumulation in afforestation soil over the long-term (Luo et al., 2004, 2006; Rovira and Vallejo, 2007). Particularly, rooting and canopy closure are largely dependent of soil N availability. Whether the open areas without plant cover during afforestation can retain C and N in soil has not been well tested. In this study, we quantified soil organic C, N dynamics and their recalcitrance indexes in the Danjiangkou Reservoir region of central China, where afforested lands have low vegetation coverage and are often a mosaic of large open areas where no litter or root formation occurs due to soil erosion and poor soil fertility (Zhu et al., 2008).

This experiment was conducted at the Wulongchi Experimental Station (32°45'N, 111°13'E) in the Danjiangkou Reservoir region (Cheng et al., 2013). Human activities, such as deforestation and tillage, around the reservoir have resulted in soil erosion, water pollution and soil C and N losses (Zhu et al., 2010; Liu et al., 2012). Approximately 15 years ago, following a reorganization of land usage, a large cropland was converted to a woodland plantation of coniferous plants (*Platycladus orientalis* (Linn.) Franco), and a shrubland plantation (*Robinia pseudoacacia* and *Amorpha fruticosa*) (Zhu et al., 2010).

In the spring of 2010, three stands of approximately75 ha (500 m × 1500 m) including woodland, shrubland, and adjacent cropland were laid out in this study. Within each forest and shrub stand, we randomly placed 12 sub-plots (2 m × 2 m); six sub-plots were situated in plant rhizosphere (i.e., the area within the canopy edge) and six were situated between rows in open areas >1 m that had no input of organic matter from trees and/or shrubs. We collected soil samples from field pathways without crop residues to represent the open areas within the cropland. Samples were taken at

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two depths (0–10 and 10–30 cm) at three randomly selected locations within each sub-plot in the spring, summer and fall of 2010.

The samples were ground until they were fine enough to pass through a 20-mesh (0.84 mm) sieve. An aliquot (approximately 10 g) of dried soil was treated with 1 N HCl for 24 h at room temperature to remove inorganic carbon, and the unhydrolyzed residue was categorized as SOC (Cheng et al., 2006). Soil recalcitrant C (RC) and N (RN) were obtained by acid hydrolysis (Rovira and Vallejo, 2000). Soil C and N recalcitrance indexes (RIC and RIN) were estimated as the ratio of unhydrolyzable C and N to total C and N. In addition to the soil samples, newly produced litter and root biomass (0–10 and 10–30 cm) were measured (Cheng et al., 2006). Soil net N mineralization and nitrification rates were measured using the Polyvinyl chloride (PVC) tube closed top sequential incubation method modified from Raison et al. (1987).

This study demonstrated that soil C stock significantly increased after 15 years of afforestation in the plant rhizosphere, whereas there was no significant difference in SOC in the open areas of three land types in the Danjiangkou Reservoir region (Table S1; Fig. 1a, b). The increase in soil C stock in the plant rhizosphere may be due to the following two aspects. First, soil C accumulation could be largely driven by enhanced litter inputs during afforestation (Jiang et al., 2011). The aboveground litter and root biomass were higher in the woodland and shrubland than in the cropland (Table S1; Fig. S1a–d). Moreover, SOC in the plant rhizosphere was positively correlated with both litter input and root biomass across all land types (Fig. S2a, b). Second, soil C accumulation may also be induced by lower litter quality which may inhibit microbial decomposition (Montane et al., 2007). In this study, soil C:N ratios in the plant rhizosphere increased from cropland to shrubland to woodland (Table S2; Fig. 1e, f) and were positively correlated with the litter and root C:N ratios across all land types (Fig. S2c–d). Additionally, the RIC values in the plant rhizosphere was lower in the cropland soil than the afforested soil (Fig. 2a, b), which should be attributed to an increase in the recalcitrant C inputs to the soil produced by lower-quality litter (higher C:N ratios) in the forest and shrubland, further confirming that there was lower decomposition of SOC in the afforested soil compared to cropland soil (Cheng et al., 2013).

Interestingly, the RIC in the open areas was much lower than in the plant rhizosphere, with a decreasing trend following afforestation ($p < 0.05$, Table S2; Fig. 2a, b). One possible explanation for this observation might be that cultivation promotes more C losses from soil in the labile C pool than in the recalcitrant C pool due to exposing micro-aggregate organic C to microbial decomposition by soil disturbance (Reicosky and Forcella, 1998). Alternatively, labile C from the plant rhizosphere could be transferred into the soil in the open areas after afforestation (Zhu et al., 2010); more input of labile C may stimulate the mineralization rate of recalcitrant pools (Guenet et al., 2010) leading to a priming effect on the recalcitrant C pool in the open area soils (Kuzyakov, 2002). The decreased RIC in the open areas indicates that SOC decomposition might increase following afforestation, which is likely to decrease SOC storage over the long-term (Cheng et al., 2007).

Our results demonstrated that SON did not significantly change in the plant rhizosphere, while SON in the open areas significantly decreased after 15 years of afforestation ($p < 0.05$, Table S2; Fig. 1c, d). This finding is inconsistent with the results of other studies demonstrating that soil N stock increased following afforestation (D.J. Li et al., 2012). The discrepancy between our study and other studies might be partially due to serious soil erosion, large soil N losses and low N deposition in the Danjiangkou Reservoir region (Zhu et al., 2010; Liu et al., 2012). However, SON in afforested soils was higher in the plant rhizosphere than in the open areas ($p < 0.05$; Fig. 1), suggesting that

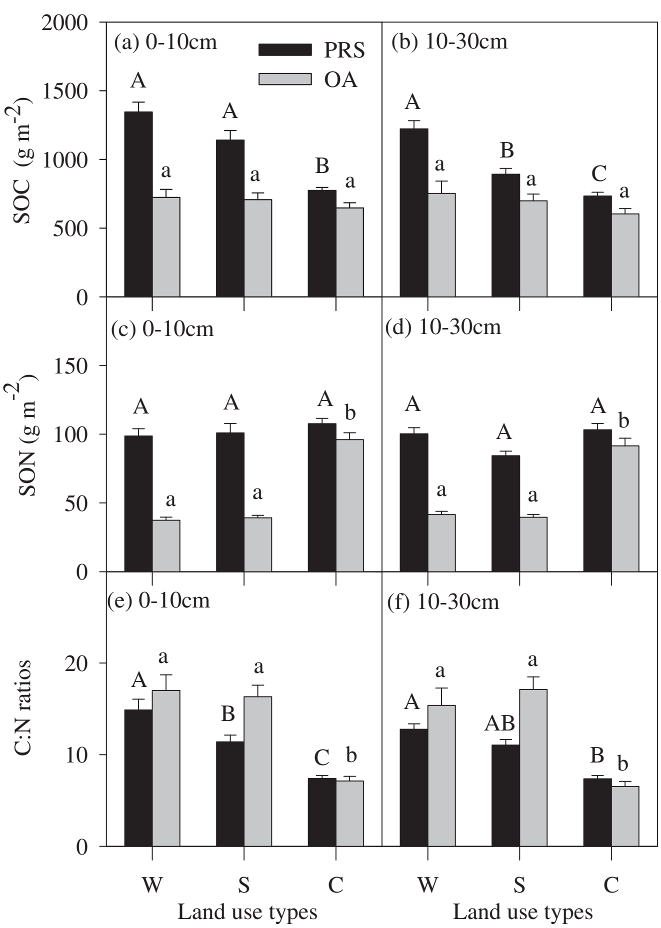

Fig. 1. Annual average of soil organic carbon (SOC), nitrogen (SON) and C:N ratios under different land use. Different capital (plant rhizosphere, PRS) and lowercase (open area, OA) letters over the bars of root indicate statistically significant differences between the land use types. Abbreviations: W, woodland; S, shrubland; C, cropland.

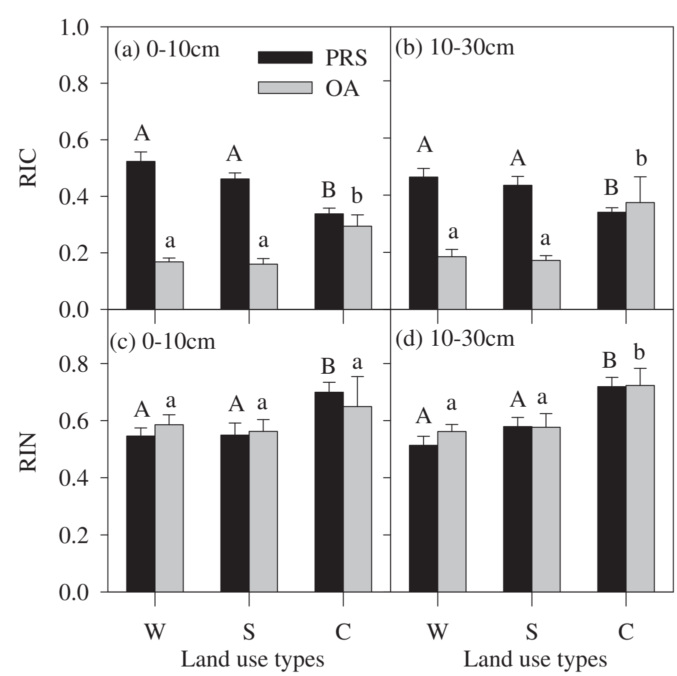

Fig. 2. Annual averages of recalcitrance indexes (RIC and RIN) under different land use. Different capital (PRS) and lowercase (OA) letters over the bars of root indicate statistically significant differences between the land use types. See Fig. 1 for abbreviations.

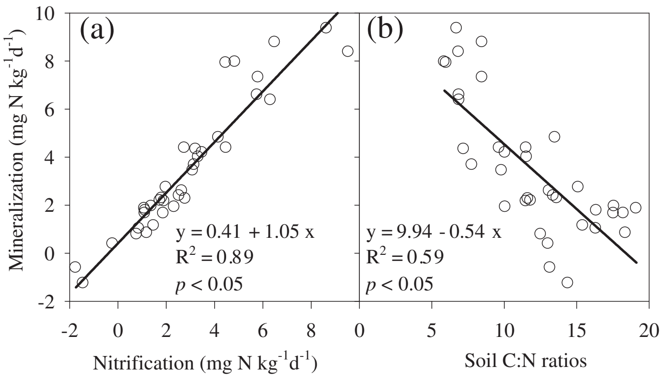

Fig. 3. The relationships of soil net N mineralization rates with nitrification rates (a) and soil C:N ratios (b) cross the land use and seasons.

afforestation could retain N due to the increased plant C supply to the soil and subsequent enhanced microbial N immobilization (Cheng et al., 2011; Laungani and Knops, 2012). A two-year field experiment with straw mulching also confirmed that input of plant litter was effective in reducing soil nitrogen and phosphorus losses in the Danjiangkou Reservoir region, China (Liu et al., 2012).

Afforestation caused slower microbial decomposition due to an increase in the recalcitrant C input, and ultimately regulated N mineralization and availability (Templer et al., 2005; M. Li et al., 2012). The observed negative relationship of mineralization with soil C:N ratios across all land use types indicated that the soil N net mineralization rate was regulated by soil organic SOC quality (Fig. 3b). The quantity and quality of SOC supplied by afforestation can regulate soil N mineralization, which can affect the total amount of soil inorganic N produced and leached from ecosystems (Knops et al., 2002). Similar to other studies, soil N mineralization often drives soil N nitrification (Templer et al., 2005; Fig. 3a). As a result, afforestation significantly decreased soil net N mineralization, net N nitrification and total amount of inorganic N (Table S3; Fig. S3 and S4), which is consistent with previous studies demonstrating that soil net N mineralization decreased by nearly 50% following afforestation (Templer et al., 2005). The decreased soil net N mineralization, net N nitrification and inorganic N following afforestation will likely result in the occurrence of progressive N limitations in the long-term, thereby reducing the rate of soil C sequestration (Luo et al., 2004, 2006).

To conclude, increased SOC following 15-year afforestation was largely induced by the large volume of low-quality litter inputs. In open areas where no litter or roots occur, SOC did not increase while RIC significantly decreased, indicating a possible loss of SOC storage in these open areas over time. Afforestation had a negative effect on soil organic N stock, particularly in open areas. Interactions between SOC and N have led to a significant decrease in net N mineralization and inorganic N in the afforested soils. This decrease most likely resulted in the occurrence of progressive N limitations, thus limiting rooting into open areas and canopy closure over time. Therefore, the decreasing N availability, together with increasing SOC decomposition in the open areas, could have a limiting effect on long-term C sequestration in the afforestation soils at the Danjiangkou Reservoir region of China.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.soilbio.2013.10.053.

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