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Soil Carbon Cycling and Soil CO_2 Efflux in a Red Pine (*Pinus densiflora*) Stand

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ABSTRACT: This study was conducted to evaluate forest carbon cycling and soil CO_2 efflux rates in a 42-year-old pine (*Pinus densiflora*) stand located in Hamyang-gun, Korea. Aboveground and soil organic carbon storage, litterfall, litter decomposition, and soil CO_2 efflux rates were measured for one year. Estimated aboveground biomass carbon storage and increment in this stand were 3,250 gC/m^2 and 156 gC m^{-2} yr^{-1}, respectively. Soil organic carbon storage at the depth of 30 cm was 10,260 gC/m^2. Mean organic carbon inputs by needle and total litterfall were 176 gC m^{-2} yr^{-1} and 235 gC m^{-2} yr^{-1}, respectively. Litter decomposition rates were faster in fine roots less than 2 mm diameter size (< 220 g kg^{-1} yr^{-1}) than in needle litter (< 120 g kg^{-1} yr^{-1}). Annual mean and total soil respiration rates were 0.37 g CO_2 m^{-2} h^{-1} and 2,732 g CO_2 m^{-2} yr^{-1} during the study period. A strong positive relationship existed between soil CO_2 efflux and soil temperature (r = 0.8149), while soil CO_2 efflux responded negatively to soil pH (r = −0.3582).

Key words: Carbon dynamics, Carbon storage, Red pine, Soil respiration

INTRODUCTION

Carbon cycling in forests has been the focus of research (Nakane 1995, Davis et al. 2003, Laporte et al. 2003), because forests have an important role in global climate change, as defined in a recent IPCC report (Watson et al. 2000). However, the role and the importance of forests as sources or sinks for carbon are likely to be quite variable with region, type of forest, age of the trees and forest management activities (Johnson 1992, Nakane 1995, Lee and Jose 2003, Pypker and Fredeen 2003). Forests have been considered as potential carbon sinks that may play a role in storing some of the carbon dioxide emitted in the atmosphere (Watson et al. 2000, Janssens et al. 2002). In addition, the evaluation of carbon storage and soil respiration changes in forest is a key factor in improving the carbon sequestration because of a major carbon sink to carbon dioxide in the atmosphere (Fox 2000). Despite progress in the quantification of the carbon balance in forests, major uncertainties remain in relation to the importance and behavior of forest carbon cycling in Korea.

The red pine (*Pinus densiflora*) constitutes the most dominant type of coniferous forest throughout the country. There has, however, been little attempt to study quantitatively the cycling of carbon in red pine stands. The objectives of this study were to determine a forest carbon cycling in a red pine stand. This entailed 1) dynamics in organic carbon storage (aboveground biomass and 30 cm of soil depth), carbon inputs (litterfall production) and carbon losses (litter and fine root decomposition); 2) dynamics in soil respiration by closed chamber infrared gas analyzer techniques.

MATERIALS AND METHODS

The study was conducted in the Sambong Exhibition Forests located in Hamyang-gun, Gyeongsangnam-do administered by the Western National Forest Office, Korea Forest Service. Annual average precipitation in this area is 1,322 mm/yr and annual average temperature is 12.8℃. The soil in this study site was characterized as a well-drained, slightly wet brown forest soil. The stand was established with planting of red pine seedlings in 1963. Dominant understory species in the study site were *Rhododendron mucromulatum*, *Quercus serrata*, *Q. aliena*, *Lindera glauca*, *L. obtusioloba*, *Smilax china*, and *Juglans mandshurica* etc. Soil texture was silt loam. Soil pH was 4.75 with acidic property. The experimental design consisted of three 20 m × 10 m plots. Mean stand density of the stand was 216 trees/ha and contained 200~250 trees/ha. Mean tree diameter and height were approximately 32.4 cm and 14.6 m, respectively. Stand basal area averaged 19.0 cm^2/m^2.

The carbon storage of aboveground tree species was measured by equations for dry matter estimation (Y= 0.017963(DBH)^2 ×(Height), R^2=0.90) developed from Korea Forest Research Institute

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(Kim et al. 1998). Aboveground carbon storage was calculated assuming a carbon concentration of 50 % of the dry matter (McPherson and Simpson 1999, Davis et al. 2003).

Soil samples to measure soil carbon content were collected in November 2003 from three randomly selected points in each plot. At each point, a soil pit of 50 cm × 50 cm was dug to collect soil samples at three depths (0~10 cm, 10~20 cm, 20~30 cm). Soil bulk density at each soil depth was determined after the drying (105 ℃) of samples stored in 100 cc stainless steel cans. Five bulk soil samples to measure soil carbon content were collected at three depths. Collected soil samples were air-dried and sifted through a 2 mm sieve prior to soil carbon analysis. Loss on ignition at 375℃ for 16 hours (Soon and Abboud 1991) was determined for mineral soil samples and converted to carbon percentage (Davis et al. 2003).

To measure organic carbon input by litterfall, eight circular litter traps each with 0.25 m^2 surface area were installed at 60 cm above the forest floor. Litter was collected between July 2004 and June 2005. Litter from each trap was transported to laboratory and oven-dried at 65℃ for 48 hours. All dried samples were separated into needle, bark, fruit, branches and miscellaneous components, and each portion was weighed. Mass loss rates in decomposing litter were estimated using the litterbag technique. Fresh needle litter from each plot was collected on the forest floor in late November 2003. After collection, the litter was air-dried at room temperature for 14 days. And approximately 10 g was placed in 30 cm × 30 cm nylon net bags each with a 0.3 mm size mesh. Subsamples from the litter were also taken to determine oven-dried mass at 65℃ for 48 hours. Six litterbags within each plot were randomly placed on the forest floor in July 2004. The litterbags were held fast by metal pins of 10 cm length, and collected from each plot after one year (June 2005). After collection, each litterbag sample was oven-dried at 65℃ for 48 hours, weighed , and mass loss rates were determined.

Fine root decomposition rates were estimated using *in situ* buried root decay bag technique which employs 15 cm × 15 cm nylon bags each with 0.3 mm size mesh. Fresh fine roots from each plantation were randomly collected from sampling points in mineral soil depth in June, 2004. For this study, the fine root system was defined as non-woody and woody root, <1 mm, 1~2 mm, and 2~5 mm in diameter and their associated root tips. After collection, the fine roots were gently rinsed in tap water, classified by size, and air dried to constant mass at room temperature for 14 days. The root samples with an air dried mass of 1 g were weighed and placed in numbered bags. Subsample from each root type was also taken to determine oven-dried mass at 65℃ for 48 hours. Three root bags with three root size classes were placed randomly on the mineral soils in each plot in July 2004. The bags were inserted vertically into the mineral soil at the depth of 15 cm with a straight-blade shovel. The bags were collected after one year of incubation (June 2005). After collection, each bag sample was oven-dried at 65℃ for 48 hours and their mass loss rates were determined.

Soil CO_2 efflux was measured *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). At the time of measurement, the forest floor was removed and the chamber was inserted 3 cm into the soil. Measurement at each sampling point took 120 seconds. Intervals between samplings were long enough to get reliable estimates of CO_2 efflux with the equipment used. Measurements were performed between 10:30 a.m. and 12:30 p.m. for one years (from July 2004 to June 2005) except for snow season (January, February, March) in the study site. During the measurement, soil temperature was measured at 20 cm depth adjacent to each chamber. Also, adjacent to each chamber, soil samples using an oakfield soil sampler were collected at 15 cm depth to measure soil moisture content, soil pH and soil organic carbon content.

RESULTS AND DISCUSSION

Aboveground and Soil Carbon Storages

Estimated aboveground organic carbon storage and increment in this stand were 3,250 gC/m^2 and 156 gC m^{-2} yr^{-1}, respectively (Table 1). The carbon storage and increment in this stand were lower than in other pine stands. The carbon storage in a 42-year-old *Pinus rigitaeda* stand near the study site were 7,720 gC/m^2 (Kim and Cho 2004) and the carbon increment in a 31-year-old *Pinus rigida* stand in Gwangnung was 323 gC m^{-2} yr^{-1}, respectively (Kim and Jeong 2001). Melillo et al. (1994) reported that annual carbon increment of temperate coniferous forests averaged 470 gC $m^{-2}yr^{-1}$. Aboveground organic carbon storage and increment in coniferous plantations was attributed by difference of stand basal area due to common forest management such as a thinning intensity (Kim and Jeong 2001, Kim and Cho 2004).

Soil carbon content decreased with depths (Table 2). Carbon con-tent was higher in surface depth (0~10 cm) than in subsurface

Table 1. Aboveground organic carbon storage and increment in a red pine stand (n=3)

Year	DBH (cm)	Aboveground carbon storage (gC/m^2)	Aboveground carbon increment (gC m^{-2} yr^{-1})
2003	32.7 (1.7)	3,094 (322)	-
2004	33.2 (1.7)	3,250 (318)	156 (13)

- not determined. Numbers in parenthesis indicate standard errors.

depth (20~30 cm). High carbon content of the surface depth could be due to the inputs of organic matter decomposed by litterfall and fine roots (Jeong et al. 1998). Carbon content was much higher in this stand than in the other Korean forest soils. Jeong et al. (1998) reported that carbon content in the surface depth (A horizon) of the Korean forest soils was less than 26 gC/kg. Soil carbon storage at the depth of 30 cm in this study site (10,260 gC/m^2) was slightly higher than in other coniferous stands near the study site. Soil carbon storage at the depth of 30cm was 9,120 gC/m^2 for a 42-year-old *L. leptolepis* and 9,420 gC/m^2 for a 42-year-old *P. rigitaeda* stand (Kim and Cho 2004). The soil carbon storage of this stand was also higher than that of 6,700 gC/m^2 of Korean forest soils (Jeong et al. 1998).

Litterfall Inputs

Organic carbon inputs by needle and total litter were 176 gC m^{-2} yr^{-1} and 236 gCm^{-2} yr^{-1}, respectively (Table 3). Needle litter accounted for about 75 % of the total annual litterfall. Annual litterfall obtained in this study site was higher than that (206 gC m^{-2} yr^{-1}) observed in the 40-year-old *L. leptolepis* plantation (525 trees/ha), Gyounggi Province (Hwang 2004).

Litter and Root Decomposition Rates

Decomposition rates were faster in fine roots (<2 mm) than in needle litter during one year incubation (Fig. 1). Similarly, Cronan (2003) reports that root decomposition rates were higher than needle decomposition rates for mature Norway spruce stands. He has presumed that the rapid decay rates in root litters were the result of low C/N ratios in root tissues, and the favorable moisture conditions of mineral soils with resident communities of soil fungi and detritivores. Needle litter or root decomposition can be influenced by abiotic factors such as temperature and moisture and by soil properties such as soil texture and N availability, and by biotic factors such as N and lignin concentration and/or the decay organism present in the soil (Joslin and Henderson 1987, Cronan 2003, Hwang

Table 2. Soil organic carbon content and storage in a red pine stand (n=6)

Depth	Bulk density (g/cm^3)	Rock percentage (g/kg)	Carbon content (gC/kg)	Carbon storage (gC/m^2)
0~10 cm	0.56 (0.02)	179 (6)	85.1 (3.6)	3,860 (151)
10~20 cm	0.68 (0.05)	238 (14)	66.6 (2.5)	3,430 (173)
20~30 cm	-	222 (14)	56.8 (2.6)	2,990 (190)
Total	-	-	-	10,260 (510)

-: not determined. Numbers in parenthesis indicate standard errors.

Table 3. Organic carbon inputs by litterfall in a red pine stand (n=8)

Litterfall components	Organic carbon (gC m^{-2} yr^{-1})
Needle	176.46 (28.52)
Branch	8.98 (3.84)
Bark	10.70 (1.94)
Miscellaneous	39.58 (10.90)
Total	235.80 (34.47)

Numbers in parentheses indicate standard errors.

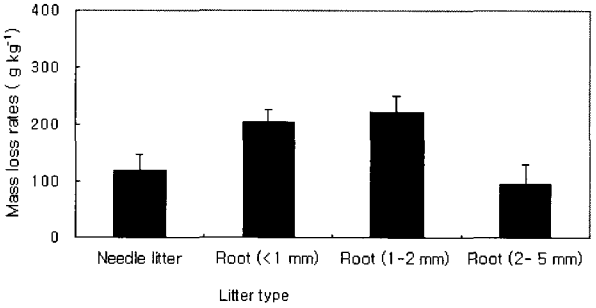

Fig. 1. Needle and root decomposition rates in a red pine stand (n=9). Vertical bars indicate standard errors.

2004). Decomposition rates of roots were lower in < 2~5mm size (96 g kg^{-1} yr^{-1}) than in other size classes (205~220 g kg^{-1} yr^{-1}) (Fig. 1). This difference in mass loss among the root diameter classes is probably due to differences in root C/N ratio or lignin concentration which are major factors controlling decomposition (Fogel and Cromack 1977, Edmonds 1991). Decomposition rates of roots in this study were lower than those reported for other deciduous or coniferous forests. Decomposition rates of fine roots using *in situ* buried root decay bag were about 330 g kg^{-1} yr^{-1} in *Quercus accutisima* and 370 g kg^{-1} yr^{-1} in *P. koraiensis* stands in Korea (Kim 2002). In comparison, annual decomposition rates of fine roots in North America ranged from 270 g kg^{-1} yr^{-1} to 520 g kg^{-1} yr^{-1} (McClaugherty et al. 1982, Joslin and Henderson 1987).

Soil CO_2 Efflux Rates

Soil CO_2 efflux showed a clear seasonal variation. The rates increased during spring and summer, and reached maximum values in July and August (Fig. 2). During the fall (October, November), the rates declined again, reaching values close to those in spring (April and May). In addition, temporal variation in the rates was closely related to soil temperature fluctuation rather than the variation of soil moisture content, soil organic carbon content, or soil pH (Fig. 2). Many studies reported that soil CO_2 efflux in temperate forests

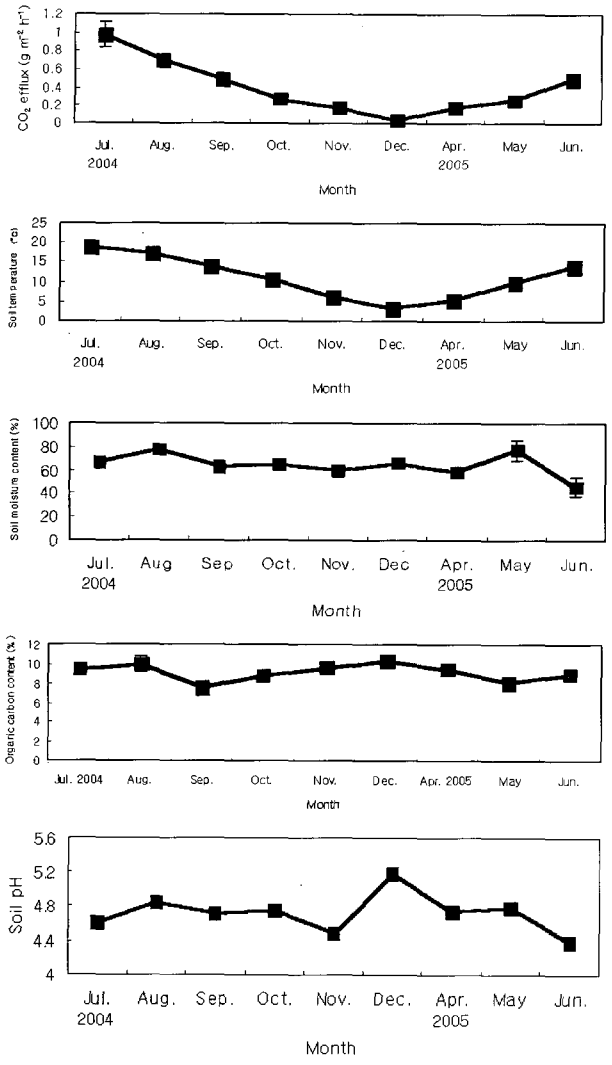

Fig. 2. Monthly variation of soil CO_2 efflux, soil temperature at 20 cm depth, soil moisture content, organic carbon content and soil pH at 15 cm depth in a red pine stand (n=9). Vertical bars indicate standard errors.

is typically higher in summer and lower in winter, corresponding to changes in ambient temperature because roots and soil organisms

Table 4. Correlation coefficients between Soil CO_2 efflux and soil factors in a red pine stand (n=90)

	Soil moisture content	Soil organic carbon content	Soil pH	Soil CO_2 efflux
Soil temperature	−0.0638 (0.5501)	−0.0876 (0.4116)	−0.4538 (0.0001)	0.8220 (0.0001)
Soil moisture content		0.0971 (0.3627)	0.1586 (0.1355)	0.0500 (0.6396)
Soil organic carbon content			0.1542 (0.1468)	0.0387 (0.7169)
Soil pH				−0.3790 (0.0002)

Numbers in parentheses indicate *p*-values.

(bacterial and fungal detritivores) contribute to soil CO_2 efflux through respiration (Son and Kim 1996, Ohashi et al. 1999, Wiseman and Seiler 2004).

A correlation coefficient between soil CO_2 efflux and soil temperature at the 20 cm depth (r = 0.8220, p<0.05) or soil pH (r = −0.3790, p<0.05) was highly significant (Table 4). Previous investigators report similar results that soil respiration was correlated strongly with soil temperature (Son and Kim 1996, Ohashi et al. 1999, Laporte et al. 2003, Lee and Jose 2003). However, a negative correlation between soil CO_2 efflux and soil pH might be attributed to monthly variation of soil pH. Soil pH showed a low value in summer season when soil CO_2 efflux reached to maximum values. The correlation coefficient of soil CO_2 efflux against soil moisture content or soil organic carbon content was not significant (p>0.05).

Annual mean soil respiration rates during the study period of one year were 0.37 g CO_2 m^{-2} h^{-1}. These values were similar to other coniferous stands in Korea (Table 5). Total soil respiration rates in this study were 2,732 g CO_2 m^{-2} yr^{-1}. Similar range has been reported in other coniferous studies in Korea (Son and Kim 1996, Hwang 2004) or Japan (Ohashi et al. 1999). Son and Kim (1996)

Table 5. Soil respiration rates of coniferous forest ecosystem in Korea

Stand	Stand age (yr)	Stand density (tree/ha)	Mean soil respiration (g CO_2 m^{-2} h^{-1})	Total soil respiration (g CO_2 m^{-2} yr^{-1})	Methods	Reference
Larix leptolepis	36	387	0.39	2,920	IRGA	Kim (2004)
L. leptolepis	40	548	0.32	2,370	soda-lime	Son and Kim (1996)
L. leptolepis	44	525	0.37	1,960	IRGA	Hwang (2004)
Pinus rigida	40	667	0.38	2,680	soda-lime	Son and Kim (1996)
P. rigida	40	1,100	0.45	2,420	IRGA	Hwang (2004)

and Hwang (2004) observed that annual soil respiration was ranged from 2,420 to 2,680 g CO_2 m^{-2} yr^{-1} in a 40-year-old *P. rigida* plantation in Gyounggi Province, Korea. Ohashi et al. (1999) reported that annual soil respiration rates in a *Cryptomeria japonica* plantation of Japan were ranged from 2,570 to 3,060 g CO_2 m^{-2} yr^{-1}. However, the value of the study site was slightly higher than average respirations (2,374~2,550 g CO_2 m^{-2} yr^{-1}) reported by Raich and Schlesinger (1992) in a review of studies involving temperate deciduous forests and coniferous forests.

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