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Comparison of soil CO_2 efflux rates in *Larix leptolepis*, *Pinus densiflora* and *P. rigitaeda* plantations in southern Korea

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Abstract: This study compared soil CO_2 efflux rates in three adjacent coniferous plantations consisting of larch (*Larix leptolepis* Gordon), red pine (*Pinus densiflora* S. et Z.) and rigitaeda pine (*P. rigitaeda*: *P. rigida* Mill × *P. taeda* L.) species planted in the same year (1963). Soil CO_2 efflux, litter fall carbon (C) and root decomposition rates were measured with soil environmental factors for two years.
The mean annual soil CO_2 efflux rates (g CO_2 m^{-2} hour^{-1}) were the highest in rigitaeda pine (0.30), followed by red pine (0.27) and larch (0.24) plantations. An exponential regression of the CO_2 efflux rates against their corresponding soil temperatures showed a significant ($P < 0.05$) relationship (red pine $R^2 = 0.69$; rigitaeda pine $R^2 = 0.67$; larch $R^2 = 0.63$). The soil CO_2 efflux rates were negatively correlated with soil pH, but the soil water and soil organic C content were not significantly correlated with the CO_2 efflux rates. Soil CO_2-C efflux rates were correlated by litter fall C inputs in the larch and red pine plantations, and the decomposition rates of 5–10 mm diameter roots in the larch plantation.
This result is useful in understanding potential responses of soil CO_2 efflux rates with changes in stand and soil environmental factors induced by different tree species.

Keywords: carbon cycling, carbon dynamics, litter fall, root decomposition, soil respiration

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Introduction

Quantitative evaluation of soil CO_2 efflux rates among different tree species is key to understanding the C cycling in forest ecosystems because tree species can have a significant influence on soil CO_2 efflux rates (Pangle & Seiler 2002; Lee & Jose 2003; Lee et al., 2010) due to their different nutrient requirements (Dijkstra et al., 2009), litter fall fluxes (Vesterdal et al., 2012), litter decomposition mechanisms (Davidson & Janssens, 2006), fine root production (Valverde-Barrantes, 2007) and decomposition (Jeong & Kim, 2014). However, it is difficult to compare the soil CO_2 efflux rates of different tree species due to the potentially confounding effects of site macroclimatic and forest management factors (Kim et al., 2009). In addition, conflicting results have been reported regarding the influences of different tree species on soil CO_2 efflux rates. For example, tree species affected soil CO_2 efflux rates (Lee & Jose, 2003; Bréchet et al., 2009; Metcalfe et al., 2011), while others did not affect by different tree species (Valverde-Barrantes, 2007; Olsson et al., 2012). This disparity could be due to differences in soil environmental factors, such as nutrient availability, soil water content and soil temperature (Raich & Tufekcioglu, 2000), as well as stand environmental factors such as tree density, litter fall production and litter decomposition (Søe & Buchmann, 2005; Davidson & Janssens, 2006; Noh et al., 2010) induced by different tree species.

Although many studies generally describe the relationship between soil CO_2 efflux rates and biotic and abiotic factors, including soil temperature, nutrient supply, soil water, litter fall, litter decomposition and root decomposition, at regional and global scales (Davidson et al., 2000; Davidson & Janssens, 2006; Metcalfe et al., 2011), few studies describe the relationship between soil CO_2 efflux rates and soil and stand attributes (Søe & Buchmann, 2005; Noh et al., 2010), which are more important criteria that govern the soil CO_2 efflux rates of different tree species at a small, plot-based scale given similar site conditions.

Red pine (*Pinus densiflora* S. et Z.), rigitaeda pine (*P. rigitaeda*: *P. rigida* Mill × *P. taeda* L.) and larch (*Larix leptolepis* Gordon) have been the three most important coniferous tree species planted throughout Korea during the last forty years. Red pine is the most important coniferous tree species occupying more than 23.5% (about 1.5 million ha) of Korean forest lands. Larch forests were also planted on about 600,000 hectares and rigitaeda pine showed good growth characteristics compared with rigida pine (*P. rigida* Mill.) in Korea. Information is needed to enable evaluation of the direction and rates of change in soil CO_2 efflux rates by various tree species because of C storage potential in plantations (Fox, 2000). The objectives of this study were as follows: 1) to quantify the impacts of established forest stands on soil CO_2 efflux rates in adjacent, even-aged larch and pine plantations under similar site conditions, and 2) to correlate soil CO_2 efflux rates with stand (litter fall C and root decomposition) and soil environmental factors (soil temperature, soil water content, soil pH, soil organic C concentration).

Methods

The study was conducted in the Sambong National Exhibition Forests, administered by Korea Forest Service. The mean annual precipitation in this area is 1,322 mm and the annual mean temperature is 12.8°C. Experimental plots consisting of one decid-

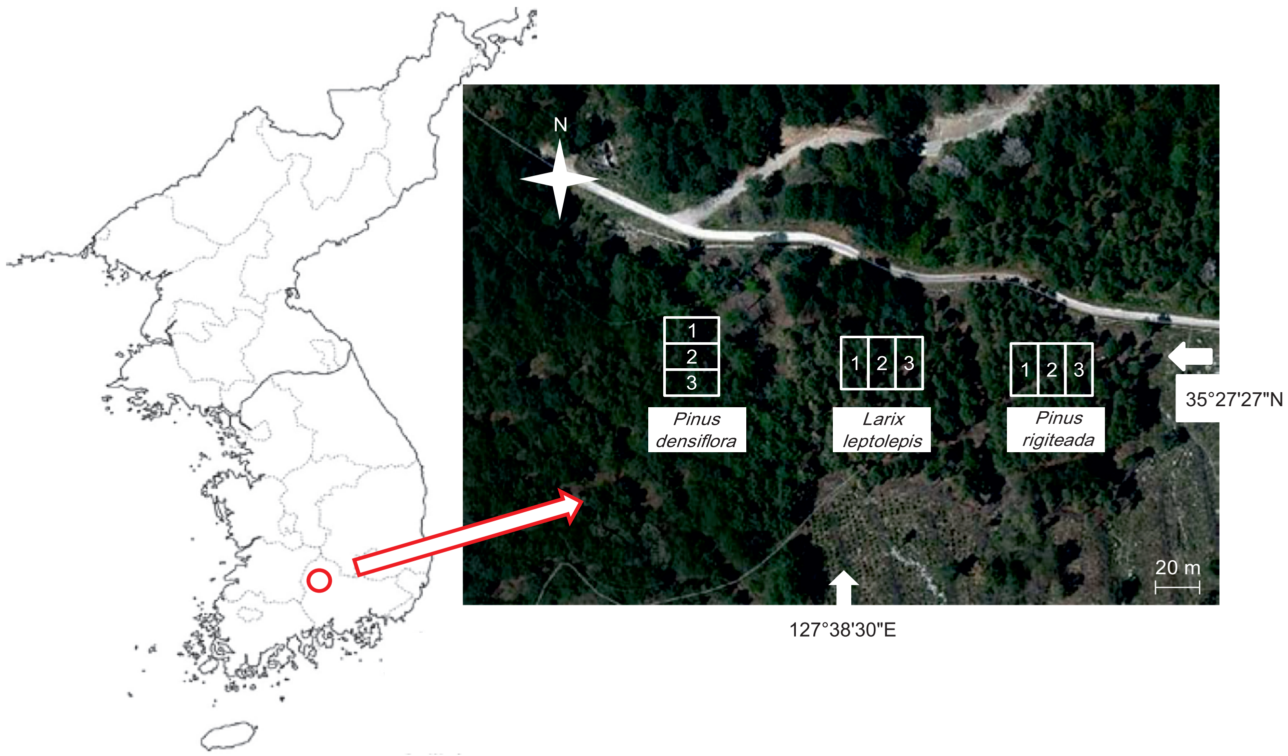

Fig. 1. Location of the study site in Gyeongnam province, southern Korea. Box indicates three replicated plots in each plantation

Table 1. General characteristics in *Larix leptolepis, Pinus densiflora* and *P. rigitaeda* plantations

Plantation	Location	Elevation (m)	Stand density (trees ha^{-1})	DBH (cm)		Basal area ($m^2 ha^{-1}$)	
				2006	2007	2006	2007
L. leptolepis	35°27'27" N 127°38'30" E	669	350 (17)	31.07 (2.58)	31.55 (2.57)	27.57 (5.13)	28.43 (5.14)
P. densiflora	35°27'27" N 127°38'28" E	665	216 (58)	34.80 (1.76)	35.27 (1.69)	20.70 (0.51)	21.27 (0.41)
P. rigitaeda	35°27'27" N 127°38'33" E	671	550 (29)	29.40 (0.54)	29.88 (0.49)	35.78 (3.29)	37.18 (3.83)

N=3 plots per plantation. Values in parenthesis indicate standard error. DBH: diameter at breast height.

uous (larch) and two evergreen (red pine; rigitaeda pine) coniferous plantations were located adjacent to each other (Fig. 1). All three plantations were established in 1963 on northeast facing slopes (5–15°). The study sites were characterized by identical macroclimatic conditions and plantation age. The data for this study were collected from three replicated plots (20 m × 10 m) as an experimental unit of each tree plantation, with a small distance (<20 m) among plantation types because sampling bias due to differing site components can be reduced by using a sampling scheme with identical designs for adjacent sites (Oksanen, 2001). Sampling within each plantation was repeated monthly enough to interpret the magnitude and consistency of treatment effects because plantations of each tree species were not replicated (Hurlbert, 1984). Thus, the results from a single replicate need to be viewed and interpreted cautiously due to pseudoreplication (Hurlbert, 1984; Binkley, 2008).

Mean stand densities, diameters at breast height (DBH), and basal areas of the three plantations are shown in Table 1. More information about the soil conditions, understory vegetation, and nutrient dynamics in relation to litter fall and root decomposition of this study site can be found elsewhere (Kim et al., 2010; Kim et al., 2013; Jeong & Kim, 2014).

Soil CO_2 efflux rates were measured monthly *in situ* using an infrared gas analyzer system (Model EGM-4, PP systems, Hitchin, UK) equipped with a flow-through closed chamber (Model SRC-2, same manufacturer) from three randomly selected locations of each plot across each plantation, at time between 13:00 and 17:00, monthly from July 2006 through June 2008. The soil CO_2 efflux rates from each date were considered the midpoint of a sampling month and were used to calculate the monthly CO_2 efflux rates (Bowden et al., 2004).

To compare soil factors among the three plantations, soil temperature was measured monthly at 20 cm depth using a soil temperature probe (Model STP-1) attached to the EGM-4. Soil samples to measure soil water content were collected monthly at 20 cm depth using an Oakfield soil sampler. The core samples were placed in plastic bags, transported to a laboratory and dried in an oven for 48 hours at 105°C to quantify the soil gravimetric water content. The organic C concentration of the collected soil samples was determined by loss on ignition at 550°C for 4 hours, and soil pH was measured by glass electrode.

To measure the litter fall, three circular litter traps made of 1.5 mm nylon net with individual surface area of 0.25 m^2 were installed at randomly chosen locations in each plot (total 27 traps). Litter was collected at monthly intervals between July 2006 and June 2007. The collected litter from each trap was transported to a laboratory and then oven-dried at 65°C for 48 hours. The dried samples were then separated into needles and other components, and the mass of each portion was recorded. The C concentrations of litter samples were determined by elemental analyzer (Thermo Scientific, Flash 2000, Italy).

Root decomposition rates were estimated using the *in situ* buried root decay bag technique, which has been the most common approach for comparisons of root decay rates (Silver & Miya, 2001; Jeong & Kim, 2014), employing 15 cm × 15 cm nylon bags with < 0.5 mm mesh size. Fresh roots from each plantation were collected from a sampling point located randomly in each plot at approximately 15 cm mineral soil depth on July 15, 2006. For this study, the root system was defined as woody and non-woody roots < 2 mm, 2–5 mm and 5–10 mm in diameter together with their associated root tips. After collection, the roots were gently rinsed with tap water, sorted into these size classes, and air dried to constant mass at room temperature for 20 days. Root samples with an air-dried mass of 1 g were weighed to the nearest 0.01 g and placed in numbered bags. Sub-samples from each root type were also taken to determine oven-dried mass at 65°C for 48 hours. A total of 81 root bags (3 tree species types × 3 replication plots × 3 root diameter size classes × 3 replication samples) were incubated in the mineral soil layer of each plantation (installed 29 July 2006). The bags were inserted vertically into the mineral soil to a depth of 15 cm with a straight-blade shovel and collected after 378 days (11 August 2007). Collected bags were oven-dried at 65°C for 48 hours, cleaned by gentle brushing with a soft paintbrush to remove mineral soil and weighed to

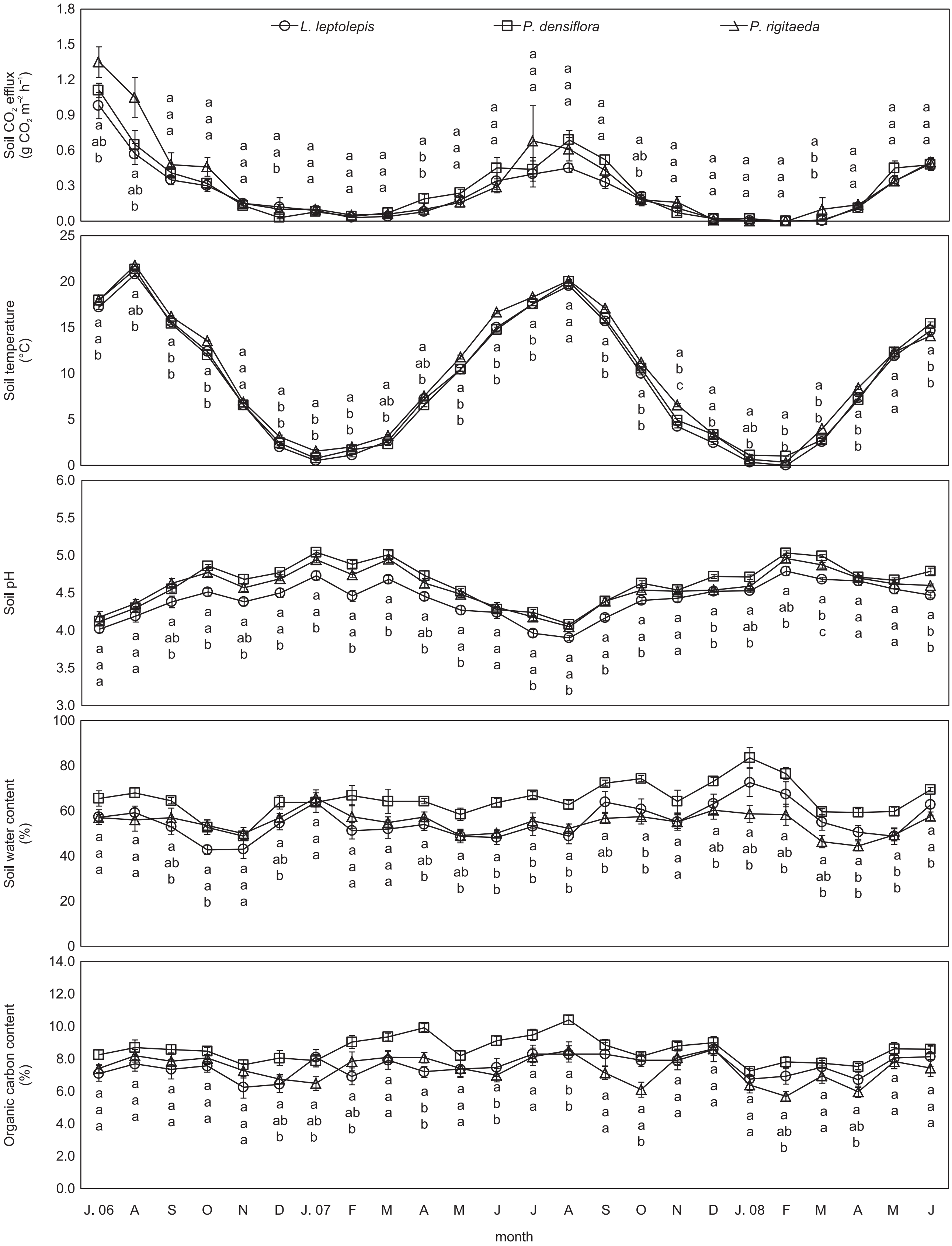

Fig. 2. Monthly fluctuations of soil CO_2 efflux, soil temperature, soil pH, soil water content and organic carbon content in *Larix leptolepis, Pinus densiflora* and *P. rigitaeda* plantations. Mean and standard error are shown (n = 9). Different letters among plantations of each month represent a significant difference at $P < 0.05$

determine root mass loss rates. Information about the C and nitrogen dynamics in fine root decomposition processes of this study site can be found elsewhere (Jeong & Kim, 2014).

The exponential regressions between the soil CO_2 efflux rates and soil temperature were calculated as follows:

$$\text{Soil } CO_2 \text{ efflux rates} = B_0 e^{b_1 ST}$$

where B_0 and b_1 are the coefficients estimated through the regression analysis and ST is the soil temperature. The Q_{10} values were calculated by the equation $Q_{10} = e^{10\times b_1}$.

The effect of tree species on soil CO_2 efflux rates and soil or stand environmental factors was evaluated by a nested analysis of variance (Kroodsma et al., 2011) with the PROC MIXED procedure in SAS (SAS Institute Inc., 2003). Three experimental units of each plantation were considered to be a possible covariate (a random effect) in the analysis. When significant differences at $P < 0.05$ occurred, a comparison of the treatment means was compared using Tukey adjustment of least squares means. Pearson correlation coefficients were also calculated for the soil CO_2 efflux rates and the stand or soil environmental factors.

Results

Factors affecting the fluctuation of monthly soil CO_2 efflux rates

Temporal fluctuations in soil CO_2 efflux rates for the three plantations were closely related to soil temperature fluctuations. Soil CO_2 efflux rates reached their maximum values in July and August (Fig. 2) but declined during the fall (September and October) and spring (April and May). An exponential regression of monthly CO_2 efflux rates against the corresponding soil temperature at a depth of 20 cm (Fig. 3) was significant in all three plantations (larch: $R^2 = 0.63$, $P < 0.05$; red pine: $R^2 = 0.69$, $P < 0.05$; rigitaeda pine: $R^2 = 0.67$, $P < 0.05$; all plantations: $R^2 = 0.66$, $P < 0.05$). Q_{10} values in the three plantations were 4.76 in red pine, followed by 4.61 in rigitaeda pine and 3.96 in larch plantations.

Monthly fluctuations of CO_2 efflux rates were negatively correlated (Fig. 4) with the fluctuations of soil pH in all three plantations (larch: $r = -0.71$, $P < 0.01$; red pine: $r = -0.79$, $P < 0.01$; rigitaeda pine: $r = -0.66$ $P < 0.01$). In contrast to soil pH, the correlation coefficient of soil CO_2 efflux rates against soil water content was not significant ($P > 0.05$) because no monthly fluctuation in soil water contents was ob-

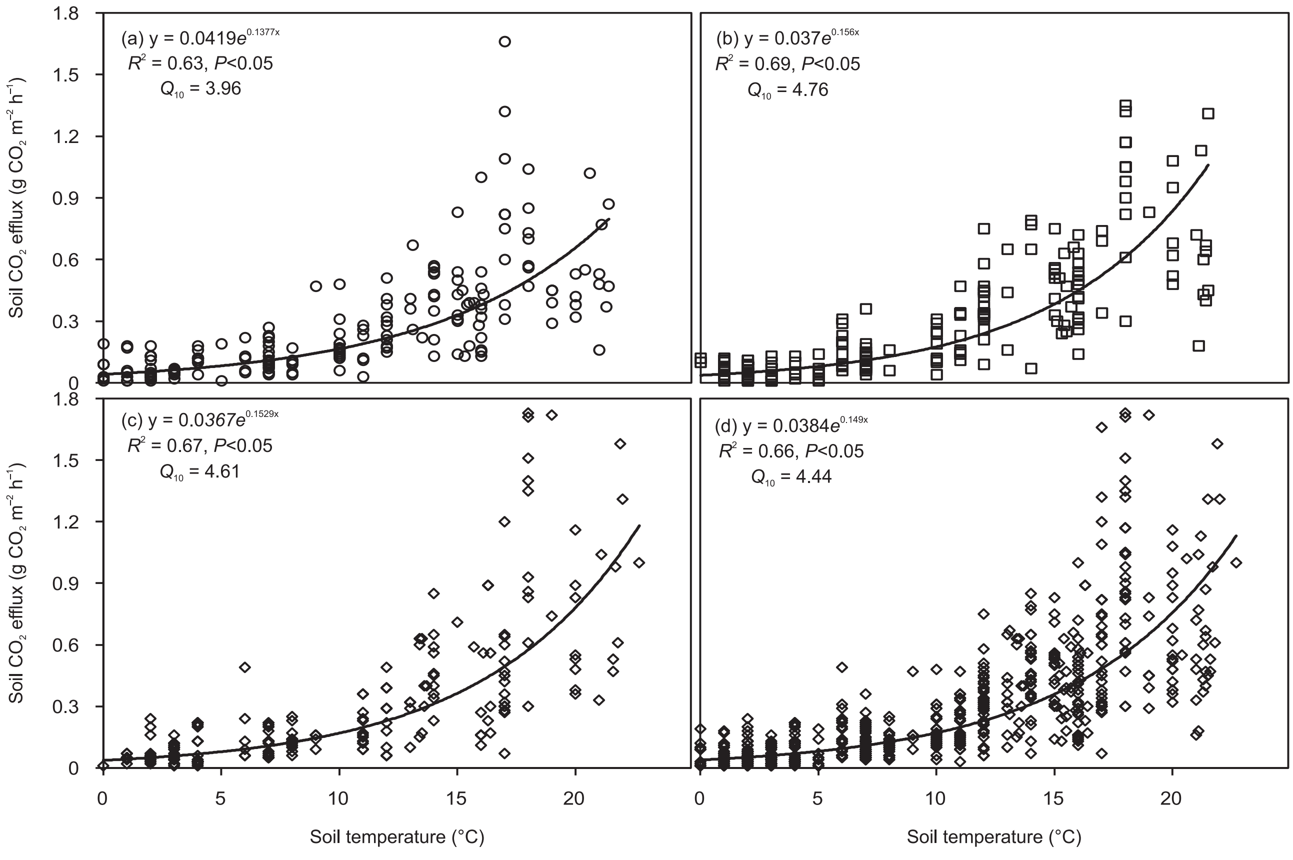

Fig. 3. An exponential regression of CO_2 efflux rates against the soil temperature in *Larix leptolepis* (a), *Pinus densiflora* (b), *P. rigitaeda* (c) and all plantations (d)

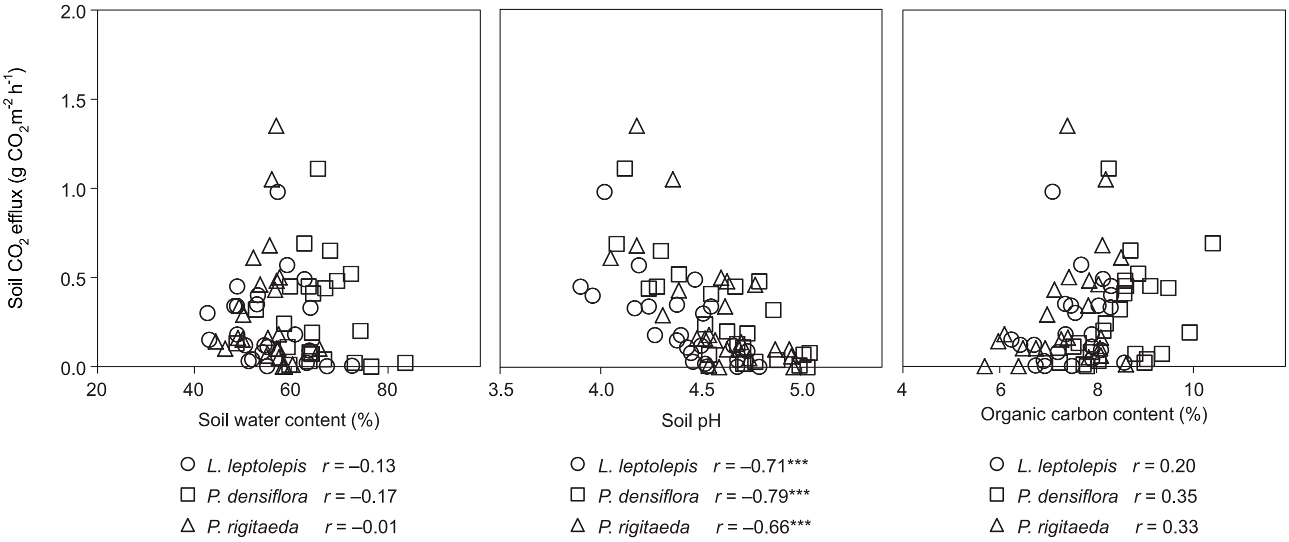

Fig. 4. Correlation relationships between CO_2 efflux rates and soil pH, soil water content and soil organic carbon content in *Larix leptolepis, Pinus densiflora* and *P. rigitaeda* plantations (***: P <0.001)

served in the study stands. Soil organic C availability was not the major controlling factor (r = 0.20–0.35) of monthly fluctuations of soil CO_2 efflux in the three plantations.

Factors affecting mean annual soil CO_2 efflux rates

The mean annual soil CO_2 efflux rates for the 2-year study period were significantly higher in rigitaeda pine (0.30 g CO_2 m^{-2} $hour^{-1}$) than in larch (0.24 g CO_2 m^{-2} $hour^{-1}$), but the rates were not significantly different between the red pine (0.27 g CO_2 m^{-2} $hour^{-1}$) and rigitaeda pine plantations (Fig. 5). In this study, abiotic factors such as the mean annual soil temperature, mean annual soil water content, mean annual soil pH and mean annual soil organic C content, which are regarded as the main factors influencing soil respiration, were significantly different among the three plantations (Fig. 5).

The soil CO_2-C efflux rates were the highest in rigitaeda pine (8.48 Mg C ha^{-1} $year^{-1}$), followed by red pine (7.23 Mg C ha^{-1} $year^{-1}$) and larch (6.45 Mg C ha^{-1} $year^{-1}$) plantations. There was a significant negative correlation between annual soil CO_2-C efflux rates and total litter fall C fluxes during the study period in the larch and pine plantations (Fig. 6), although the efflux rates were not significantly correlated with the needle litter C fluxes in the rigitaeda pine plantation. There was no correlation between soil CO_2-C efflux rates and decomposition rates from various sizes of roots in three plantations, except for the decomposition rates of 5–10 mm roots of larch (Fig. 7).

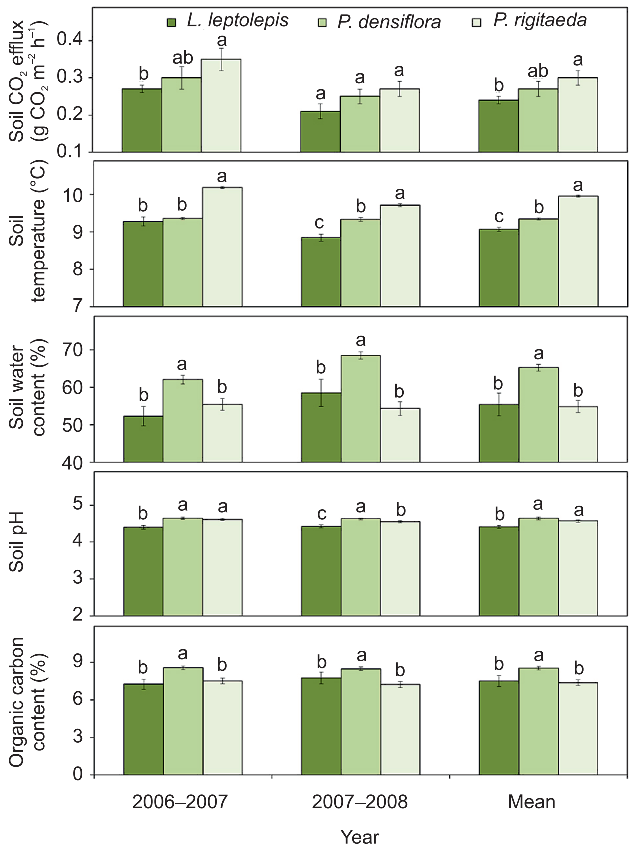

Fig. 5. Mean (n = 9) annual soil CO_2 efflux rates, soil temperature, soil pH, soil water content and organic carbon content in *Larix leptolepis, Pinus densiflora* and *P. rigitaeda* plantations. Vertical bars indicate standard error. Different letters on the bars represent a significant difference at P < 0.05

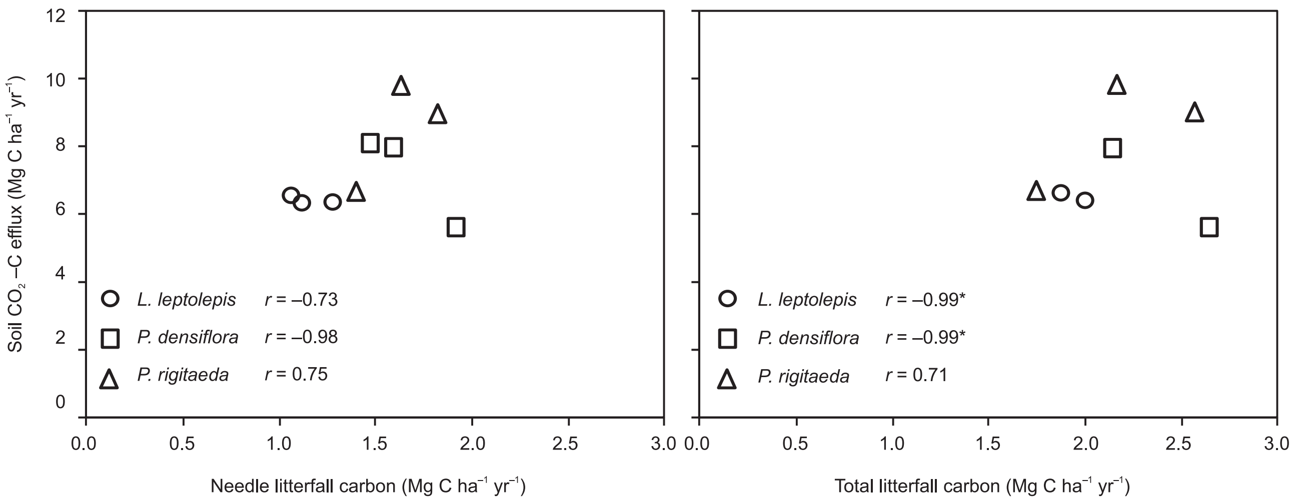

Fig. 6. Correlation relationships between soil CO_2-C efflux rates and needle or total litterfall carbon fluxes in *Larix leptolepis, Pinus densiflora* and *P. rigitaeda* plantations (*: $P < 0.05$). Each data point is the mean value of 3 observations within each replication plot

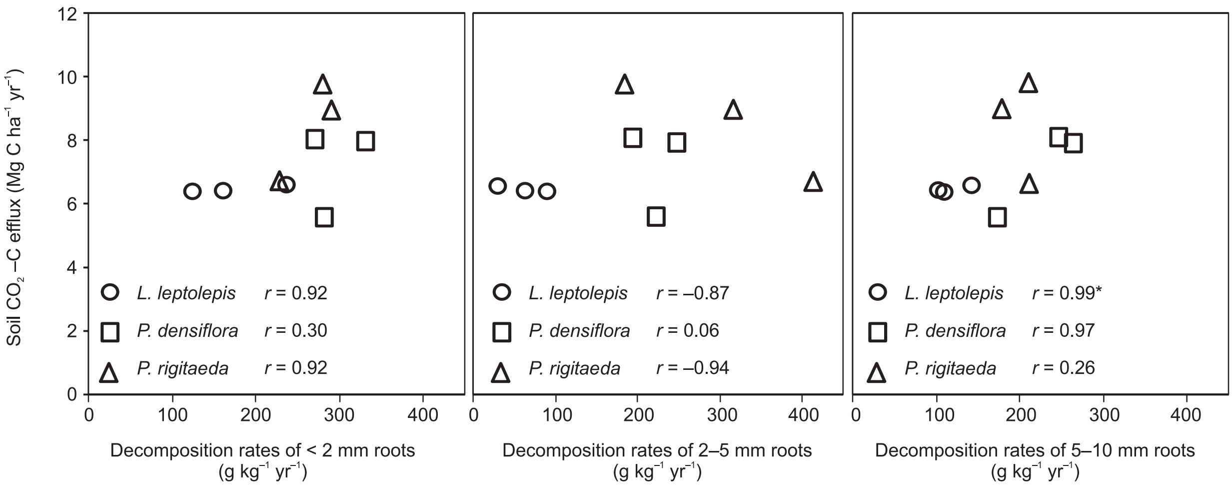

Fig. 7. Correlation relationships between soil CO_2-C efflux rates and decomposition rates of various root sizes in *Larix leptolepis, Pinus densiflora* and *P. rigitaeda* plantations (*: $P < 0.05$). Each data point is the mean value of 3 observations within each replication plot

Discussion

Factors affecting the fluctuation of monthly soil CO_2 efflux rates

Temporal fluctuations in monthly soil CO_2 efflux rates were affected by different tree species. Relatively low soil CO_2 efflux in the larch plantation could be attributed to the difference in soil temperature compared to the two pine plantations (Fig. 2). For example, soil temperatures in July and August 2006 were significantly lower for the larch (17.2°C) than for the rigitaeda pine (18.0°C) plantations. Several studies have reported significant effects of soil temperature on monthly soil CO_2 efflux rates because microbial activity increases with rising soil temperature (Buchmann, 2000; Davidson & Janssens, 2006). An exponential increase in monthly soil CO_2 efflux rates with respect to soil temperature has been observed in other different forest types in Korea (Kim et al., 2009; Noh et al., 2010) because of the temperature dependency of microbial decay and root growth activity. Also, sensitivity of soil CO_2 efflux rates to soil temperature is commonly expressed by the coefficient Q_{10} values (Bond-Lamberty, 2011). However, Q_{10} values were not related to the difference of soil temperature among the three plantations because mean annual soil temperature was significantly lower for red pine than for rigitaeda pine plantations. The highest Q_{10} value at 20 cm soil depth in red pine could have resulted mainly from high C availability for microbial decay with adequate soil water content (Fig. 5). The Q_{10} values in this study are comparable to those observed in other pine forests in Korea, which have been reported as 3.45–3.77 at 12 cm soil depth in red pine stands (Noh et al., 2010). The difference in Q_{10} values between this previous study and the current one may be due to the difference in soil depth at which temperature was measured. For example, in another study, Q_{10} values increased from 1.9 to 3.5 with increasing soil depth in European beech, Norway spruce, and Scots pine forests (Borken et al., 2002).

The strong correlation between monthly CO_2 efflux rates and soil pH has been observed due to a seasonal trend in soil pH, which was depressed in the summer season when soil CO_2 efflux reached its maximum value and was elevated in the winter season when soil CO_2 efflux reached its minimum value. In contrast to soil pH, no monthly fluctuation in soil water contents was observed during the study period. Generally, the effect of soil water content on soil CO_2 efflux is limited to either extremely high or low water levels, such as those observed during heavy rainfall events or prolonged droughts (Pangle et al., 2002; Tang et al., 2005), whereas seasonal soil temperature variation is minor (Davidson & Janssens, 2006). Soil organic C availability was not the major controlling factor (r = 0.20–0.35) of monthly fluctuations of soil CO_2 efflux in the three plantations because of large temporal and spatial variations of its component (Reth et al., 2005).

Factors affecting mean annual soil CO_2 efflux rates

Mean annual soil CO_2 efflux rates in forest ecosystems can be affected (Lee & Jose, 2003; Metcalfe et al., 2011) or relatively be unaffected (Valverde-Barrantes, 2007; Olsson, 2012) by different tree species. Many studies reported that differences in CO_2 efflux between tree species could be attributed to differences in the conditions for decomposition of organic matter and root respiration, which are the two main sources of soil CO_2 efflux rates (Metcalfe et al., 2007; Lee et al., 2010). For example, rigitaeda pine plantations showed favorable environmental conditions for microbial or root growth activity and organic matter decomposition, such as higher soil temperature (approximately 0.61–0.89°C) and soil pH (approximately 0.16 units), compared to red pine or larch plantations (Fig. 5). Soil pH is an important variable that affects soil CO_2 efflux rates because it is closely related to microbial activity and nutrient availability (Lee & Jose, 2003). In addition, the soil organic C content was significantly lower in rigitaeda pine plantations than in red pine plantations (Fig. 5), indicating an accelerated turnover for soil C pools due to relatively high soil temperature compared to the other two plantations. Low soil water content in rigitaeda pine has also been attributed to enhanced diffusivity for CO_2 due to increased air-filled pore space (Tang et al., 2005).

The soil CO_2-C efflux rates observed in these larch and pine plantations were comparable to those reported for other pine forests (6.21–7.45 Mg C ha^{-1} year^{-1}) in central Korea (Noh et al., 2010) and for temperate evergreen coniferous forests (6.81 Mg C ha^{-1} year^{-1}) and deciduous needle-leaved forests (6.41 Mg C ha^{-1} year^{-1}) in the world's terrestrial vegetation (Raich & Schlesinger, 1992). There was a significant correlation between annual soil CO_2-C efflux rates and total litter fall C fluxes during the study period in the larch and red pine plantations. This result supports the previously reported finding that annual soil CO_2 efflux rates were correlated to annual litter fall production across forest ecosystems (Yan et al., 2006). In this study, annual soil CO_2-C efflux rates were 3.9 times more than the total litter fall C fluxes in rigitaeda pine, 3.3 times more in larch and 3.1 times more in red pine plantations. The annual soil CO_2-C efflux rates observed in these three plantations were slightly higher than those reported for a global compilation of litter fall and soil CO_2 efflux data, which showed an average value of 3.0 (Raich & Tufekcioglu, 2000).

There was no correlation between annual soil CO_2-C efflux rates and annual rates of decomposition from various sizes of roots in three plantations except for the decomposition rates of the larch roots, although heterotrophic soil respiration contributed approximately 66% of temperate coniferous forests in Korea (Lee et al., 2010). Other study reported that root decomposition in forest soils was related to soil CO_2 efflux rates for approximately 3 months after initial incubation (Raich & Schlesinger, 1992) due to species-specific differences in fine root productivity, tissue chemistry, and turnover rates of organic matter (Søe & Buchmann, 2005).

Conclusions

Three coniferous plantations in this study are capable of altering the soil CO_2 efflux and various soil resource and environmental variables such as soil temperature, soil pH, soil water and soil organic C content. The increased soil CO_2 efflux in the rigitaeda compared with the larch plantations was attributed to changes in soil temperature and soil pH that may have enhanced the decomposition rates of stored organic matter and microbial activity and root growth in the mineral soil layer. Soil CO_2-C efflux rates were influenced by total litter fall C fluxes of larch or red pine plantations, while these efflux rates were not affected by needle litter fall C fluxes and decomposing roots. This study indicates that soil CO_2 efflux rates in one deciduous and two coniferous plantations could be determined by changes in stand and soil resource factors caused by the different tree species when established at sites with similar macroclimatic and management conditions.

Acknowledgments

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