Research paper

Comparison of Seasonal Variations in Carbon Dioxide Concentrations between a Natural Hardwood Stand and a Fir Plantation at the Guandaushi Subtropical Forest, Taiwan

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【Summary】

The purpose of this study was to understand variations in carbon dioxide concentrations at different canopy heights in a natural hardwood stand and a China-fir (*Cunninghamia lanceolata*) plantation at the Guandaushi subtropical forest. The measurements began in September 2004 and continued to the end of June 2005. There were 4 sampling heights, including 0.5, 4, and 12 m above ground level (agl) and 3~4 m above the canopy at the 2 stands. Results showed that the highest concentration of carbon dioxide was near the forest floor, and the lowest ones were at 12 m agl and 3~4 m above the canopy for both the natural hardwood stand and fir plantation. Seasonal and yearly variations of sampling heights between 12 m agl and 3~4 m above the canopy were not significant. The carbon dioxide concentrations of the 4 sampling heights were higher in spring and summer than in winter. Variations in carbon dioxide concentrations of the sampling height at 12 m in the natural hardwood forest were influenced by light intensity, regardless of daily or yearly variations. We concluded that the forest floor soil of the natural hardwood stand had a higher respiration rate, and there was a lower photosynthetic rate at the 12-m level of the canopy. Therefore, at all sampling points, the concentrations of carbon dioxide were higher than these in the China-fir plantation. This concentration gradient was more significant in the higher-temperature season (June) than in the lower-temperature season (December to January).

Key words: carbon dioxide, canopy, seasonal variation, spatial variation, subtropical forest.

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研究報告

臺灣關刀溪亞熱帶天然闊葉林和人工杉木林二氧化碳濃度時間變異比較

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摘 要

本研究目的為了解關刀溪天然闊葉林與人工杉木林於不同冠層高度二氧化碳濃度之分佈概況及垂直梯度的變化情形。採樣期間自2004年9月至2005年6月，於天然林與杉木林分別設置0.5 m、4 m、12 m及冠層上3~4 m等4個採樣高度，進行二氧化碳濃度的量測。結果顯示天然林與杉木林二氧化碳濃度分佈呈現梯度分層的現象，而其中以0.5 m處的二氧化碳濃度為最高，而12 m處與冠層上二採樣點的二氧化碳濃度，在季節與近一年的變化皆無顯著差異。天然林與杉木林之二氧化碳濃度在季節的變化上，各採樣點之日夜間二氧化碳濃度的差異以春季及夏季較大，秋冬季則略小。由一年間監測的結果顯示，天然林由於土壤呼吸作用較旺盛，且冠層12 m處光合作用固定二氧化碳的能力較低，因此在任何採樣點二氧化碳濃度均較人工杉木林為高，且此種差異在溫度較高的6月比較低溫度的12~1月更形顯著。

關鍵詞：二氧化碳、冠層、時間變異、空間變異、亞熱帶森林。

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INTRODUCTION

CO_2 is known as one of the major greenhouse gases, and the increase in its atmospheric concentration over the last 250 yr has begun to change the global climate. The potential effects of global changes on forests are of increasing concern because forests can potentially slow down the increase in atmospheric CO_2 (Kirschbaum 2001). However, the contribution of the terrestrial biosphere, forests in particular, to the “missing CO_2 sink” is still at present poorly understood (Friedlingstein et al. 1995, Kirschbaum 2003a, b, Ramankutty et al. 2007).

Forest ecosystem C sequestration is of particular interest to researchers and policy makers because, at global scales, forests account for 80~90% of terrestrial plant C and 30~40% of soil C (Landsberg and Gower 1997, Heath et al. 2002, Griffis et al. 2003). Forests and forest soils have large capacities to both store and release C (Cannell et al. 1996, Granier et al. 2000, Ladegaard-Pedersen et al. 2005), and detailed forest ecosystem C budgets would be helpful in improving our understanding of the terrestrial C cycle and for supporting decision-making processes in forest management. To elucidate the influence of forests on the global carbon cycle and their response to increases in atmospheric CO_2 concentrations, the main CO_2 sinks, sources, and stocks of C must be quantified more accurately. Large variations in C sequestration capacities of various forest ecosystems have been reported (McMurtrie et al. 2001, Masera et al. 2003, Ladegaard-Pedersen et al. 2005). These variations depend on climate, species, site productivity, and silvicultural regime. Forest ecosystems might significantly contribute to the global C sink (Grace et al. 1995, Turner et al. 1995, Malhi et al. 1998, Phillips et al. 1998, Heath and Smith 2000, Goodale et al. 2002, Heath et al. 2002, Turner et al. 2004, Bonan 2008). Nevertheless, large uncertainties remain regarding spatial and temporal patterns and forces driving the terrestrial C sink (Houghton 1999, Pacala et al. 2001, Clark 2002, 2004, Clark et al. 2003, Rice et al. 2004, Sierra et al. 2007).

Tree canopies exhibit strong vertical patterns in photosynthesis, leaf nitrogen, leaf mass per area, and chlorophyll content that together ultimately regulate their ability to exchange CO_2 with the atmosphere (Baldocchi et al. 2002). Photosynthetic capacity varies greatly through the canopy, decreasing toward the bottom of the crown (Ceulemans and Mousseau 1994, Kellomäki and Wang 1997). Because canopies mediate the magnitude of CO_2 uptake from the atmosphere, there is increasing interest in understanding variations in concentrations at different canopy levels and in different stands. Four factors have a disproportionate influence on the seasonal variation of CO_2 flux densities: photon flux densities (during the growing season), temperature (during the dormant season), leaf area index, and the occurrence of drought. A drought period that occurred during the peak of the growing season caused a significant decline in daily and hourly CO_2 flux densities, compared to observations at a stand when soil moisture was plentiful (Greco and Baldocchi 1996).

The objective of this study was to understand variations of CO_2 concentrations at different canopy levels and differences in CO_2 concentrations at each canopy level between a natural hardwood stand and a fir plantation at the Guandaushi subtropical forest, central Taiwan for a period covering both the dormant and growing seasons.

MATERIALS AND METHODS

Study site

This study site was located on a 47-ha watershed of the Guandaushi experiment site in Nantou County, central Taiwan (Fig. 1). The elevation of the site ranges 1100~1700 m. The annual rainfall is 2300~2700 mm, and the rainy season is from March to September. In addition, the occasional occurrence of typhoons may cause high intensity of precipitation and disturbance between June and September. During the experiments, the maximum and minimum annual mean temperatures were 22.4 and 9.8℃, respectively. This site is a typical subtropical mixed-hardwood forest in central Taiwan which is characterized by steep topography and composed of abundant riparian ferns, virgin hardwood forests, and abundant epiphytes. The forests on the ridge have been cut and planted with fir (*Cunninghamia lanceolata*) over the past 30 yr.

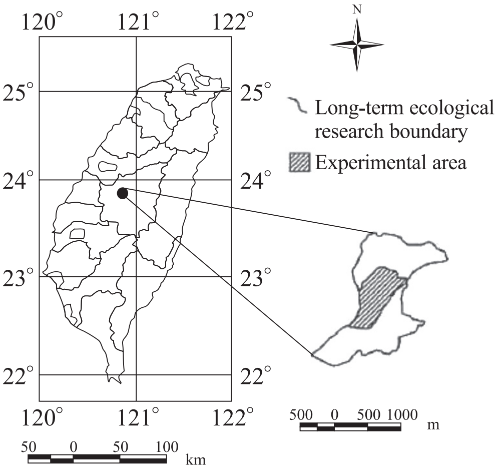

Fig. 1. Location of the study site in the Guandaushi Forest, central Taiwan.

Two adjacent stands of a fir plantation and a natural hardwood forest in the same 47-ha watershed were investigated. The hardwood is a typical Lauro-Fagaceae association of Taiwan. The Lauraceae (15 species) and Fagaceae (14 species) are the major families in this study area. According to the results of a matrix cluster analysis, the vegetation at the study area can be divided into 7 forest types, including *Helicia formosana*, *Litsea acuminata*, *Chamaecyparis obtusa*, *Cunninghamia lanceolata*, *Engelhardtia roxburghiana-Cinnamomum randaience*, *Rhododendron formosanum*, and *Pinus morrisonicola* forest types (Lu and Ou 1996). Soils of the Guandaushi forest ecosystem are derived from 3 parent materials: sandstone, shale, and slate. The soil is very acidic at pH < 4 in the water, and the content of soil organic matter (SOM) in the China-fir plantation was less than that in the natural hardwood forest (Wang et al. 2004).

Experimental design

A set of meteorological instruments mounted on the top of a 24-m tower were used to continuously monitor environmental conditions. Incoming photosynthetically active photon flux density (PPFD) was measured at the top of the tower with a quantum sensor (LI-190SA, LI-COR, Lincoln, NE, USA), while total, direct, and diffuse PPFD were measured with a solar-radiation sensor (BF3, Delta-T Devices, Cambridge, UK). We also measured temperature and humidity (RH/temperature logger, HOBO H8 Pro, Onset, USA) at 1.2 m above the ground within the natural hardwood forest and fir plantation. Three sample trees were selected, and 4 different canopy heights (0.5, 4, and 12 m agl and 3~4 m above the mean canopy height) were set on the trees in the 2 stands, respectively (Fig. 2). Finally, all measurement points were connected by tubes (4 mm inner diameter × 6 mm outer diameter) of polyethylene to the analytical station.

Air was continuously drawn via inlets, which were equipped with a glass funnel and covered with a 0.2-mm filter on 4 samplers (Fig. 3). We used vacuum pumps (F-16, 50 cmHg, 40 W, Taiwan) to keep the gas flowing at all times. While measuring the CO_2 concentration, only one of the tubes was open to an infrared gas analyzer (IRGA) (LI-840, LI-COR). The switch among the tubes was controlled by an electromagnetic valve (model DC221C, KSD, Taiwan). The flow rate to the IGRA was set to 1 L min^{-1}. In general, we checked and calibrated the instrument every 2 wk.

Control signals and data logging were implemented through programmable logic (PLC) run on a PC in the field. The temporal and spatial dynamics of CO_2 concentrations within the 2 forest ecosystems were monitored using a customized 24-port sequential sampler connected to the IRGA. Sampled air was pumped sequentially from each port through a 3-way solenoid valve and routed through the gas analyzer. Each channel was measured for 5 min, and only the readings of the last 2 min were recorded to avoid contamination by the air in the preceding tube. The measurements were begun in September 2004 and continued until the end of June 2005, except for missing data in February, when the cable was stolen.

Statistical analysis

In general, continuous CO_2 concentration data are presented as 5-min records. Data were smoothed with moving averages (intervals of 7 data points) using Microsoft Office Excel 2007. The statistical package JMP (vers. 6.12, SAS Institute, Cary, NC, USA) was used for most of the data analyses. Analyses of variance (ANOVAS) were performed with Duncan's multiple-range test. If the interac-

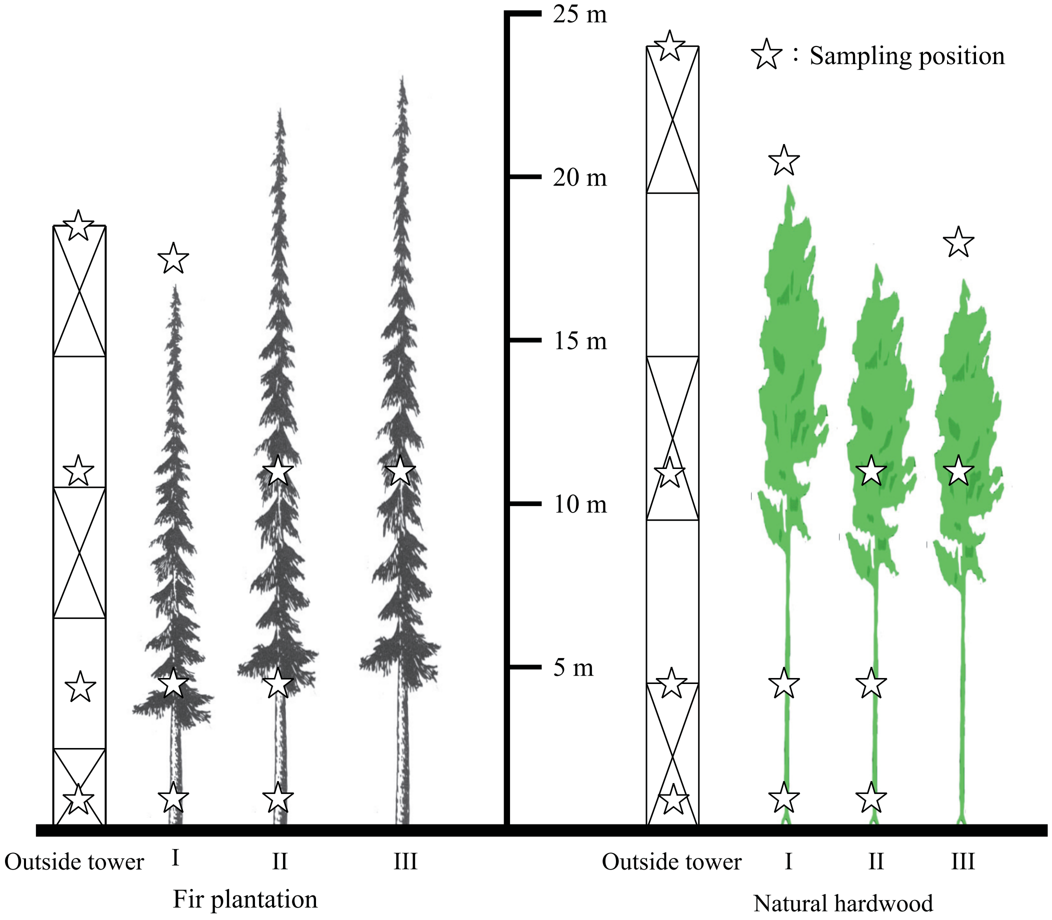

Fig. 2. Sampling positions in the fir plantation and natural hardwood stand.

tion terms were not significant ($p > 0.05$), data were pooled and a one-way ANOVA was calculated. Student's *t*-test or the Tukey-Kramer HSD (honest significant difference) test (at the 0.05 level) was used to distinguish among the means of 2 or more groups, respectively.

RESULTS

Monthly changes were observed in the concentrations of CO_2 and environmental factors (temperature and PPFD) in the fir plantation and natural hardwood forest (Fig. 4). The vertical profile of CO_2 in the natural hardwood showed that the highest concentration (402.1±19.2 ppm) was at 0.5 m, followed by 4 m (383.6±11.6 ppm), and the values for 12 m (369.7±8.6 ppm) and above the canopy (369.8±7.4 ppm) were almost the same. On the other hand, the average CO_2 concentration was > 368 ppm (CO_2 concentration of the atmosphere, Keeling et al. 2001) throughout the year, except at 12 m and above the canopy during September to December. The CO_2 concentration also showed the highest value at 0.5 m (377.6±13.4 ppm) in the fir plantation. The average CO_2 concentrations were < 368 ppm at 12 m (361.8±4.3 ppm) and above the canopy (364.0±3.9 ppm) during September to March of the following year.

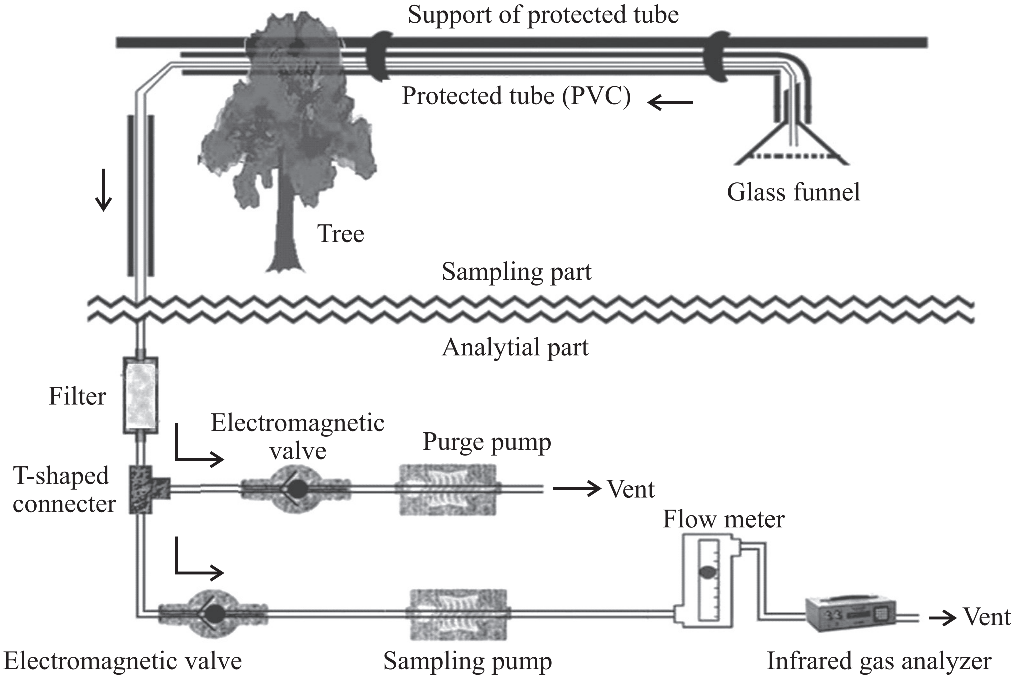

Fig. 3. Schematic of CO_2 monitoring setup in the field.

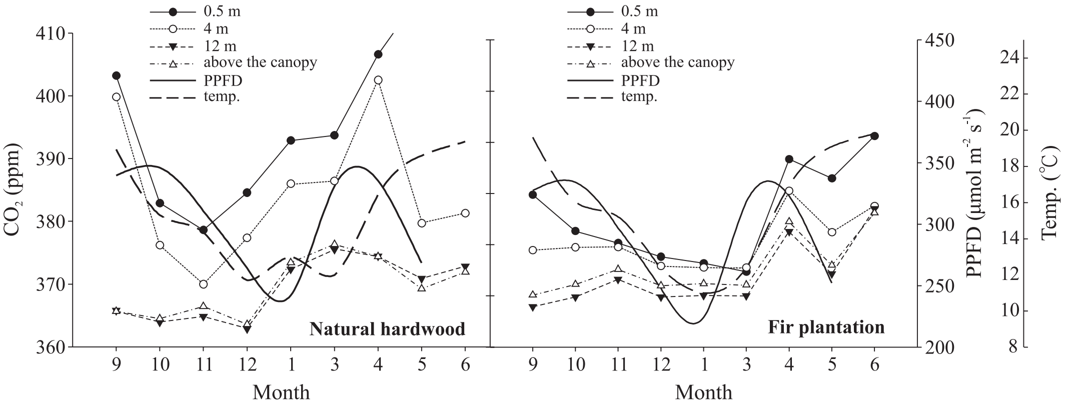

Fig. 4. Monthly variations in CO_2 concentrations monitored at 0.5, 4, and 12 m above the ground and 3~4 m above the canopy in a natural hardwood forest and fir plantation. PPFD, photosynthetically active photon flux density.

The light compensation point within most tree canopies is about 10~40 μmol m^{-2} s^{-1} (Larcher 2003). Therefore, a 40 μmol m^{-2} s^{-1} irradiance level was applied to separate daylight hours and nighttime to compare CO_2 concentrations between daylight hours and nighttime (Table 1). The most significant difference in CO_2 concentrations between daylight hours and nighttime was in summer, when the temperature was the highest in the natural hardwood forest. In winter, differences in CO_2 concentrations were small between

Table 1. Comparision of CO_2 concentrations (ppm) between daylight hours and nighttime in a natural hardwood forest and fir plantation

Natural hardwood	Height	Fall	Winter	Spring	Summer
CO_2 concentration in daylight hours (PPFD > 40 μmol m^{-2} s^{-1})	0.5 m	383.9±8.9	385.3±10.3	399.7±16.6	413.3±20.0
	4 m	375.8±17.3	376.1±7.6	375.5±14.2	368.2±6.1
	12 m	357.7±3.3	363.2±3.8	365.6±8.1	363.7±6.2
	Above the canopy	359.3±2.1	364.5±2.1	365.6±5.0	364.6±5.3
CO_2 concentration at nighttime (PPFD < 40 μmol m^{-2} s^{-1})	0.5 m	389.6±7.6	393.6±16.2	420.5±19.6	438.6±20.1
	4 m	384.8±8.1	388.2±9.8	397.6±17.0	394.4±20.3
	12 m	370.7±4.7	373.5±10.2	379.5±12.7	382.0±16.3
	Above the canopy	370.5±4.6	374.2±8.0	377.8±10.7	379.2±12.3
Temperature (℃)		16.0	11.6	15.5	19.1
Fir plantation					
CO_2 concentration in daylight hours (PPFD > 40 μmol m^{-2} s^{-1})	0.5 m	366.5±5.6	360.6±2.8	374.1±7.6	380.9±8.5
	4 m	362.2±1.7	361.3±1.2	368.3±3.1	370.1±3.3
	12 m	365.5±1.2	357.5±0.8	362.7±1.4	367.9±1.3
	Above the canopy	359.1±1.7	359.8±0.9	364.9±1.4	368.9±1.4
CO_2 concentration at nightime (PPFD < 40 μmol m^{-2} s^{-1})	0.5 m	380.3±4.2	371.3±4.4	387.6±6.5	401.5±7.2
	4 m	375.7±3.0	368.7±2.4	378.4±3.8	385.0±5.0
	12 m	363.5±0.9	361.8±1.2	368.6±1.5	386.2±1.6
	Above the canopy	365.4±0.8	364.0±1.0	370.1±1.6	383.5±2.4
Temperature (℃)		17.0	12.3	16.1	20.0
PPFD (μmol m^{-2} s^{-1})		667.0	533.1	611.7	893.0

Values are the mean±SD for the monitoring data. PPFD, photosynthetically active photon flux density.

the daylight hours and nighttime, reflecting reduced biological activities in winter. There were similar seasonal variations in the fir plantation, and the difference was small between daylight hours and nighttime.

The CO_2 concentration difference between daylight hours and nighttime tended to decrease with height in the fir plantation. In the natural hardwood forest, on the other hand, changes in CO_2 concentration were reflected by changes in canopy height (Table 1). During the daytime, for the difference between winter and summer, the monitored CO_2 concentration was 28.5 ppm at 0.5 m in the natural hardwood forest compared to 20.3 ppm in the fir plantation. On the contrary, the differences were 0.5 ppm in the natural hardwood forest and 10.4 ppm in the fir plantation at 12 m. On the other hand, during the nighttime at 0.5 m, CO_2 concentration differences between summer and winter were 45.0 and 30.2 ppm in the natural hardwood forest and fir plantation, respectively.

Figure 5 shows the mean CO_2 concentration variations of the vertical profiles of the natural hardwood and fir plantation in daylight hours and nighttime. The highest CO_2 concentration was seen at 0.5 m in both stands, and the decrease in CO_2 concentration with height was attributed to CO_2 uptake by enhaned photosynthesis activity.

The CO_2 concentration increased rapidly at 0.5 m of the natural hardwood forest in summer when temperatures were higher

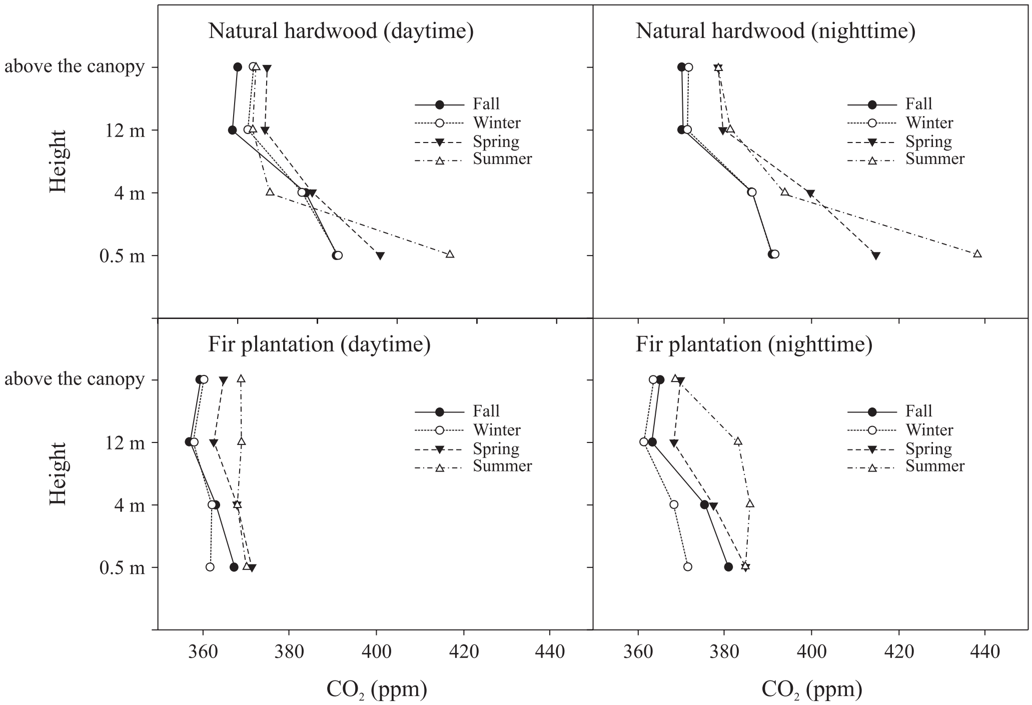

Fig. 5. Mean CO_2 concentration variations of the relative vertical profile of a natural hardwood forest and fir plantation in daylight hours and nighttime.

Table 2. Comparsion of CO_2 concentrations (ppm) at different heights of the natural hardwood forest and fir plantation during different seasons

Stand	Height	Fall	Winter	Spring	Summer
Natural hardwood	0.5 m	388.3 ± 8.2^{a}	388.7 ± 9.4^{a}	405.5 ± 18.2^{a}	426.0 ± 20.0^{a}
	4.0 m	382.0 ± 13.2^{b}	381.7 ± 6.3^{b}	389.5 ± 15.7^{b}	381.3 ± 15.0^{b}
	12.0 m	364.9 ± 4.1^{c}	367.6 ± 4.8^{c}	373.6 ± 10.6^{c}	372.8 ± 12.3^{c}
	above the canopy	365.5 ± 3.6^{c}	368.5 ± 3.5^{c}	373.3 ± 8.4^{c}	371.9 ± 9.5^{c}
Fir plantation	0.5 m	374.2 ± 4.9^{a}	366.0 ± 2.6^{a}	378.1 ± 7.1^{a}	391.7 ± 7.9^{a}
	4.0 m	369.3 ± 2.5^{b}	365.7 ± 1.3^{a}	372.8 ± 3.5^{b}	377.6 ± 4.2^{b}
	12.0 m	360.3 ± 1.1^{c}	359.9 ± 0.7^{c}	365.6 ± 1.5^{c}	377.0 ± 1.4^{c}
	above the canopy	362.5 ± 1.3^{c}	362.2 ± 0.7^{b}	367.5 ± 1.5^{c}	376.2 ± 1.9^{c}

Values in the same column with different letters significantly differ at the 5% significance level by Duncan's multiple-range test.

resulting in abundant respiration. Compared to the fir plantation (Table 2), lower CO_2 concentrations were measured at all heights in all seasons. The diurnal variation in CO_2 concentration from 0.5 to 12 m was higher in the natural hardwood stand than the fir plantation, especially in summer.

DISCUSSION

According to the vertical profile of CO_2 in the natural hardwood forest, the highest CO_2 concentration was observed at 0.5 m, and the second highest was at 4 m agl. In contrast, the concentrations at 12 m agl and above the canopy were almost the same (Fig. 4), and were the lowest. These profiles were similar to those observed by Bazzaz and Williams (1991), Skelly et al. (1996), Buchmann et al. (1997), Law et al. (1999), and Rannik et al. (2004). Moreover, it was found that the mean CO_2 concentration was higher than the global ambient concentration of 368 ppm (Keeling et al. 2001) throughout the year, except for the period from September to December 2004 at the heights of 12 m agl and above the canopy.

In the fir plantation, the highest values observed for the CO_2 concentration profiles were also at 0.5 m agl. Similarly, the mean CO_2 concentrations were < 368 ppm at 12 m agl and above the canopy during September 2004 to March 2005. This result could have been due to the thin distribution (leaf area index of 1.99 compared to 3.12 in the natural hardwood forest, unpublished data) of the fir plantation which allowed the gas to mix well and the abundant photosynthesis of the dense understory vegetation consuming huge amounts of CO_2. Kondo et al. (2005) found that the percentage of respired CO_2 refixed by understory vegetation was 15% in a cool-temperate deciduous broadleaf forest at the Takayama Experimental Site. In fact, CO_2 released by respiration is either lost from the forest through turbulent mixing or refixed by photosynthesis within the canopy (CO_2 recycling). CO_2 concentrations in a forest generally increase from the canopy layer toward the soil surface due to the emissions of CO_2 from the respiration of plants and bacteria in the soil. In contrast, the understory vegetation is capable of fixing the respired CO_2 through photosynthesis, and this process influences the carbon dynamics within a forest.

The light compensation point within most tree canopies is about 10~40 μmol m^{-2} s^{-1} (Larcher 2003). Therefore, a 40 μmol m^{-2} s^{-1} irradiance level was applied to separate daylight hours and nighttime to compare CO_2 concentrations between daylight hours and nighttime (Table 1). The most significant difference in CO_2 concentrations between daylight hours and nighttime was in summer, when the temperature was the highest in the natural hardwood forest. The difference in CO_2 concentrations in winter was very small between the daylight hours and nighttime, indicating that biological activities are lower in winter. There was a similar seasonal variability in the fir plantation, and the difference was small between daylight hours and nighttime.

The small diurnal variation and small vertical difference in winter and early spring reflect reduced biological activities at the sites during these seasons. The large diurnal CO_2 variation and large variability of the vertical profile of CO_2 in the summer were due to enhanced biological activities (photosynthesis and respiration) under higher temperatures in this season. The CO_2 concentration difference between daylight hours and nighttime tended to decrease with height in the fir plantation. In the natural hardwood forest, on the other hand, CO_2 concentration changed with canopy height (Table 1), indicating the CO_2 respired by the forest is efficiently refixed by the canopy and understory vegetation in the fir plantation. For the difference between winter and summer, the monitored CO_2 concentration difference was 28.5 ppm at 0.5 m in the natural hardwood forest, compared to 20.3 ppm in the fir plantation. On the contrary, the differences were 0.5 ppm in the natural hardwood forest and 10.4 ppm in the fir plantation at 12 m, reflecting that the CO_2 sink in the fir plantation was higher than that of the natural hardwood forest during the growing season. This finding has significant implications for carbon allocation. If less canopy closure (i.e., fir plantation) is one of the factors that contributes to higher turbulent mixing and thus, lower recycling, even sustainable anthropogenic manipulations of the forest such as selective thinning, will affect the loss of respiratory CO_2 to the troposphere (Buchmann et al. 1997a, Sternberg et al. 1997).

During the nighttime at 0.5 m, the CO_2 concentration differences between summer and winter were 45.0 and 30.2 ppm in the natural hardwood forest and fir plantation, respectively. The higher CO_2 difference in the natural hardwood forest might have been due to higher soil respiratory activity via soil temperature. With the higher respiration coinciding with lower photosynthesis during daylight hours, the CO_2 concentration was higher at the 4 heights of the natural hardwood forest throughout the year (Table 1). Forests have been proposed as possible sinks of the 'missing' atmospheric carbon that is not accounted for by global carbon cycle models (Francey et al. 1982, Tans et al. 1990, Keeling et al. 1996, Fan et al. 1998, Bonan 2008). While young and recovering forests have obvious potential as carbon sinks, forests older than approximately 100 yr are thought to be in equilibrium between carbon uptake and total ecosystem respiration, sequestering little and are generally considered to be insignificant carbon sinks (Jarvis 1989, Melillo et al. 1996). In contrast, research by Desai et al. (2005), Guan et al. (2006), and Zhang et al. (2006) indicated that some old forest ecosystems (400, 300, and 200-yr-old forests, respectively) have not reached a steady-state carbon flux and can continue to act as a net sink for atmospheric CO_2, especially in summer. Long-term measurements of whole-ecosystem carbon exchange are needed to determine the sink/source and budget status of ecosystems, and to analyze how carbon exchange varies with seasonal and interannual variations in environmental conditions and other factors (i.e., forest structure, density, and species).

The highest CO_2 concentration at 0.5 m at both stands and the decrease in CO_2 concentration with height (Fig. 5) were attributed to CO_2 uptake by enhanced photosynthesis activity. This phenomenon was also confirmed by Garrett et al. (1978), Bazzaz and Williams (1991), and Skelly et al. (1996). The dependence of daylight-hour carbon exchange on light was stimulated by temperature and forest phenology (Luo et al. 1996, Davidson et al. 1998, Flanagan et al. 2002).

As a result, the CO_2 concentration increased rapidly at 0.5 m in the natural hardwood forest in summer when temperatures were higher resulting in abundant respiration. The dependence of ecosystem respiration on temperature may reflect the different temperature sensitivities for autotrophic and heterotrophic respiration and turnover times of multiple carbon pools (Xu and Baldocchi 2004). Soil temperature was the only significant driver of ecosystem respiration when surface soil water content was abundant. The forest was a carbon source caused by the rapidly rising temperature and surface soil moisture (Kondo et al. 2005). The fir plantation (Table 2) had lower CO_2 concentrations at all heights in all seasons. Diurnal variations in CO_2 concentrations from 0.5 to 12 m were higher in the natural hardwood stand than the fir plantation, especially in summer. This also proves that CO_2 concentration is strongly affected by temperature and PPFD among canopy levels.

CONCLUSIONS

The vertical profile of CO_2 in the natural hardwood showed that the highest concentration (402.1 ± 19.2 ppm) was at 0.5 m, followed by 4 m (383.6 ± 11.6 ppm), and the values at 12 m (369.7 ± 8.6 ppm) and above the canopy (369.8 ± 7.4 ppm) were almost the same. The CO_2 concentration also showed the highest value at 0.5 m (377.6±13.4 ppm) in the fir plantation. The CO_2 concentration increased rapidly at 0.5 m of the natural hardwood in summer when temperatures were higher resulting in abundant respiration. In the fir plantation, lower CO_2 concentrations were measured at all heights in all seasons. On the other hand, diurnal variations in CO_2 concentrations were strongly affected by PPFD in these 2 stands, but monthly variations in CO_2 concentrations were particularly affected by PPFD and temperature interactively in the fir plantation. Comparison of CO_2 concentration difference values between summer and winter, reflected the CO_2 sink in the fir plantation as it was higher than that of the natural hardwood plantation during the growing season.

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