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Root rather than leaf litter input drives soil carbon sequestration after afforestation on a marginal cropland

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ABSTRACT

Afforestation on croplands has been proposed as a means to mitigate the increasing emission of anthropogenic CO_2. However, the relative contribution of above- and belowground litter input on soil organic carbon (SOC) sequestration following afforestation is not fully understood. We used a 270-day laboratory incubation experiment to examine the impact of litter type (i.e., leaf vs. fine root litter) of a poplar tree (*Populus simonii* Carr., C_3 plant) on soil respiration and the turnover of new vs. old soil C in surface (0–10 cm) and subsurface mineral soils (40–50 cm) collected from a marginal cropland planted to maize (*Zea mays* L., C_4 plant) in a semi-arid region in northeast China. Our results showed that fine root rather than leaf litter addition helps to sequester SOC even though soil microbial respiration rates were stimulated by both leaf and fine root litter input. Neither leaf nor fine root litter addition stimulated mineralization of old soil C across the two soil layers, but more new C was incorporated into the soil with fine root addition as compared with leaf litter addition. Moreover, the subsurface soil had greater potential to sequester SOC as compared to the surface soil. Our results suggest that root rather than leaf litter input drives soil carbon sequestration on the marginal soil, especially in the subsurface soil, and planting deep-rooted trees with large belowground biomass production could be used to increase SOC sequestration in marginal croplands.

1. Introduction

Land use change from treeless agricultural lands to forests, defined as afforestation, has been proposed as one of the most important means to mitigate anthropogenic CO_2 emissions (Paul et al., 2002; Arevalo et al., 2009). Soil C stocks in temperate and boreal forests are estimated to be about four times as high as that stored in the vegetation (IPCC, 2000). Thus, there have been extensive studies on soil organic C (SOC) sequestration potentials following afforestation on croplands and grasslands (Paul et al., 2002). The beneficial role of trees in adding C to the soil after afforestation has been widely reported (Galdo et al., 2003; Hernandez-Ramirez et al., 2011; Hu et al., 2014) and is related to the increased above- and belowground litter input following afforestation (Arevalo et al., 2011). However, the relative contribution of leaf and root litter to SOC sequestration after afforestation is not yet fully understood, considering the differences in morphological and chemical characteristics of litter, location of litter input in the soil and the decomposition pathways of leaf and root litter (Bird and Torn, 2006; Mambelli et al., 2011).

Input of fresh plant C (e.g., leaf litter, root litter and root exudates) to the soil plays a major role in the potential for SOC sequestration (Heath et al., 2005; Dijkstra and Cheng, 2007; Rubino et al., 2010; Sayer et al., 2011). For example, Gale and Cambardella (2000) used ^{14}C labeling to demonstrate that 42% of root-derived C was retained in the soil, while only 16% of surface residue-derived C was retained in the soil after 360 days of incubation. Similarly, Bird and Torn (2006) found that fine root C input resulted in 70.5% of the C being retained in the soil as compared with 42.9% of needle C being retained, after 1.5 years, in a temperate coniferous forest, because needles contain a larger proportion of the C as labile C compounds. The higher chemical recalcitrance of root tissues was suggested to be responsible for the longer residence time of root-derived C than leaf litter-derived C in the soil (Crow et al., 2009). Moreover, the decomposition of root litter can enhance aggregate formation and thereby physicochemical protection of SOC (Gale and Cambardella, 2000), increasing the mean residence time of root-derived C in deeper soils (Rasse et al., 2005).

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A recent meta-analysis of litterfall manipulation experiments showed that soil respiration rates increased by an average of 31% with litter addition (Xu et al., 2013). Soil CO_2 emission rates may increase with increasing litter input (Sulzman et al., 2005; Liu et al., 2009; Sayer et al., 2011). Enhanced soil C release induced by increasing litterfall may result from the accelerated mineralization of previously stored soil C (old C) through the 'priming effect' (Bingeman et al., 1953). Fontaine et al. (2007) found that fresh C supply could increase the decomposition of recalcitrant old SOC in deeper soils by stimulating microbial activities, implying that increased fresh C input in deeper soils due to land use change might enhance the loss of ancient C buried deep in the soil. In addition, a greater priming effect of root input in the surface soil as compared with the subsurface soil was observed due to differences in the structure and function of soil microbial communities and variation in soil nutrient availability in the soil profile (de Graaff et al., 2014). Consequently, increased ecosystem productivity does not necessarily translate into increased soil C stocks (Crow et al., 2009), and further research is needed on the formation of new soil C derived from above- and belowground litter input and the mineralization of old soil C following plant litter addition into different soil layers.

In recent years, carbon stable isotope composition at natural abundance level on sites experiencing a succession from C_3 to C_4 vegetation has been widely used to evaluate the turnover of SOC (Balesdent and Balabane, 1996; Rubino et al., 2007; Werth and Kuzyakov, 2008; Mazzilli et al., 2014). In general, there is a distinct value of ^{13}C abundance for C_3 and C_4 plants ($\delta^{13}C$ around −27‰ and −12‰, respectively), due to differences in their photosynthetic pathways (Smith and Epstein, 1971). Because most soil organic matter originates from plant residues, the changes in soil $\delta^{13}C$ can serve as a marker to indicate the source and turnover of SOC (Mazzilli et al., 2014). For example, Rubino et al. (2007) incubated three sets of ^{13}C-depleted leaf litter (C_3 plant) in the laboratory in jars containing ^{13}C enriched soil (i.e., from a field with C_4 vegetation), and after 8 months of incubation the $\delta^{13}C$ of the soil decreased, and litter C input to the soil was estimated to be 13% of total C loss. In addition, the distribution and fate of litter C among soil respiration and microbial biomass and among the different SOC pools can be evaluated using natural and artificial ^{13}C labeling approaches (Williams et al., 2006; Werth and Kuzyakov, 2008; Rubino et al., 2010; Steffens et al., 2015).

The objectives of this study were to evaluate the relative contribution of leaf and fine root (diameter < 2 mm) litter of a poplar tree (*Populus simonii* Carr., C_3 plant) to soil C sequestration after their addition to a marginal cropland soil planted to maize (*Zea mays* L., C_4 plant) and to compare the differences between surface (0–10 cm) and subsurface mineral soils (40–50 cm). We conducted a 270-day laboratory incubation experiment by adding leaf and fine root litter of the poplar tree to a soil from a maize field. We hypothesized that: (1) plant C input could enhance SOC stocks, but soil microbial respiration rates would be stimulated through the decomposition of newly added plant C and previously stored soil C; (2) fine root litter would contribute more new C to the soil as compared to leaf litter; and (3) the sequestration of root-derived C would be higher in the subsurface than in the surface mineral soil because of slower mineralization of newly added soil C derived from plant litter input in the subsurface soil.

2. Materials and methods

2.1. Field litter and soil sampling

Leaf and fine root litter were collected from a 21-year-old poplar plantation afforested on a marginal cropland at the Daqinggou Ecological Station (42°54′7.90″N, 122°24′43.03″E) established by the Institute of Applied Ecology, Chinese Academy of Sciences, in south-eastern Horqin Sandy Lands in Inner Mongolia, in northeast China. The climate is a typical temperate continental monsoon climate, with a mean annual temperature of 5.7 °C from 1959 to 2006 (ranging from −23.2 °C in January to 32.4 °C in July) and a mean annual precipitation of about 450 mm from 1959 to 2006. The poplar trees were on average 15.07 m in height and 20.39 cm in diameter at breast height (DBH). In late September 2012, several litter traps (1 × 1 m) were set up for collecting composite leaf litter samples from the poplar stand. Fine roots of poplar trees were excavated and soils adhering on fine roots were carefully washed off with distilled water. Leaf litter and fine roots were air-dried, and stored in paper bags prior to use for the incubation experiment. Three sub-samples of leaf litter and fine roots were oven dried at 70 °C for 48 h and ground for measurement of C and N concentrations and ^{13}C abundance as described below.

In June 2013, ^{13}C-enriched soils were collected from the surface (0–10 cm) and subsurface layers (40–50 cm) from a cropland (42°54′18.43″N, 122°23′55.42″E) with long-term cultivation with maize that was adjacent to the poplar stand. The soil is classified as an Entisol, belonging to the Semiaripsamment subgroup according to the USDA Soil Classification System. Soil samples were immediately taken back to the laboratory and passed through a 2 mm sieve and plant residues were pick out by hand. The samples were then stored at 4 °C for less than 1 week until the incubation experiment was set up. The C and N concentrations and ^{13}C abundance in the surface and subsurface mineral soils were determined (as described below) in three replications after being ground and passed through a 0.25 mm sieve. The initial C and N concentrations, the ratios of C to N, and ^{13}C abundance in plant and soil samples are shown in Table 1.

2.2. Preparation of experimental microcosms

An unbalanced factorial experimental design was used in this study. We set up six treatments: surface mineral soil (SS), surface mineral soil plus leaf litter (SSL), surface mineral soil plus fine root litter (SSR), surface mineral soil plus leaf and root litter (SSLR), and subsurface mineral soil (DS) and subsurface mineral soil plus fine root litter (DSR), with each treatment replicated five times. For the subsurface mineral soil, we only studied the input of fine root litter as leaf litter input to subsurface mineral soils does not usually occur although bioturbation and leaching of leaf litter from surface to subsurface soil layers can happen.

Table 1
Initial C and N concentrations, C:N ratio and $\delta^{13}C$ value in leaf litter and fine root of poplar trees, and in surface and subsurface mineral soil planted to maize.

	C (g kg^{-1})	N (g kg^{-1})	C:N ratio	$\delta^{13}C$ (‰)
Leaf litter	417.15(0.28)***	7.60(0.02)**	54.88(0.08)	−27.02(0.02)***
Fine root	467.56(0.53)	8.70(0.19)	53.77(1.12)	−27.67(0.04)
Surface soil	6.16(0.29)**	0.62(0.01)***	9.96(0.51)**	−19.53(0.24)***
Subsurface soil	4.36(0.04)	0.33(0.01)	13.35(0.41)	−17.37(0.06)

Values are means (n = 3) with standard errors in the brackets.
** and *** indicate a significant difference at $p < 0.01$ and $p < 0.001$ between leaf and fine root litter, and between surface and subsurface mineral soil, respectively.