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Effects of soil physicochemical properties and stand age on fine root biomass and vertical distribution of plantation forests in the Loess Plateau of China

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Abstract The responses of aboveground parts of the forest to changes in environmental factors and stand age is well studied, but the same is not true for the belowground parts of the forest. Two plantation black locust (*Robinia pseudoacacia* L.) forest sites were taken in the Loess Plateau of China, one in the drier, infertile, more sandy area of the middle Loess Plateau, and another in the wetter, fertile, more clay-filled area of the southern Loess Plateau. At each site, both a younger (8-year-old) plantation stand and an older (30-year-old) plantation stand were included to study the effects of soil physicochemical properties and stand age on the fine root (< 2 mm) biomass and vertical distribution of black locust forests. Root samples were taken with soil cores to a depth of 100 cm. The fine root biomass decreased from the middle site to the southern site for both stand ages, as expected, and the decrease could be due to a higher fine root N concentration associated with a higher fine root turnover rate at the southern site. There was a similar rooting pattern, though not deeper, in the drier, sandy site as predicted based on soil water infiltration and evaporation demands. The different effects of stand characters (e.g., tree density, tree height) on the fine root distribution as compared with the environmental properties may contribute partly to the similar pattern found in the two sites. The fine root biomass increased with stand age in both sites. In contrast to the evident difference in fine root biomass, there was no clear trend in the fine root vertical distribution pattern with stand age. Our results indicate that fine roots are likely to respond to changes in soil physicochemical properties and stand age by changing fine root biomass rather than by varying rooting pattern.

Keywords Coefficient of rooting distribution · N concentration of fine roots · Dryland forest · Functional balance theory · Constant allocation theory

Introduction

Fine root production and turnover account for over one-third of the net primary productivity in forest ecosystems (Hendricks et al. 2006; Jackson et al. 1997; Vogt et al. 1995). When accounting for future climate change, the production and turnover of fine roots as a percentage of new primary productivity (NPP) is expected to increase (Norby et al. 2004). It is recognized widely that forest fine roots play a significant role in nutrient cycles and soil carbon sequestration in terrestrial ecosystems due to the large carbon input into soil from fine roots and the stabilization of the associated carbon derived from roots (Guo et al. 2007; Kuzyakov and Schnepf 2004; Matamala et al. 2003; Ruess et al. 2003).

The activity of fine roots in the forest is suggested to be under strong genetic control (Espeleta et al. 2009; King et al. 2005; Pregitzer et al. 2002), but fine roots also show plasticity in their biomass and vertical distribution in response to environmental prosperity and stand age (Finér et al. 2007; Hodge 2004; Schenk 2005; Yuan and Chen 2010). Two existing theories give good descriptions of how environmental properties change the effects of the dynamics of fine roots: functional balance theory (FBT) and constant allocation theory (CAT) (Farrar and Jones 2000; Hendricks et al. 2006; Meier and Leuschner 2008; Nadelhoffer 2000; Nadelhoffer et al. 1985). According to FBT, the proportion of fine root allocation of NPP increases with decreasing soil nutrient availability; however, CAT predicts that the proportion of NPP allocation into fine roots remains relatively constant with decreasing soil nutrient availability (Hendricks et al. 2006; Meier and Leuschner 2008). In regards to fine root biomass (FRB), both theories pre-

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dict a decrease in biomass with an increase in soil resource availability (Hendricks et al. 2006). The mechanisms used to explain the reduction differ: in FBT, the reduction is ascribed to the decrease of carbon allocation in root production, but in CAT it is attributed to an increase in fine root turnover rates (Hendricks et al. 2006). Evidence of increased FRB relative to low soil nutrient or water availability have been observed in some ecosystems (Aikio et al. 2009; Espeleta and Clark 2007; Kobe et al. 2010; Nadelhoffer 2000). For example, Vanninen and Mäkelä (1999) reported that the fine root density of Scots pine (*Pinus Sylvestris* L.) in southern Finland was greater in less fertile sites than in more fertile ones.

Fine root vertical distribution can be affected by environmental factors, which is scale dependent. At the local scale, fine root vertical distribution is affected by soil bulk density (Schenk 2005), soil texture (Schenk 2005; Valverde-Barrantes et al. 2007), and soil nutrient and water distribution along the soil profile (Espeleta and Clark 2007; Zhou and Shangguan 2007). At the regional scale, fine roots are predicted to be deeper in drier sites relative to wetter ones (Achat et al. 2008; Meier and Leuschner 2008) and in coarse soils relative to clay soils based on soil water infiltration and evaporation demands (Schenk and Jackson 2002a, 2005). Globally, however, soil texture is not found to have a significant effect on variations in rooting depth. Instead, the rooting depth across various biomes and life forms is shown to be determined more by annual potential evapotranspiration (PET) and precipitation than other factors such as vegetation and soil variables (Schenk and Jackson 2002a).

With increased stand age, the proportion of FRB in the top soil has been found to either increase (Bouillet et al. 2002) or exhibit no change (Claus and George 2005). Similar to the debated effects of stand age on the fine root profile distribution, the effects of stand age on FRB are also controversial. For example, Børja et al. (2008) reported that the FRB of Norway spruce [*Picea abies* (L.) Karst.] was significantly higher in mature (30-year-old) stands than in younger (10-year-old) or older (60- and 120-year-old) stands, due partly to higher tree density in the mature stand. In contrast, the FRB of northern hardwood forests growing in the rocky soils of the US was significantly greater in older stands (56–69 years old) than in younger stands (19–27 years old; Yanai et al. 2006). These different effects of stand age on FRB may be specific to the site and/or species. Nevertheless, it is generally suggested that FRB increases until the canopy closure stage is reached, after which it levels off (Yuan and Chen 2010), decreases (Claus and George 2005; Yuan and Chen 2010), or increases (Finér et al. 2007).

Dryland forests have been shown to play a significant role in carbon sequestration (Rotenberg and Yakir 2010; Schimel 2010), and some forest fine root studies have been conducted in water-limited ecosystems (e.g., Schenk and Jackson 2002a). However, studies on the

effects of environmental properties and stand age on the dynamics of fine roots are scarce in the water-limited forests of China. Although a large percentage of the forest in the Loess Plateau region of China was established in recent decades, discovering the dynamics of the fine roots in an ecosystem with limited water availability will provide a better understanding of the role of plantation forestry.

The Loess Plateau, located in western China, is known for its serious erosion problems because of high soil erodibility and intensive human activity in the past. For the past three decades, a series of ecological programs has been launched to control soil erosion in the Loess Plateau. The ‘Grain for Green’ project is one of the most ambitious programs launched in this region. The goal of the project is to transform approximately 2.04×10^6 ha of low-yielding slope cropland into woodland and grassland. The black locust (*Robinia pseudoacacia*) was chosen widely as a plantation species across the Loess Plateau in the ‘Grain for Green’ project (Jin et al. 2011). The first aim of the present study was to examine variations in the FRB and vertical distribution of the black locust forests, comparing the drier, infertile middle area of the Loess Plateau to the wetter, fertile southern area. Two hypotheses were proposed: (1) the FRB of the black locust forests decreases from the center to the south; and (2) the fine roots of the black locust forests are deeper in the central area relative to the southern area. The second aim was to investigate changes in the FRB and distribution with stand age, with two additional hypotheses proposed: (3) the FRB of the black locust forest increases with stand age; and (4) the proportion of FRB in the topsoil increases with stand age.

Materials and methods

Site description

Two locations in the Loess Plateau were chosen: in the south, Zhaojiayuan (SS) (N 35.342°, E 109.133°), and in the middle, Zhifanggou (MS) (N 36.862°, E 109.35°). Located in the center of the ‘Grain for Green’ project area, both sites share a semiarid continental climate. The average annual precipitation ranges from 650 mm at SS to 505 mm at MS, with most precipitation occurring from June to August (Jin et al. 2011). The average annual temperature is about 8.8 °C at both sites. The elevation of SS is approximately 1,257–1,339 m with an elevation of about 1,207–1,266 m at MS. The landform is typical loess, with calcareous loamy soil (classified as an Entisol, US soil taxonomy), and a soil layer over 20 m thick (Wen 1989). Because of the deep soil layer, the groundwater level is far below the rhizosphere in this region.

In July 2009, two black locust forest stands with different stand ages (8 and 30 years at the time of sampling) were selected at each site, for a total of four stands. Each of the stands had similar slopes and as-

pects, had been converted from long-term cultivated cropland, and had the same history and land management strategy before forest plantation. Trees were planted regularly in each stand. The 8-year-old stands were established from 2000 to 2001 with little to no disturbance. The 30-year-old stands were established from 1978 to 1980, with few disturbances due to occasional livestock grazing and thinning prior to 2000. In these plantation stands, the dominant tree species is black locust and other tree species are rare. The dominant understory species are *Lycium chinense* M. and *Ampelopsis aconitifolia* Bge. in the southern 30-year-old stand, and *Leymus secalinus* (Georgi) Tzvel and *Lageidium sibiricum* (L.) Sojak in the northern 30-year-old stand, whereas understory species occurred rarely in the 8-year-old stand at the two sites.

Fine roots and soil sampling

In each black locust stand, one 20 m × 10 m plot was established in the middle of the stand. The diameter at breast height (DBH), number of trees, and average tree height for all of the black locust trees in each plot were measured (Table 1). Based on the DBH quantile values, the trees in each plot were separated into four classes, and one (in some cases two) standard tree with the mean DBH value was selected in each class. In total, four to six standard, evenly distributed live trees were selected in each plot, except in the MS for the 30-year-old stand. Because of the small number of trees and their small range of DBH values (ranging from 14.5 to 17.9 cm), only three trees were selected to represent the MS for the 30-year-old stand. One 1 m × 1 m subplot was established to collect FRB and soil physicochemical properties using a standard tree as a vertex (Fig. 1). There were four–six subplots in each stand with the exception of MS in the 30-year-old plot, which had three subplots. In addition to the three standard tree subplots in the MS for the 30-year-old stand, two subplots were established in the center of the forest gap (occupying about one-fifth of the plot area), and a total of five subplots were established in this stand.

In each standard tree subplot of each stand, FRB was measured using four soil samples that were collected separately in cores (3.3 cm diameter), with two soil samples collected at a distance of 0.5 m from the trunk of a standard tree, and another two soil samples collected at a distance of 1.0 m (Fig. 1). In each subplot in the forest gap of the 30-year-old stand in the MS, another soil sample (3.3 cm diameter) was collected for FRB, together with the fine root samples in the standard tree subplots in order to estimate the FRB of this stand. There were 14–24 total soil cores in each stand. All soil sample cores were partitioned into 0–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm increments. The organic soil layer was not separated from the mineral soil layer because the organic layer was thin (on average 1.0–1.5 cm) in all stands. Roots were collected from soil

Table 1 Trees census, soil clay content and biomass, N concentration and 50 % rooting depths of fine roots in each stand (sample sizes in parentheses)

Sites	Plantation age (years)	Mean tree height (m)	Mean DBH (cm)	Tree density (trees/ha)	Fine root biomass in 100 cm layer (mean ± SE, g/m ²)	Fine root biomass per tree (kg/tree) ^a	N concentration of fine root (mean ± SE, g/kg) ^b	50 % rooting depth (cm) ^c	Clay content
Middle site	8	6.5	6.1	1,950	317.9 ± 13.7 (16)	1.63		26.8	15.0 ± 0.5 (4)
	30	10.0	16.1	500	921.2 ± 73.8 (14)	18.42	17.9 ± 0.6 a (4)	31.4	17.6 ± 0.6 (5)
Southern site	8	8.0	5.6	3,200	70.7 ± 6.0 (24)	0.22		30.8	35.4 ± 0.1 (5)
	30	13.0	13.8	1,550	317.8 ± 32.2 (20)	2.05	29.0 ± 2.3 b (5)	32.2	34.3 ± 0.8 (5)

DBH Diameter at breast height

^aFine root biomass per tree was calculated by dividing the root biomass for the whole stand by the tree density in the stand

^bN concentration of fine roots was analyzed only for the 30-year-old stand. A different letter means a significant difference at the 0.05 level

^c50 % rooting depths calculated based on Eq. (1)

Fig. 1 Soil sampling pattern for fine roots and soil physicochemical properties

by washing, and roots less than 2 mm in diameter (fine roots) were dried at 65 °C until a constant mass was reached in order to estimate the FRB. After weighing the biomass, the fine roots in a plot were mixed and the N concentration was analyzed using a dry combustion method (Vario EL Element Analyzer). Live or dead fine root separation was not done because the dead root biomass was too small based on visual measurement, which may be due partly to the frailness of dead fine roots and consequently loss of roots during the washing process. Nevertheless, because of the small dead fine roots, the FRB collected here was assumed to be equal to the biomass of the live fine roots. In addition, the fine roots of the understory vegetation were not separated from the total collected roots because of the intensive labor required and difficulties in discrimination, and thus the FRB reported refers to the fine roots of black locust trees and the understory plants mixed together.

In each subplot of all stands, another soil sample was collected with a core of 3.3 cm in diameter in increments of 0–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm to analyze the soil organic carbon, total nitrogen, and texture using a potassium-dichromate oxidation method (Lu 1999), dry combustion method, and particle size analyzer (Malvern Instruments, Malvern, UK), respectively. The soil samples used to investigate the water content were collected with a 100 cm³ cylindrical corer in each subplot and dried at 105 °C until a constant mass was reached. The samples were then weighed to determine the soil water content and were segregated into 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90, and 90–100 cm increments.

Fine root vertical distribution

The fine root vertical distribution was described using a coefficient of rooting distribution (β) based on Eq. (1), as proposed in Gale and Grigal (1987).

$$Y = 1 - \beta^d \quad (1)$$

where d is the soil depth (cm), Y is the cumulative proportion (from 0 to 1) of root biomass from the soil surface to depth d , and β is the coefficient of rooting distribution. The β values can be used to describe the rooting pattern. Higher β values indicate a deeper root distribution, while lower values refer to a shallow rooting pattern (Jackson et al. 1996). Because of the high spatial heterogeneity in FRB, we used the FRB mean value in each stand to calculate the coefficient of rooting distribution for the stand.

Calculations and statistical analysis

The FRB was calculated at stand level (g/m²) using the sample value. Because tree density has been found to have a positive effect on FRB (Børja et al. 2008; Litton et al. 2003), the FRB at tree level (kg/tree) was calculated by dividing the FRB at stand level by the stand density (trees/ha).

The FRB at stand level and soil physicochemical properties were compared between older and younger stands in MS and SS, as well as between MS and SS for both younger and older stands, respectively. Initial statistical analysis indicated that the data were distributed normally and had equal variance, so Student's t test method with two independent samples was used to compare the FRB values. All analyses were examined using significance levels of 0.05, and the statistical program used was SPSS 11.0.

Results

Trees census and soil physicochemical properties in the middle and southern site

The mean tree height was higher in SS than in MS for both younger and older stands, whereas the mean DBH was slightly greater at MS (Table 1). Compared to the younger stands, both the mean tree height and mean DBH were greater in the older stands for both sites (Table 1). The tree density increased from about 1,900 trees/ha in MS to 3,200 trees/ha in SS for the younger stand, and from about 500 trees/ha in MS to 1,550 trees/ha in SS for the older stand (Table 1).

The soil organic carbon, total N concentration, and C/N ratios decreased with soil depth in all stands (Fig. 2). Soil water content was similar along the soil profile in SS, whereas it showed a decreasing trend with soil depth in MS (Fig. 2). As compared with MS, the soil

Fig. 2 Soil water, soil organic carbon, total N content, and C/N ratio profile distribution for 8-year-old stands [$n = 4$ for middle site (MS) and $n = 5$ for southern site (SS)] and 30-year-old stands ($n = 5$ for the two stands in both sites). Error bars Standard errors of the mean

organic carbon, water, and total N concentration in each detected soil layer were significantly greater in SS for both younger and older stands ($P < 0.05$ for each soil layer for younger and older stands, respectively; Fig. 2). The soil clay content was significantly higher at SS relative to MS for both younger and older stands ($P < 0.05$ for younger and older stands, respectively; Table 1).

In both sites, higher soil organic carbon and total N concentrations were found in the older stands in the top 20 cm layers compared to the younger stands ($P < 0.05$), but the subsoil (40–100 cm) water levels in the older stands were lower than those in the younger stands ($P < 0.05$; Fig. 2).

Comparison of FRB and distribution of black locust forests between MS and SS in the Loess Plateau

As compared with SS, the FRB at stand level in MS was significantly greater in the top 20 cm layers, 20–40 cm layers, subsoil (40–100 cm), and entire soil profile (0–100 cm) for both younger and older stands ($P < 0.05$ for each detected layer; Fig. 3). For younger and older stands, the FRB at tree level was even lower in SS relative to MS as a result of the higher tree density in SS (Table 1). The fine root N concentration was higher at SS (Table 1).

In all stands, FRB decreased with soil depth (Fig. 4). The coefficients of rooting distribution (β) were similar

Fig. 3 Comparison of fine root biomass between the 8-year-old ($n = 24$ and $n = 16$ for SS and MS, respectively) and 30-year-old ($n = 20$ and $n = 14$ for the SS and MS, respectively) stands. Error

bars Standard error of the mean. Different letters in the same soil layer indicate a significant difference at the 0.05 level

for SS and MS in both the younger and older stands (Fig. 4). Approximately 50 % of the roots accumulated in the top 30 cm soil layers for all stands (Table 1).

Effects of stand age on FRB and vertical distribution

At MS, the FRB at stand level in the 30-year-old stand was significantly greater in the top 20 cm layers, 20–40 cm layers, subsoil (40–100 cm), and entire soil profile (0–100 cm; $P < 0.05$ for each layer; Fig. 3) as compared with the 8-year-old stand. Similar to MS, the FRB at stand level in SS was significantly greater for the older stand in each detected soil layer ($P < 0.05$ for each layer; Fig. 3). In both sites, the FRB per tree was lower for the younger stands relative to the older stands (Table 1). At both sites, the coefficients of rooting distribution (β) were similar between the older and younger stands (Fig. 4).

Discussion

Greater FRB at the middle drier, infertile site relative to the southern wetter, fertile site

Although black locust forests have been established widely in the Loess Plateau, especially in recent decades, relatively little FRB data have been reported. Our study was the first to report FRB values of about 317 g/m² for the 8-year-old stand and 921 g/m² for the 30-year-old stand in the middle area of the Loess Plateau. At SS, the FRB in the top 100 cm soil layers in the 8-year-old stand (70.7 g/m²) and 30-year-old stand (317.8 g/m²) were greater than the values in the top 50 cm soil layers of a 5-year-old (29.4 g/m²) and 26-year-old black locust forest (238.7 g/m²) stand, respectively, reported in Wang et al. (2007). This dif-

Fig. 4 Cumulative fine root biomass along the soil profiles and the coefficients of the rooting distribution (β) for the 8-year-old and 30-year-old stands in both the SS and MS sites. A larger β means deeper rooting

ference in FRB could have contributed, in part, to the differences detected in the soil layers and stand age, and another main reason could be lower tree density (about 30 % lower than our stands), as also found in Wang et al. (2007). The average FRB (619.5 g/m^2) for the 30-year-old stands in the two sites was similar to the average values for temperate deciduous forests of 780, 637, and 775 g/m^2 reported in reviews by Jackson et al. (1997), Leuschner and Hertel (2003), and Finér et al. (2011), respectively.

The FRB at stand level was significantly greater for MS than SS, regardless of stand age and soil depth. The FRB at tree level was even smaller for SS than MS because of the higher tree density in SS, supporting the first hypothesis that FRB increases in the middle site, which is drier and infertile. Our results were in line with the findings that FRB has a negative relationship with soil water or fertility in some forest systems (Finér et al. 2007; Gower 1987; Hendricks et al. 2006; Kobe et al. 2010; Leuschner et al. 2004; Nadelhoffer 2000; Yuan and Chen 2010). However, there is a positive or no relationship between FRB and soil water or fertility for other forest species (Finér et al. 2007; King et al. 2005; Leuschner and Hertel 2003; Meier and Leuschner 2008; Yuan and Chen 2010; Zhou and Shanguan 2007). These conflicting results may reflect the species-specific adaptations to the environment (Finér et al. 2007; Helmisaari et al. 2007; King et al. 2005; Leuschner et al. 2004; Yuan and Chen 2010). For example, the FRB of spruce is found to respond positively to soil fertility in central Europe (Leuschner and Hertel 2003), while beech forests show a negative response (Leuschner et al. 2004). A greater spruce sensitivity to H- and/or Al-ions in acidic fertile soil could explain the contrast (Leuschner et al. 2004). Here, the negative response of black locust

forests to soil water suggests that this forest type is not a drought-sensitive species, which could change the FRB in adapting to the drier environment.

The N concentration of fine roots was found to be greater at SS than at MS, and this difference in fine root N content was related to the trend in the soil N content between the two sites. This positive relationship between fine root N and soil N was also found in other studies (Burton et al. 2000; Helmisaari et al. 2007). The N concentration of fine roots was suggested to be positively related to root respiration (Pregitzer et al. 1998; Zogg et al. 1996), but negatively related to root longevity (Burton et al. 2000; Eissenstat et al. 2000; Yuan and Chen 2010). The higher fine root N concentration at SS indicated that soil nutrient absorption in SS was enhanced by higher root metabolism, while the lower fine root N concentration at MS was associated with longer longevity of fine roots, which was an optimization of nutrient-poor conditions. This idea is supported by Nadelhoffer (2000), whose results indicate that fine root production, mortality, and turnover increase with increasing soil nitrogen availability. Therefore, the declining trend of the FRB of black locust forests towards SS can be ascribed partly to greater root turnover as a result of the higher root N concentration, which seems to support the CAT. However, more data on the fine root production of black locust forests in this region are needed in order to test this theory in future studies. In addition, root herbivores have been found to have more negative effects on the FRB in fertile sites as compared with infertile sites (Stevens and Jones 2006). Because the fine roots at SS with higher N concentrations may have higher susceptibility to root herbivory, they may have a smaller FRB.

Fine root biomass distribution from the middle to the southern site

Fine root biomass decreased with soil depth in all stands. The 50 % rooting depths in both sites (from 26.8 to 32.2 cm) were similar to the 21 cm average of cool, temperate forests (including plantations) reported by Schenk and Jackson (2002a) in a study on global rooting patterns. Our findings were in accordance with results indicating that FRB is concentrated in the surface soil layer in most forests (Jackson et al. 1996, 1997; Schenk and Jackson 2002a). Soil nutrient profiles showed steeper increases in the top 20 cm layers in all stands and, consequently, fine roots have better access to nutrients in the topsoil, which could lead to a proliferation of fine roots as suggested in Zhang et al. (2010). On the other hand, plants can exhibit shallow C and N profile distributions through biogeological cycling (Jackson et al. 2000; Jobbágy and Jackson 2001).

Based on the increase in soil water infiltration and evaporation demands from the southern to the middle Loess Plateau, the vertical distribution of the black locust forest fine roots were predicted to be deeper at MS relative to SS due to the lower soil water and clay content at MS (the second hypothesis). However, the

fine root vertical distribution, instead of being deeper, was similar, which was not in accordance with the second hypothesis or previous findings (Achat et al. 2008; Meier and Leuschner 2008; Schenk and Jackson 2002a, 2005). The differences in stand characteristics between the two sites could contribute partly to this condition. First, the trees at SS were larger, and larger plants are suggested to root deeper in water-limited ecosystems (Schenk and Jackson 2002b). Second, fine roots tend to proliferate in areas such as the SS site to compete with neighbors for nutrients (Leuschner et al. 2001; Schenk and Jackson 2005), developing a deeper fine root system when there is more intense belowground competition. Thus, as a result of having greater tree density, the black locust trees at SS tended to root deeper, possibly due to the increased intense belowground competition. Therefore, at the Loess Plateau scale (regional scale), although soil water evaporation demand may have affected fine root vertical distribution, as partly supported by the dramatic decrease in soil water along the soil profile in MS, the changes in stand characters (e.g., tree density, tree height) along this environmental gradient may have had a different effect on fine root vertical distribution, possibly offsetting the effect of the former, at least in part.

Effects of stand age on FRB and its distribution

In some forests, FRB was found to peak at about 30 years (Borja et al. 2008; Peichl and Arain 2007) or older (Yuan and Chen 2010); however, the FRB in other forests types can reach a steady level at earlier stages (e.g., Claus and George 2005). For example, a similar FRB was reported between 9- and 16-year-old stands, but a lower FRB was reported in a 3-year-old stand in European oak (*Quercus cerris* L.) forest (Claus and George 2005). Our findings show that the FRB increased from 8-year-old stands to 30-year-old stands in both sites, supporting the third hypothesis that FRB increases with stand age, which suggests that the FRB of the black locust forest in the Loess Plateau did not reach a steady level within 30 years. However, the stand age with peak FRB could not be obtained, and future investigations focused on older stands are needed.

The effects of stand age on FRB have been shown to be negative at the stand level but positive at the tree level (Finér et al. 2007). In our study, however, the FRB values at both stand and tree levels were found to increase with stand age. The increase in FRB might be due to synchronous development, with aboveground parts during forest development (Farrar and Jones 2000). Generally, the forest NPP increased from young (> 10 years) to medium-aged (30–120 years) forests in a global analysis (Pregitzer and Euskirchen 2004). Meanwhile, the allocation of NPP to belowground parts increases (Ryan et al. 2004) or stays constant with stand age (Litton et al. 2004; Yang and Luo 2011), resulting in a higher FRB in older stands relative to younger ones.

Claus and George (2005) found significant differences in FRB between different age classes in the top soil layers (0–10 cm) but not in lower layers (10–20 and 20–30 cm). In contrast, our results showed that FRB increases with stand age in both the top soil layer (0–20 cm) and lower layers (20–40 and 40–100 cm, respectively). This increase in FRB in the top soil layers could be related partly to the increase in fertility in the top soil, as discussed above. On the other hand, the increase in the FRB of the black locust (N-fixing species) might result in higher topsoil soil organic carbon and N content with stand age. The increase in FRB in the lower soil layers could be a result of an increase in root competition for soil water with stand age in water-limited forests, as supported by the lower subsoil (40–100 cm) water levels in the older stands.

Although the FRB of black locust forests was found to increase in the surface and subsurface soil layers in the 30-year-old stands relative to the 8-year-old stands, there was no clear trend in rooting pattern between the younger and older stands. This result was in opposition to our expectation in the fourth hypothesis, which stated that fine roots are shallower in older stands. The synchronous development of fine roots in the surface and subsurface layers could be ascribed, in part, to the root competition resulting from water-limited conditions, as discussed above. In contrast, Bouillet et al. (2002) found that the proportion of FRB in the surface soil layer in *Eucalyptus* forest plantations increased from 1- to 9-year-old stands due to thicker organic soil layers in the older stands. In our study, however, the organic layer was thin and similar (on average 1–1.5 cm in all stands) in the younger and older stands, which could contribute to a similar root profile distribution corresponding to the stand age.

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