Characteristics of Soil CO₂ Efflux in Even-aged Alder Compared to Korean Pine Plantations in Central Korea

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Abstract

We investigated the relationship between vegetation type and soil carbon dynamics in even-aged alder (*Alnus hirsuta*) and Korean pine (*Pinus koraiensis*) plantations in central Korea. Both forests were located on the same soil parent material and occupied similar topographic positions. Soil CO₂ efflux in the two plantations was determined using a dynamic chamber method accompanied by measurements of soil moisture content and temperature. Mean soil temperature was similar in the two plantations, but mean soil water content was significantly higher in the alder plantation than in the pine plantation. In both plantations, seasonal patterns in soil CO₂ efflux exhibited pronounced variation that corresponded to soil temperature. Soil water content did not affect the seasonal variation in soil CO₂ efflux. However, in summer, when soil temperature was above 17°C, soil CO₂ efflux increased linearly with soil water content in the alder plantation. Estimated Q_{10} was 3.3 for the alder plantation and 2.7 for the pine plantation. Mean soil respiration during the measurement period in the alder plantation was 0.43 g CO₂ m⁻² h⁻¹, which was 1.3 times higher than in the pine plantation (0.33 g CO₂ m⁻² h⁻¹). Higher soil CO₂ efflux in the alder plantation might be related to nitrogen availability, particularly the concentration of NO₃⁻, which was measured using the ion-exchange resin bag method.

Key Words: alder (*Alnus hirsuta*), pine (*Pinus koraiensis*), nitrogen availability, soil respiration, Q_{10} value

Introduction

Soil respiration, an essential variable for evaluating net ecosystem productivity (Schulze et al. 2005), mainly comprises root respiration, microbial respiration, and soil fauna respiration (Luo and Zhou 2006). Soil CO₂ efflux is influenced by various factors, e.g. soil temperature and soil moisture condition (Keith et al. 1997; Law et al. 1999; Janssens et al. 2001; Jiang et al. 2005), the quantity and

quality of soil organic matter (Coûteau et al. 1995), root and microbial biomass, root nitrogen content (Ryan et al. 1996), and resulting stand productivity (Raich and Schlesinger 1992; Davidson et al. 2002). Soil CO₂ efflux is inevitably influenced by the local vegetation type through both litter production and the turnover rates of fixed CO₂ in above- and belowground productivities, which depends on leaf type (Raich and Tufekcioglu 2000). As a result, soil CO₂ efflux varies significantly among major biome types

Received: September 7, 2012. Revised: October 25, 2012. Accepted: October 25, 2012.

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(Raich and Schlesinger 1992) and side-by-side comparisons of different plant communities frequently reveal differences in soil CO₂ efflux (e.g. Luo and Zhou 2006). For example, coniferous forests have lower rates of soil CO₂ efflux than adjacent broad-leaved forests growing on the same soil type (Raich and Tufekcioglu 2000; Yanagihara et al. 2006). Forest productivity is expected to show a positive correlation with soil respiration because high productive forests require high turn over rate in the root including symbiotic microbes. However, strong evidences are not well described (Luo and Zhou 2006).

Korean pine (*Pinus koraiensis*) is a popular plantation and revegetation tree species in Korea, but they usually have low fertility in soils that originate from granite. Therefore, alder (*Alnus hirsuta*) is usually planted in the pine plantations to enrich the soil nitrogen content, since it has symbiotic nitrogen fixing microbes (*Frankia* sp.) (Gardner and Barrueco 1995; Huss-Danell 1997; Kim et al. 2009). Alder litter contains high nitrogen levels that improve soil fertility (Harmon et al. 1990). Soil CO₂ efflux in alder plantations with *Frankia* sp. is expected to be higher than in pine plantations, even with similar topography and edaphic conditions.

To test this expectation for determining reproducible differences in soil CO₂ efflux as a result of differences in vegetation type, we selected two even-aged plantations, namely alder and pine, which were afforested on the same soil parent material and in similar topographic positions. Soil CO₂ efflux and several environmental factors were measured in the two plantations. Based on these observations, we discuss factors influencing soil CO₂ efflux in the different vegetation types and derive carbon turnover rates as a contribution to carbon sequestration in forest ecosystem.

Materials and Methods

Study site

Our study site was located on Mt. Yeonyeob (850 m) in the Experimental Forest of Kangwon National University (37°47' N, 127°48' E) in central Korea. Mean annual precipitation over 30 recent consecutive years (1971–2000) was 1266 mm, of which about 50% falls between July and August. Mean annual temperature was 10.9°C, with a maximum of 29.2°C in July and a minimum of −9.2°C in January (Korea Meteorological Administration 2005). During the study period, mean annual precipitation and temperature were 1634 mm and 13.3°C, respectively. Mean monthly temperature ranged from −4.1°C (January) to 24.7°C (July and August). This area corresponds meteorologically to cool-temperate deciduous broad-leaved forests.

We studied two forest types, *Alnus hirsuta* Rupr. (alder) and *Pinus koraiensis* Sieb. et Zucc. (pine). The alder is symbiotic with nitrogen-fixing microbes in its roots and is indigenous to northeast Asia, with high growth rates in central Korea. Korean pine is an endemic tree species that is more shade-tolerant than many other pine species (Makoto and Koike 2007). Needle longevity may reach 5 years under shady conditions. The study site was logged and then established with planted alder and pine seedlings in 1976. About 0.5-ha alder and 2-ha pine plantations were contiguous and site elevation was similar among all research plots. We set three research plots (10×10 m) in each plantation, independently, in December 2002. The three research plots in each plantation were spaced regularly, at least 10 m apart. In June 2003, we tagged all of the trees and measured diameter at breast height (DBH) and height in each plot. Table 1 shows the basic information of the study site. Based on statistical analyses (e.g. *t*-tests), stand structure was similar

Table 1. Site descriptions for 27-year-old alder and pine plantations

Stand	Altitude (m)	Slope (°)	Stand density (stems ha ^{−1})	Height (m)	DBH (cm)	Basal area (m ² ha ^{−1})
Alder	523 ± 1.2	22 ± 0.3	2,333 ± 66.7	12.0 ± 0.3	11.1 ± 0.4	29.5 ± 1.5
Pine	507 ± 1.8	23 ± 0.9	1,033 ± 33.3	13.5 ± 0.1	18.9 ± 0.3	30.6 ± 0.3
<i>t</i> -tests	—	—	***	*	***	NS

Data are given as the mean ± standard error. Asterisks indicate significant effects according to *t*-tests: *, *p* < 0.05; ***, *p* < 0.001; NS, Not significantly different.

among the three plots in each plantation, and we therefore pooled the data into a single set.

Measurement of soil CO₂ efflux

Soil CO₂ efflux was measured *in situ* using an infrared gas analyzer (EGM-3; PP Systems, Inc., Amesbury, MA, USA) with a soil respiration chamber (internal diameter 15 cm) at approximately 45-day intervals from April 2003 through December 2004. The chamber was gently inserted into the mineral soil to a depth of less than 1 cm. Three replicate measurements were generally performed in each research plot between 09:00 and 12:00 h on all measurement dates. During measurements of soil CO₂ efflux, soil temperature and volumetric soil water content were measured aside of the chamber at 10 cm soil depth, with a soil temperature probe (STP-1; PP Systems, Inc.) and a soil water sensing probe (CD620-HydroSense; Campbell Scientific Inc., Logan, UT, USA). No soil CO₂ efflux was measured from January to March 2004 because the soils were frozen and covered with snow.

Soil sampling and analysis

In May 2003, soil samples were collected from three randomly selected points in each plot. At each sampling point, 30x30 cm soil samples were collected at three depths (0-10, 10-20, and 20-30 cm). Prior to physical and chemical analyses, all samples were air-dried at room temperature and sieved through a 2-mm mesh net. Particle size fractions were determined by a hydrometer after dispersion in a mixer with hexametaphosphate. Soil pH was measured using a pH meter (Orion 720⁺; Orion Research, Cambridge, MA, USA); soil was combined with distilled water in a ratio of 1:5 for 1 h. Soil organic matter (SOM) was determined by the Tyurin method (Schollenberger 1927). Total-N was analyzed on a micro-Kjeldahl apparatus (B324; Buchi, Zurich, Switzerland) following wet digestion in concentrated H₂SO₄ on a block digester (K438; Buchi) (Bremner and Mulvaney 1982). Bulk density was determined by the core method (Blake and Hartge 1986).

Soil nitrogen availability

From December 2002 to November 2003, ion-exchange resin bags were placed in the field to measure ammonium (NH₄⁺) and nitrate (NO₃⁻) from the soil solution

(Binkley and Matson 1983). Five resin bags were placed at a depth of 5 cm below the surface of the mineral soil at 2-m intervals along a single transect across each plot. The resin bags were prepared by adding 14 mL of cation resins (IONAC C-251 H⁺; Sybron International, Milwaukee, WI, USA) and 14 mL of anion resins (Sybron IONAC ASB-1P OH⁻) into separate nylon stockings (Garcia-Montiel and Binkley 1998; Son et al. 2007). The resin bags were retrieved and replaced at approximately 45-day intervals, except in winter. Retrieved resin bags were extracted by shaking for 1 h with 100 mL of 2 M potassium chloride. Extracts were settled for 24 h and filtered. NH₄⁺ and NO₃⁻ concentrations in the extracts were measured using a Lachat flow-injection autoanalyzer (Lachat Instruments, Milwaukee, WI, USA).

Annual litter production and organic layer

To measure annual C input to the soil due to litterfall, three circular litter-traps (surface area=0.25 m²) were installed 1 m above the forest floor in each plot. Litter was collected at 45-day intervals from December 2002 to December 2004. Litter from each trap was oven-dried in the laboratory at 65°C for at least 48 h and weighed. In September 2003 and 2004, to measure organic matter on top of the mineral soil, and to estimate the decomposition parameter *k*, three 50x50-cm subplots were established randomly within each plot, and all organic matter within each subplot was collected. These samples were oven-dried in the laboratory at 65°C for at least 48 h and weighed. The decomposition parameter *k* was estimated using Olson's simple mathematical model ($k=L/X_{ss}$, where *L* is the ratio of annual litter production and *X_{ss}* is the amount of litter accumulated on top of the mineral soil in a steady-state); see Olson (1963).

Statistical analyses

Statistical analyses were performed using the software SAS 8.1. General linear models were used for all data analyses (SAS Institute Inc. 2001). Significant differences in mean soil CO₂ efflux, soil temperature, soil water content, and environmental conditions between the two study plantations were assessed using *t*-tests and two-way ANOVA. Linear and nonlinear regression analyses were used to quantify the relationships among soil CO₂ efflux, soil temperature, and soil water content. Paired comparisons of soil

CO₂ efflux between coniferous and broad-leaved forests were conducted to determine the effects of vegetation type alone on soil CO₂ efflux.

RESULTS

Environmental conditions in alder and pine plantations

Two study plantations were located on a northeastern slope that appeared relatively stable, at elevations of 505–525 m a.s.l., with an even slope of 22–25°. Mean tree height and DBH were greater in the pine plantation than in the alder plantation (height: $p < 0.05$, DBH: $p < 0.001$). Mean tree density was about twice higher in the alder plantation than in the pine plantation ($p < 0.001$). In basal area, however, no difference was observed between the alder and pine plantations (Table 1). Although no significant difference was found in aboveground biomass (Son et al. 2007), annual litter production and accumulated organic matter

differed between the alder and pine plantations ($p > 0.05$), and the decomposition parameter k , estimated from annual litter production and accumulated organic matter, was higher in the alder plantation ($p < 0.05$). Therefore, litter decomposed faster in the alder plantation than in the pine plantation (Table 2).

The two study plantations were set in a well drained, slightly wet brown forest soil (B₄). The silt loam soil in the two study plantations had developed from granite gneiss (Table 3). Soil in the alder plantation had a slightly lower pH than soil in the pine plantation ($p < 0.05$). The SOM concentration tended to decrease slightly with increasing soil depth ($p < 0.01$). The concentration of SOM was higher in the alder plantation than in the pine plantation ($p < 0.001$). Also, the total-N concentration tended to decrease slightly with increasing soil depth, but the difference was not significant ($p > 0.05$). Between the two study plantations, the total-N concentration was higher in the alder plantation than in the pine plantation ($p < 0.05$). No significant inter-

Table 2. Aboveground conditions in the two study plantations

Stand	Aboveground biomass ^a (Mg ha ⁻¹)	Annual litter production (Mg ha ⁻¹)	Accumulated organic matter (O-layer, mg ha ⁻¹)	Litter decomposition parameter k
Alder	147.3 ± 9.7	6.3 ± 0.3	10.0 ± 0.6	0.63 ± 0.04
Pine	174.8 ± 18.6	5.2 ± 0.1	11.5 ± 0.7	0.45 ± 0.02
<i>t</i> -tests	NS	NS	NS	*

^aSon et al. 2007. Data are given as the mean ± standard error. Asterisks indicate significant effects according to *t*-tests: *, $p < 0.05$; NS, Not significantly different.

Table 3. Soil characteristics in the two study plantations

Stand	Depth (cm)	Soil texture	pH (1:5, H ₂ O)	SOM (%)	Total-N (%)
Alder	0-10	Silt loam	4.8±0.2	6.11±0.22	0.42±0.03
	10-20		5.0±0.2	4.34±0.29	0.31±0.05
	20-30		5.1±0.1	3.74±0.51	0.27±0.05
Pine	0-10	Silt loam	5.1±0.1	4.48±0.22	0.29±0.02
	10-20		5.3±0.2	3.68±0.20	0.25±0.01
	20-30		5.4±0.2	3.47±0.24	0.24±0.01
Two-way ANOVA					
Stand (S)		—	*	***	*
Depth (D)		—	NS	**	NS
SxD		—	NS	NS	NS

Data are given as the mean ± standard error. Asterisks indicate significant effects according to two-way ANOVA: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; NS, Not significantly different; SOM, Soil organic matter.

actions were detected between stand and depth for any of the soil chemical variables ($p > 0.05$).

Soil resin NH_4^+ , NO_3^- , and total inorganic N concentrations in the two study plantations are presented in Table 4. The resin-bag method revealed a strong effect of species on N availability; resin NH_4^+ , NO_3^- , and total inorganic N concentrations were significantly higher in the alder plantation than in the pine plantation (NH_4^+ : $p < 0.05$, NO_3^- and total: $p < 0.001$). Maximum values for the resin NH_4^+ concentration were observed in spring. Large amounts of soluble NH_4^+ accumulated in the soil during winter when the soil was frozen. As the growing season began, the resin NO_3^- concentration peaked in the middle of the growing season, when NH_4^+ was utilized and the concentration in the soil decreased (data not shown). In particular, soils under the influence of alder showed at least a two-fold increase in resin NO_3^- concentrations, indicating that nitrification was higher in the alder plantation than in the pine plantation.

Seasonal variations in soil water content, soil temperature, and soil CO₂ efflux

Seasonal patterns in soil CO₂ efflux are shown in Fig. 1, together with soil water content and soil temperature in the alder and pine plantations. Soil CO₂ efflux in the alder and pine plantations showed clear seasonal changes; efflux increased during the early growing season, peaked in August, and decreased from early fall to December ($p < 0.05$).

During the measurement period, mean soil CO₂ efflux (in $\text{g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$) was 0.43 in the alder plantation, with a range of 0.00–1.58, and 0.33 in the pine plantation, with a

Table 4. Soil NH_4^+ , NO_3^- , and total inorganic N concentrations measured using ion resin bags from December 19, 2002 through November 18, 2003 in the two study plantations

Stand	NH_4^+	NO_3^-	Total
	$(\mu\text{g N bag}^{-1})$		
Alder	3.08 ± 0.17	24.83 ± 1.57	27.91 ± 1.50
Pine	2.40 ± 0.19	11.91 ± 1.08	14.31 ± 1.25
<i>t</i> -tests	*	***	***

Data are given as the mean $\pm$ standard error. Asterisks indicate significant effects according to *t*-tests: *, $p < 0.05$; ***, $p < 0.001$; NS, Not significantly different.

range of 0.00–1.23. Mean soil CO₂ efflux values were significantly higher in the alder plantation than in the pine plantation ($p < 0.05$); Table 5 shows that no difference was observed in soil CO₂ efflux between 2003 and 2004 ($p > 0.05$). Soil water content ranged from 14.8% to 42.9% in the alder plantation and from 10.9% to 33.3% in the pine plantation, with no clear seasonal patterns. Soil water content did not follow the pattern of precipitation; slightly dry soil conditions were maintained throughout the measurement periods. Mean soil water content was 27.1% in the alder plantation and 22.1% in the pine plantation; soil water content was significantly higher in the alder plantation throughout the measurement period ($p < 0.001$). Soil temperature ranged from 0.2°C to 21.2°C in the alder plantation and from 0.0°C to 21.7°C in the pine plantation; a clear seasonal pattern was observed, with the temperature increasing during the early growing season, peaking in August, and declining from early fall to December ($p < 0.05$). However, no significant difference in soil temperature was found between the two sites ($p > 0.05$).

Discussion

Environmental edaphic conditions and CO₂ efflux

Soil respiration was markedly affected by the planted tree

Fig. 1. Seasonal patterns in soil CO₂ efflux, soil temperature, and soil water content in alder and pine plantations. Snow indicates the period when the soil was frozen and covered in snow.

Table 5. Mean soil water content, soil temperature, and soil CO₂ efflux for each measurement period in the two study plantations

Measurement period	Stand	Soil water content (%)	Soil temperature (°C)	Soil CO ₂ efflux (g CO ₂ m ⁻² h ⁻¹)
1st year	Alder	25.5 ± 1.6	11.5 ± 0.8	0.42 ± 0.04
	Pine	22.3 ± 1.3	10.8 ± 0.9	0.36 ± 0.04
2nd year	Alder	28.9 ± 1.1	10.4 ± 1.1	0.43 ± 0.07
	Pine	21.8 ± 1.0	10.2 ± 1.1	0.29 ± 0.04
Two-way ANOVA				
Measurement period (M)		NS	NS	NS
Stand (S)		***	NS	*
MxS		NS	NS	NS
All seasons	Alder	27.1 ± 1.0	11.1 ± 0.7	0.43 ± 0.04
	Pine	22.1 ± 0.9	10.5 ± 0.7	0.33 ± 0.03
<i>t</i> -tests		***	NS	*

Data are given as the mean ± standard error. Asterisks indicate significant effects according to two-way ANOVA and *t*-tests: *, $p < 0.05$; ***, $p < 0.001$; NS, Not significantly different. 1st year: April 2-December 16, 2003. 2nd year: April 5-December 11, 2004.

species. Alder is able to symbiotically fix atmospheric N₂, which has an effect on physical and chemical soil properties (Rhoades et al. 2001; Rothe et al. 2002; Son et al. 2007). Alder leaves and roots have higher N and lower lignin concentrations than conifer litter (Harmon et al. 1990); they improve the substrate quality of the soil organic matter (Van Miegroet et al. 1992; Chapin et al. 2002) and lead to higher rates of N turnover (Clein and Schimel 1995). As a result, alder is regarded as a “soil-improving” tree species. Despite having lower pH values, soils under the influence of alder at least double their resin NO₃⁻ and total inorganic N concentrations. Nitrification of NH₄⁺ was greater in the soil of the alder plantation than in that of the pine plantation because of very rapid decomposition of alder litter, which has high N concentrations in the leaves. Actually nitrogen addition stimulates plant primary production (Vitousek and Howarth 1991) as well as tree root and microbial activity, which provides more substrate for soil respiration.

Soil CO₂ efflux in the two study plantations showed similar seasonal pattern as reported by several forests developed on granite soil (Son and Kim 1996; Kang et al. 2003; Moon 2004; Yi et al. 2005). As we expected, mean CO₂ efflux values (g CO₂ m⁻² h⁻¹) were significantly higher in the alder plantation (0.43) than in the pine plantation (0.33) ($p < 0.05$). These values were slightly lower, in the range of 0.51-0.57, for 44- to 50-year-old natural oak forests (Yi 2003) and 0.54 for a 38-year-old alder plantation on a southern slope

(Kim et al. 2009) in the region. Interannual variation in soil CO₂ efflux appears to be a ubiquitous phenomenon resulting from interannual changes in climatic variables, physiological and ecological changes in response to climatic variation, natural or anthropogenic disturbances, and nutrient availability. In a previous study, interannual variation in soil CO₂ efflux was attributed to climatic changes (Luo and Zhou 2006). In our test sites, however, mean soil water content, soil temperature, and soil CO₂ efflux in each plantation did not differ significantly between 2003 and 2004 ($p < 0.05$; see Table 4). This phenomenon may be due to relatively mild climatic condition during study period.

Soil temperature and soil water content were limiting factors that influenced soil CO₂ efflux (e.g. Schulze et al. 2005; Luo and Zhou 2006). Although soil CO₂ efflux is strongly correlated with changes in soil temperature when soil water is not a limiting factor (Drewitt et al. 2002; Curiel Yuste et al. 2003), some studies have found weak correlations between soil CO₂ efflux and soil surface temperature under drought conditions (Xu and Qi 2001; Parkin and Kaspar 2003). In xeric sites, soil water content is the main limiting factor for soil CO₂ efflux. Thus, seasonal patterns in soil CO₂ efflux closely follow dynamics in soil water content (Davidson et al. 2000; Jiang et al. 2005), and strong inhibition of soil CO₂ efflux has often been observed with low soil water content (Griffis et al. 2004; Harper et al. 2005).

In this study, soil temperature was significantly corre-

Fig. 2. Relationships between soil CO₂ efflux and soil temperature (A) and soil water content (B) in alder and pine plantations.

lated with soil CO₂ efflux in both the alder and pine sites ($R^2=0.74$, $p < 0.0001$). Soil CO₂ efflux increased exponentially with soil temperature (Fig. 2A). Although mean soil water content was significantly higher in the alder plantation than in the pine plantation, soil water content in alder sites did not affect seasonal variation in soil CO₂ efflux. But, soil CO₂ efflux increased linearly with soil water content in the summer when soil temperature was above 17°C (Fig. 2B), especially in the alder plantation ($R^2=0.80$, $p < 0.0001$). Based on this result, we conclude that soil water content can affect soil CO₂ efflux in alder forests.

Values of the temperature sensitivity index (Q_{10}) were 3.3 and 2.7 in the alder plantation and the pine plantation, respectively. These values were within the typical range of 1.3-3.3 (Raich and Schlesinger 1992), and also within the range of 2.1-6.2, which has been reported for coniferous, deciduous, and mixed forests developed on the same granite soil (Kang et al. 2003; Moon 2004; Yi et al. 2005). Moreover alder plantation has higher sensitive to changes in soil temperature than the pine plantation.

Relationship between soil CO₂ efflux and vegetation type

Vegetation influences the accumulation and turnover of soil organic matter directly as a result of the quality and quantity of plant materials, and indirectly by conditioning

Fig. 3. Paired comparisons of soil respiration rates between coniferous and broad-leaved forests located on the same soil parent material and in similar topographic positions (modified with data added from Raich and Tufekcioglu 2000). Data were converted from their original units to g C m⁻² d⁻¹. Sources of data: A, Ellis 1974; B, Rout and Gupta 1989; C, Joshi et al. 1991; D, Fernandez et al. 1993; E and F, Ruess et al. 1996; G, Longdoz et al. 2000; H, Curiel Yuste et al. 2004; I, Khomik et al. 2006; J, Wang et al. 2006; K, Wu et al. 2006; L, current study.

the pathways by which biomass is incorporated into the soil (e.g. Chapin et al. 2002). We gave further evidence of alder and pine plantations in this phenomenon. Mean annual soil

respiration varies widely within and among major biomes by up to a factor of 20 (Raich and Schlesinger 1992). On a global scale, mean annual soil respiration is positively correlated with mean plant productivity in different biomes (Janssens et al. 2001) and with aboveground litter production in forest ecosystems (Davidson et al. 2002). In fact, soil respiration rates in broad-leaved forests are 10% higher than in coniferous forests on the same soil types. These assertions are supported by the several findings in beech and Douglas-fir in Canada (Longdoz et al. 2000), in the comparison between mixed broadleaves trees and evergreen conifer in Belgium (Khomik et al. 2006) in China (Wang et al. 2006) and between oak and pine plantation in China. Also, Wang et al. (2006) reported that soil respiration was positively correlated with the soil organic-C concentration in the O-layer and with total root biomass in northeast China. Based on these results, soil respiration would be slightly higher in broad-leaved forests than in coniferous forests under the same parent material of soil and in similar topographic positions ($p < 0.001$) (Fig. 3).

In conclusion, soil respiration has been influenced by the distinct vegetation types, which may be attributed to distinct nutrient diffusion rates and carbon allocations to the belowground biomass in two species with different symbiont types. A precise difference in soil N availability, especially the resin NO_3^- concentration was an important factor affecting soil respiration rate. An increase in the amount of available N in the soil likely affects root respiration by increasing tissue N concentrations and associated protein maintenance and construction costs. Moreover, the higher soil respiration rate observed in the alder plantation may incorporate respiration by symbiotic N_2 fixing microbes (e.g., *Frankia* sp.).

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