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CO_2 flux in a cool-temperate deciduous forest (*Quercus mongolica*) of Mt. Nam in Seoul, Korea

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Abstract

The Namsan Ecological Tower Site based on a flux tower was equipped with eddy covariance and automatic opening/closing chamber systems to collect long-term continuous measurements of CO_2 flux, such as the net ecosystem exchange (NEE) and soil CO_2 efflux in a cool-temperate *Quercus mongolica* forest. The mean concentrations of atmospheric CO_2 (705 mg/m^3) during the summer were smaller than those measured (770 mg/m^3) during the winter. The mean CO_2 flux during the summer period was negative (-0.34 mg m^{-2} s^{-1}), while that during the winter period was positive (0.14 mg m^{-2} s^{-1}). CO_2 was deposited from the atmosphere to the surface in the summer. The daily mean value of soil CO_2 efflux increased from spring to summer. The seasonal pattern in the rate of soil CO_2 efflux tightly followed the seasonal pattern in soil temperatures. The Q_{10} values for soil CO_2 efflux varied in a range from 2.12 to 3.26, and increased with increasing soil depth. The maximum value of total carbon uptake (i.e., NEE) during the growing season was -8 g CO_2 m^{-2} day^{-1}. At the same time, the rate of soil CO_2 efflux was 6.9 g CO_2 m^{-2} day^{-1}. The amplitude of flux variations in NEE was approximately 14% larger than those in soil CO_2 efflux. These results suggest that in cool-temperate regions of the Korean peninsula, the forest ecosystem of *Q. mongolica* may have a larger atmospheric CO_2 uptake, due primarily to its high photosynthetic capacity and low ecosystem respiration.

Key words: CO_2 flux, eddy covariance technique, Nam-San Ecological Tower Site (NSETS), net ecosystem exchange NEE, *Quercus mongolica* forest, soil CO_2 efflux

INTRODUCTION

The sharp increase of atmospheric carbon dioxide (CO_2) concentration in anthropogenic greenhouse gases has been reported to be responsible for the present climate warming (Canadell et al. 2007). Forest ecosystems, as a major reservoir of terrestrial carbon, play a critical role in the global carbon cycle, and they can provide long-term capacity for carbon sequestration and storage (Houghton et al. 2001, Gower 2003). A better understanding of the carbon balance in forest ecosystems is required to predict future climate changes, because accelerations in climate warming may result in enormous CO_2 release, due to positive feedback of carbon cycling between the atmosphere and forest ecosystems (Cox et al. 2000, Prentice et al. 2001). Therefore, it is necessary to quantify the carbon budget of forest ecosystems, and to determine whether forests function as sinks or sources of atmospheric CO_2. In particular, a great deal of attention has focused on temperate and boreal forests, as these regions

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comprise almost 50% of the forests around the world, and may function as major sinks in the global carbon cycle (Larcher 1995, Curtis et al. 2002). Several reports have indicated that in the middle and high latitudes of the Northern Hemisphere, the remaining 1 to 2 GtC (billon tons of carbon)/y of 'missing carbon' is supposed to be assimilated by temperate and boreal forests (Wofsy et al. 1993, Denning et al. 1995, Baldocchi et al. 1996, Myneni et al. 2001). However, in temperate and boreal regions, the role of forest ecosystems responsible for the residual carbon sink remains uncertain.

Measurements of CO_2 flux between the atmosphere and forest ecosystems have been widely conducted using micrometeorological methods, such as the eddy-covariance technique in various forests, including boreal and temperate forests in Europe, North America, and East Asia (Falge et al. 2002, Saigusa et al. 2002). Recently, combinations of the eddy-covariance technique and flux tall towers for estimating the carbon budgets of forest ecosystems have been commonly adopted and proliferated, in spite of the difficulty of maintenance of the relevant instruments. These studies have demonstrated variations in net ecosystem exchange (NEE), and provided quantitative information on net photosynthesis and ecosystem respiration (Baldocchi et al. 2001, Falge et al. 2002, Shibata et al. 2005). However, in order to assess CO_2 flux and sequestration within forest ecosystems, the application of eddy-covariance techniques is limited by the difficulties associated with the complicated components of ecological and biological processes.

In the carbon cycling of forest ecosystems, the large magnitude of soil surface CO_2 efflux makes this one of the major flux pathways via changes in plant and soil. This CO_2 efflux has been estimated to account for 60-90% of total ecosystem respiration in temperate forests (Valentini et al. 2000, Law et al. 2001). In particular, cool-temperate deciduous forests are broadly distributed throughout East Asia. Several studies have quantitatively evaluated CO_2 efflux and carbon dynamics in the cool-temperate regions, according to the type of forest, the age of trees and management practices (e.g., Jia et al. 2003, Mo et al. 2005). In the case of Korea, the forest area occupies 6.3 $\times 10^6$ ha, approximately 65% of the total land area. Deciduous and mixed forests take up 1.7 $\times 10^6$ ha and 1.9 $\times 10^6$ ha, respectively, and they account for about 57% of all Korean forests (Son et al. 2004). The *Quercus mongolica* forest is one of the typical deciduous forest types in the cool-temperate regions of the Korean peninsula (Kwak and Kim 1992). Therefore, the carbon sequestration behaviors of *Q. mongolica* forests may have profound effects on the total carbon cycle of the Korean peninsula. However, the carbon budget in the forest ecosystem has received relatively little attention, and their NEE and soil respiration rates remain unclear (Kim et al. 2008). Consequently, long-term continuous observations of CO_2 flux in the forest ecosystems require simultaneously carrying out micrometeorological and ecological methods.

The Namsan Ecological Tower Site (NSETS) was established to conduct long-term ecological research and monitoring of CO_2 flux in a cool-temperate deciduous, broad-leaved forest (*Q. mongolica*). The principal objectives of this study were to 1) introduce the micrometeorological instrumentation and characteristics of the NSETS, and to 2) describe the methodology used to quantify measurements of CO_2 flux in the forest ecosystem. Additionally, we presented the available data of CO_2 flux for the summer and winter experimental periods at the NSETS.

MATERIALS AND METHODS

Study site

The NSETS (37°33' N, 126°59' E, 220 m a.s.l.) (Fig. 1) is located in a urban forest with a floor area of approximately 2.9 km^2, managed by the Korea National Long-Term Ecological Research (KNLTER) program, on the northeastern slope of Mt. Nam in the center of metropolitan Seoul, in the west-central part of the Korean Peninsula (Fig. 1a). This region has a cool-temperate zone under the influence of the Asian monsoon climate. According to the database of the Korea Meteorological Administration from the Seoul Weather Station, the annual mean air temperature and precipitation are 11.8°C (minimum of -3.4°C in January and maximum of 25.4°C in August) and 1,369.8 mm, respectively. The vegetation at the site is classified as an approximately 49-55 year old deciduous broad-leaved forest, composed mainly of *Q. mongolica* (Table 1). The dominant tree stand of *Q. mongolica* has an average diameter at breast height of 23.2 cm and a total basal area of 22.1 m^2/ha. The canopy height and density in *Q. mongolica* trees are approximately 15.1 m and 482/ha, respectively. The canopy typically reaches a peak leaf area index of approximately 5.8 in July. The mid-understory is covered by *Sorbus alnifolia*, *Styrax japonica*, and *Acer pseudo-sieboldianum*. Trees begin to develop leaves in April, and leaf fall begins in October and continues until November. The topography of this stand has both ridge forms and middle slopes (range, 18 to 22.7°).

The soil type is brown forest soil (*Dystric Cambisols*, FAO-UNESCO 1998) with a moderate organic layer depth, and the parent material is granite or granite-gneiss. The maximum fetch of the forest is about 600 m to the southeast and the minimum one is the about 300 m to the north. The ratios of the fetch to the height of the flux measurement point (30 m) from the continuous canopy height are 40 and 20, respectively. North-easterly winds mainly dominated during the observation. More details about vegetation and soil characteristics can be found in Lee et al. 1998 and 2006.

Instrumentation

The continuous NEE observation tower was established in a cool-temperate deciduous forest ecosystem in early spring 2008, 42 m away from the peak land of Mt. Nam. CO_2 fluxes between the atmosphere and forest canopy were measured from May 2008, via the eddy covariance technique. The mean height of the forest stand around the tower was approximately 15 m. Instruments of the flux and micrometeorological measurements based on the tall tower were installed on a triangular cross section with a maximum edge length of 0.6 m, at a location 30 m above the soil surface and approximately 15 m above the forest canopy (Fig. 1b). Fluctuations in wind velocity and virtual temperature are measured using a three-dimensional ultra sonic anemometer (CSAT3; Campbell Scientific Inc., North Logan, UT, USA). Vapor pressure and CO_2 fluctuations were measured using an open-path CO_2/H_2O gas analyzer (LI7500; LI-COR, Lincoln, NE, USA). These fast-response instruments, situated on the north facing side of the tower, are operated at a sampling rate of 8.3 Hz using a data-measurement and control system (CR1000; Campbell Scientific Inc.). The CO_2/H_2O gas analyzer (LI7500; LI-COR, Nebraska, USA) was calibrated by using CO_2 zero gas and standard span gases, and potable dew point generator (LI-610; LI-COR, Nebraska, USA) at least once every 6 months. The calibration was performed via the windows interface software. Downward radiation components are measured with pyranometers (LI-200SA; LI-COR) at 0.5, 3.5,

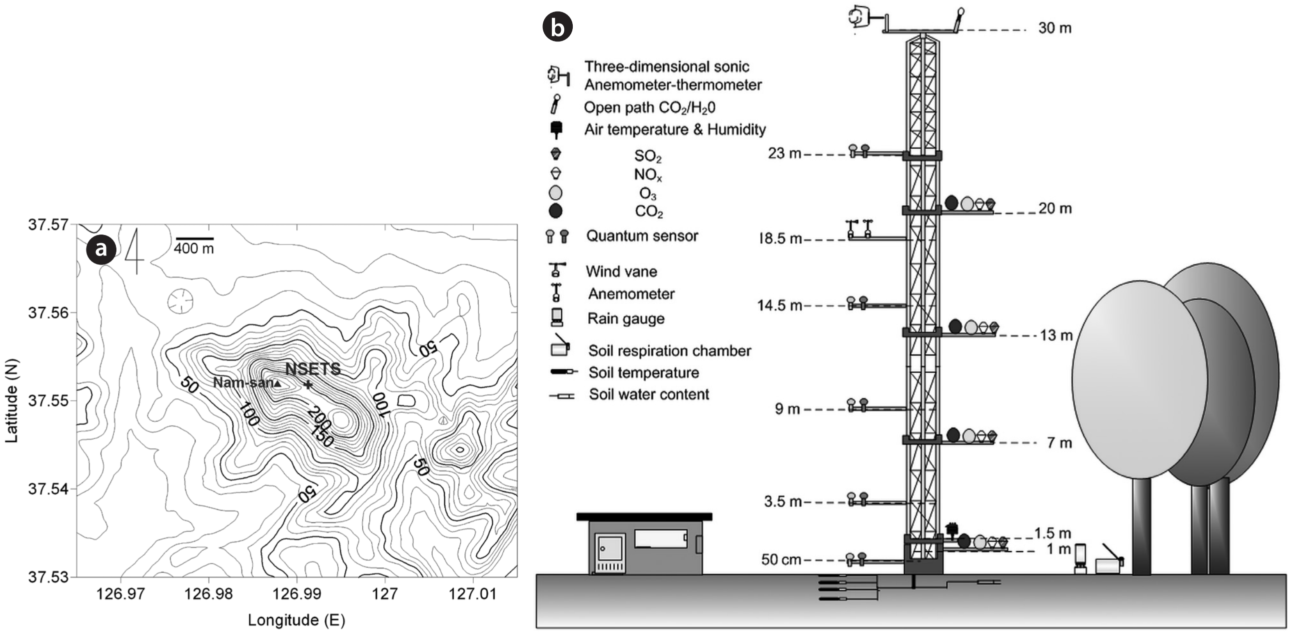

Fig. 1. Topographic map of the area around the Namsan Ecological Tower Site (NSETS) located in the Seoul metropolitan area (a) and schematic diagram of the main monitoring instrumentation at the NSETS (b). The cross and triangle denote the location of the flux tall tower and the peak of Mt. Nam.

Table 1. Characteristics of the forest stand at NSETS

Stand	Age (years)	Density (trees/ha)	DBH (cm)	Tree height (m)	Basal area (m^2/ha)	LAI (m^2/m^2)
Quercus mongolica	49-55	482	23.2	15.1	22.1	5.82

NSETS, Namsan Ecological Tower Site; LAI, leaf area index.

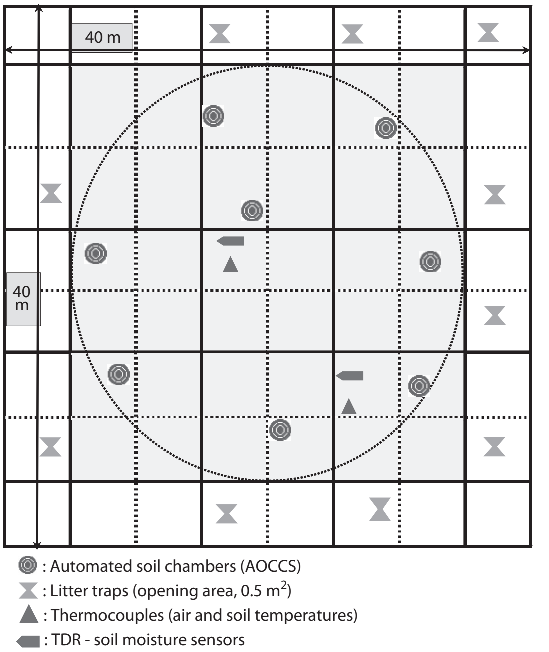

Fig. 2. Layouts of soil CO_2 efflux and environmental factor measurements beneath a flux tower at Namsan Ecological Tower Site. AOCCs, automatic opening/closing chambers.

5.9, 14.5, 18.5, and 23 m above the soil surface. Photosynthetic photon flux densities are measured at 0.5, 3.5, 5.9, 14.5, 18.5, and 23 m above the soil surface, respectively, using quantum sensors (LI-190SA; LI-COR). Wind direction and velocity at 18.5 m above the canopy are measured with an anemometer (A301P; Weather Tec., Seoul, Korea) and wind vane (V10KA; Weather Tec.). Air temperature and relative humidity are observed at a height of 1.5 m using a temperature and humidity probe (HMP45C; Vaisala, Helsinki, Finland). The soil water contents and soil temperatures are measured at 0.05, 0.1, and 0.3 m below the soil surface, respectively using profile probes (CS616; Campbell Scientific Inc.) and hand-made T-type thermocouples. The underground data are collected at a point 1.5 m from the tower.

The Automatic Opening/Closing Chamber (AOCCs) system using the closed dynamic method was employed for the continuous monitoring of soil surface CO_2 efflux at multiple points. This system features 8 automated chambers, an 8-channel gas sampler, an IRGA (LI-820; LI-COR), and a datalogger (CR1000; Campbell Scientific Inc.). The automated chambers (cylinder shape, inside diameter: 30 cm, height: 20 cm, thick: 0.5 cm) had a wall made from transparent acrylic, and a lid hinged at the side wall. The chamber lid can be closed and opened automatically by a 12-V DC motor. To ensure a gastight seal between the cylindrical chamber and the closed lid, a soft rubber gasket attached to the top edge of the chamber. When the chamber was closed, a mixing fan (KMFH-12; Nihon Blower, Tokyo, Japan) inside each chamber maintained air movement with a wind speed of approximately 0.1 m/s. The measurement plot was established on the forest floor beneath a flux tower (Fig. 2). The 8 chambers were placed randomly on the forest floor within a 1,600 m^2 area on October 2009, and were inserted 3 cm below the top of the litter layer. All the vegetation inside the chambers was removed. During the measurement period, the section of the chamber lid was raised to allow rainfall and leaf litter to reach the enclosed soil surface. The length of the Teflon tubing used to sample air from each chamber was 20 m. The chamber air was withdrawn continuously from all 8 chambers, but only the air from the closed chamber was supplied to the multichannel gas sampler system by an air sampling pump (CM-15 with a maximum flow rate of 5 l min^{-1}, EMP, Tokyo, Japan). Flow rates of chamber air were monitored and balanced by mass flow controllers (SEF-21A; STEC, Kyoto, Japan). The airstream of 5 l min^{-1} from the chamber outlet was divided by two mass flow meters, of which 0.8 l min^{-1} went to the IRGA to measure the CO_2 concentration, and the other bypassed the IRGA (4.2 l min^{-1}). The air exhausted from the IRGA went to a bypass tube, and the total remaining air continuously flowed into the inlet of the chamber. In order to avoid any increase or decrease in pressure, the same amount of air supplied to the chamber inlet was simultaneously withdrawn by an air pump from the chamber outlet. Over the course of a half-hour, the chambers were closed sequentially by the 8-channel relay driver controlled by the datalogger. We set sampling period for each chamber to 225 s. The datalogger acquired output from the IRGA at 1 s intervals, and averaged and recorded it every 10 s. The raw CO_2 signals from the IRGA were employed Eq. (I) to calculate the soil surface CO_2 efflux. The data collected were averaged from the 8 chambers over each 30 min cycle. The IRGA (LI-820; LI-COR, Lincoln, NE USA) was calibrated with CO_2 zero gas (pure nitrogen) and two span gases with different CO_2 concentrations at least once every 3 months.

The air temperature, soil temperature and soil water content (SWC, %) were measured at the same time as the soil CO_2 efflux rate. The air temperature at a height of 1.5 m above the ground and the soil temperature at depths of 0, 5, 10 cm were measured with thermocouples. The volumetric SWC (%) was measured using a TDR soil moisture sensor (CS616; Campbell Scientific Inc.) at a depth of 15 cm. These data were recorded once every 10 s by a datalogger (CR1000; Campbell Scientific Inc.).

Data and methodology

The u, v, w component of wind speed and CO_2 concentration were sampled at 8.3 Hz from the sonic anemometer and open-path CO_2/H_2O gas analyzer, respectively (Fig. 3). Sonic temperature Ts was calculated from the sonic wind velocity (Fig. 3d). Then, soft spikes, which are large short-lived departures from the period mean, were identified and removed from the raw data. The u-component of wind speed was directed to the mean wind speed direction, the v-component of wind speed to the lateral, and w-component to the vertical (Park and Park 2006). Turbulent components (u', v', w', T', C') were extracted from the raw data removed by the linear trend. The flux of CO_2 concentration above the forest canopy is calculated using the eddy covariance method ($F = \overline{w'C'}$).

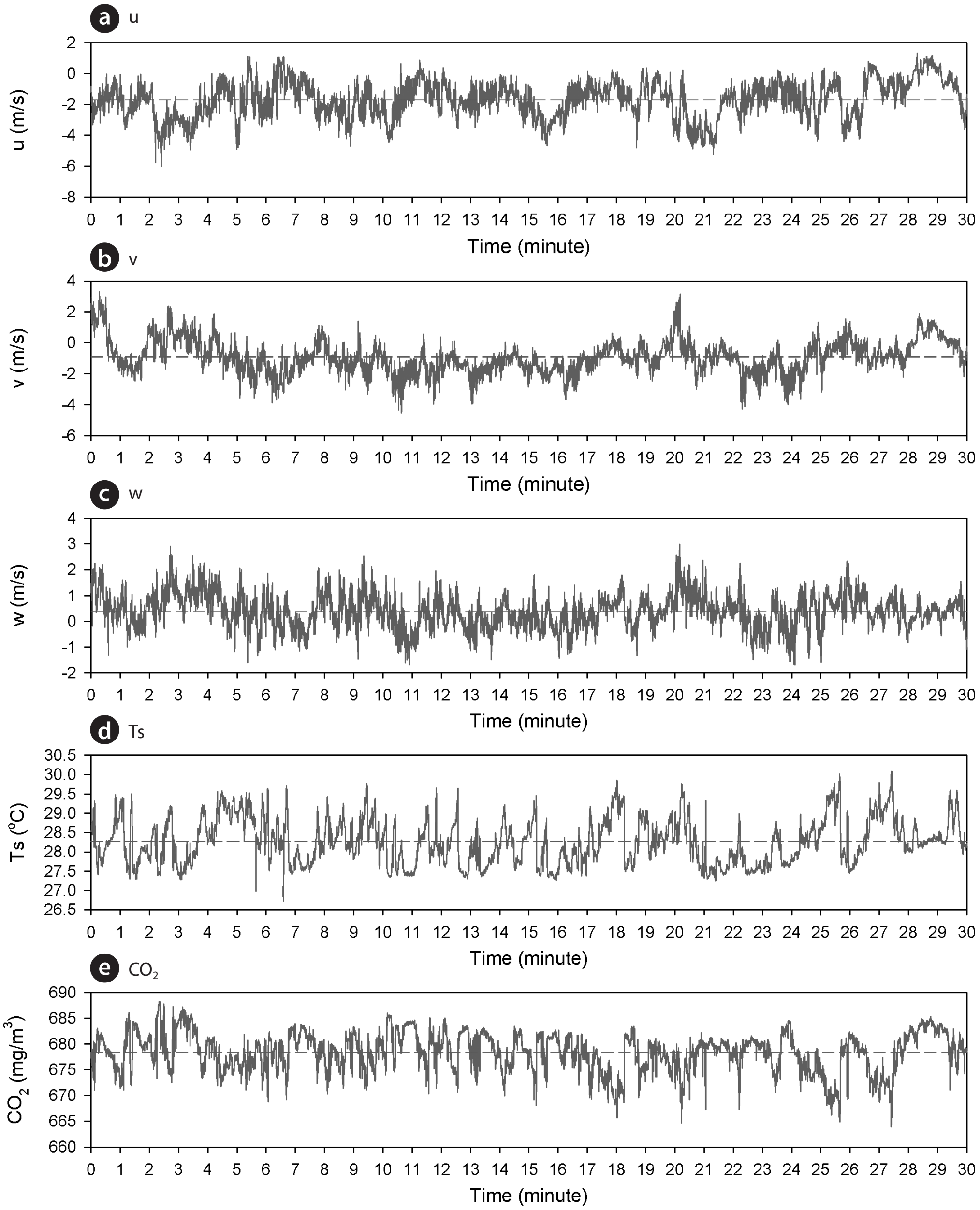

Fig. 3. Time series (solid line) of (a) u, (b) v, (c) w component of wind speed (m/s), (d) sonic temperature (˚C) measured by sonic anemometer and (e) CO_2 concentration (mg/m^3) measured by an LI7500 open-path gas analyzer during the 1200-1230 LST 4 June 2010 period. Mean value for each variable is added (dashed line).

The Webb corrections were applied to take into account the effects of density fluctuations on CO_2 flux (Webb et al. 1980, Fuehrer and Friehe 2002).

Soil CO_2 efflux (R_{soil}, mg CO_2 m^{-2} s^{-1}) is calculated as:

$$R_{soil} = 10^{-6} \cdot a \cdot p \cdot V \cdot A^{-1} \qquad \text{(I)}$$

where a is the rate of change in the CO_2 concentrations in the chamber (μmol mol^{-1} s^{-1}); p is the density of CO_2 in the air (mg/m^3); V is the volume of the chamber (including the volume of the tubes); and A is the soil surface area (m^2). The values of R_{soil} from the 8 chambers were averaged over 1 h.

Below is the exponential function used to describe the temperature sensitivity of R_{soil}.

$$R_{soil} = a \cdot e^{bT} \qquad \text{(II)}$$

where coefficient a is the efflux rate at a temperature of 0°C; coefficient b is the sensitivity of R_{soil} to temperature; T is the temperature parameter. The b values were also used to calculate the Q_{10} parameter:

$$Q_{10} = e^{10b} \qquad \text{(III)}$$

where Q_{10} is the relative increase in R_{soil} for a 10°C change in the temperature.

Regression analysis was used to examine the relationships between the R_{soil} rate and environmental factors. To evaluate the temperature response to R_{soil}, we examined the sensitivity of the mean R_{soil} rate to the temperature by fitting exponential functions to the data.

RESULTS AND DISCUSSION

We presented the amplitude and variation in CO_2 concentration and flux for 3 days each during the summer and winter seasons. Fig. 4 shows the time series of wind speed and direction, CO_2 concentration and flux during the winter period of 14-16 December, 2009. Wind speed ranged from 1-5 m/s, and the wind direction was nearly north-easterly. The concentrations of atmospheric CO_2 varied from 740 to 780 mg/m^3 (377-397 ppm), with a daily maximum at 0900 LST and a daily minimum at 1500 LST. The mean amplitude of CO_2 concentration was 33 mg/m^3. The daily maximum value of CO_2 concentration was thought to be related to the heating of houses and buildings in the Seoul metropolitan area, and the daily minimum value due to the low vegetation growth of the surface boundary layer in the winter. The mean CO_2 concentration was 770 mg/m^3 throughout this experimental period. The flux of CO_2 did not show any special diurnal variation during the winter period, during which the net CO_2 flux was 0.14 mg CO_2 m^{-2} s^{-1}. Fig. 5 shows the time series of wind speed and direction, CO_2 concentration, and flux during the summer period of 4-6 June 2010. Wind speed ranged from 0.2 to 7 m/s and the wind direction was north-easterly (valley wind) during the daytime, southerly (mountain wind), or northerly during the nighttime. The CO_2 concentration varied from 660 to 780 mg/m^3 (336-397 ppm), with mean values (705 mg/m^3) smaller than those during the winter season. However, its mean amplitude (104 mg/m^3) was larger than that in the winter period (33 mg/m^3). The daily maximum and minimum values in atmospheric CO_2 concentrations occurred at 0600-0800 LST and at 0600-0800 LST, respectively. Indeed, the reductions in CO_2 concentration during the daytime were related to the photosynthesis underlying tree and vegetation. The patterns of CO_2 flux showed diurnal variations with positive (upward) values during the nighttime, whereas during the daytime, they had negative (downward) values. The daily negative extreme of CO_2 flux was the mean value of -1.9 mg CO_2 m^{-2} s^{-1} at 0900-1100 LST, whereas the daily positive extreme was the mean value of 0.58 mg CO_2 m^{-2} s^{-1} in the nighttime. During the summer period, the net CO_2 flux was -0.34 mg CO_2 m^{-2} s^{-1}. According to a previous study of Falge et al. (2002) based on AmeriFlux (23 sites) and EUROFLUX (16 sites) measurements, the estimated value of total carbon uptake in temperate deciduous forest ecosystems accounts for approximately -5 g C m^{-2} day^{-1}, although these regions showed periods of unbalanced respiratory and assimilatory processes. In comparison with the potential estimation value of Kim et al. (2008) by applying the eddy-covariance technique over the cool-temperate *Q. mongolica* forest of Mt. Neunggyeongbong (located at the eastern Gangwon-do Province of Korea), in our study site, the maximum value of total CO_2 uptake (i.e., NEE) during the growing season was -8 g C m^{-2} day^{-1}, and was slightly smaller (i.e., largest CO_2 uptake) than the uptake value (-7 g C m^{-2} day^{-1}) determined at Mt. Neunggyeongbong. In the case of net ecosystem exchanges (NEE), the net biological flux has generally been defined as the sum of photosynthetic and respiratory components (Kowalski et al. 2008). Saigusa et al. (2008) reported that the maximum negative NEE was observed in a cool-temperate deciduous forest after leaf expansion in the beginning of the growing season (June), due to high productivity of the vegetation. Kominami et al. (2008) also showed that the minimum daily mean NEE in a warm-temperate mixes forest reached nearly -1.0 g C m^{-2} day^{-1}, and the net CO_2 uptake reached its peak in June. These findings suggest that in cool-temperate regions of the Korean peninsula, the forest ecosystem of *Q. mongolica* may have a larger atmospheric CO_2 uptake, owing to their high photosynthetic capacity and low ecosystem respiratory activity (Kim et al. 2008). Furthermore, Larcher (1995) and Hiura (2005) reported that the secondary deciduous forests, which contain relatively young trees and are in early successional stage, had a larger biomass increment and carbon sequestration rate than the mature forests. In our study site, the young age characteristics of the dominant *Q. mongolica* forest stand (Table 1) would be expected to affect the NEE. Our results also corroborate that the actual carbon sequestration and high productivity in the cool-temperate deciduous forests may have a substantial effect as carbon sinks on the global carbon cycle of the terrestrial ecosystem (Baldocchi et al. 1996, IGBP Terrestrial Carbon Working Group 1998, Saigusa et al. 2002).

In order to assess long-term continuous measurements of soil CO_2 efflux, the AOCCs system was implemented on the soil surfaces of a *Q. mongolica* forest stand. The results obtained from our field observation showed that the multichannel automated system was both reliable and stable in the field. Figs. 6 and 7 shows the diurnal variations in soil CO_2 efflux and environmental factors (air and soil temperatures, and soil moisture content), based on the results obtained from December 13 to 15 of 2009, and from June 4 to 6 of 2010. During the winter period (Fig. 6), the soil temperatures at 5 and 10 cm depths fluctuated by 3.8-7.7°C and 6.8-9.6°C, respec-

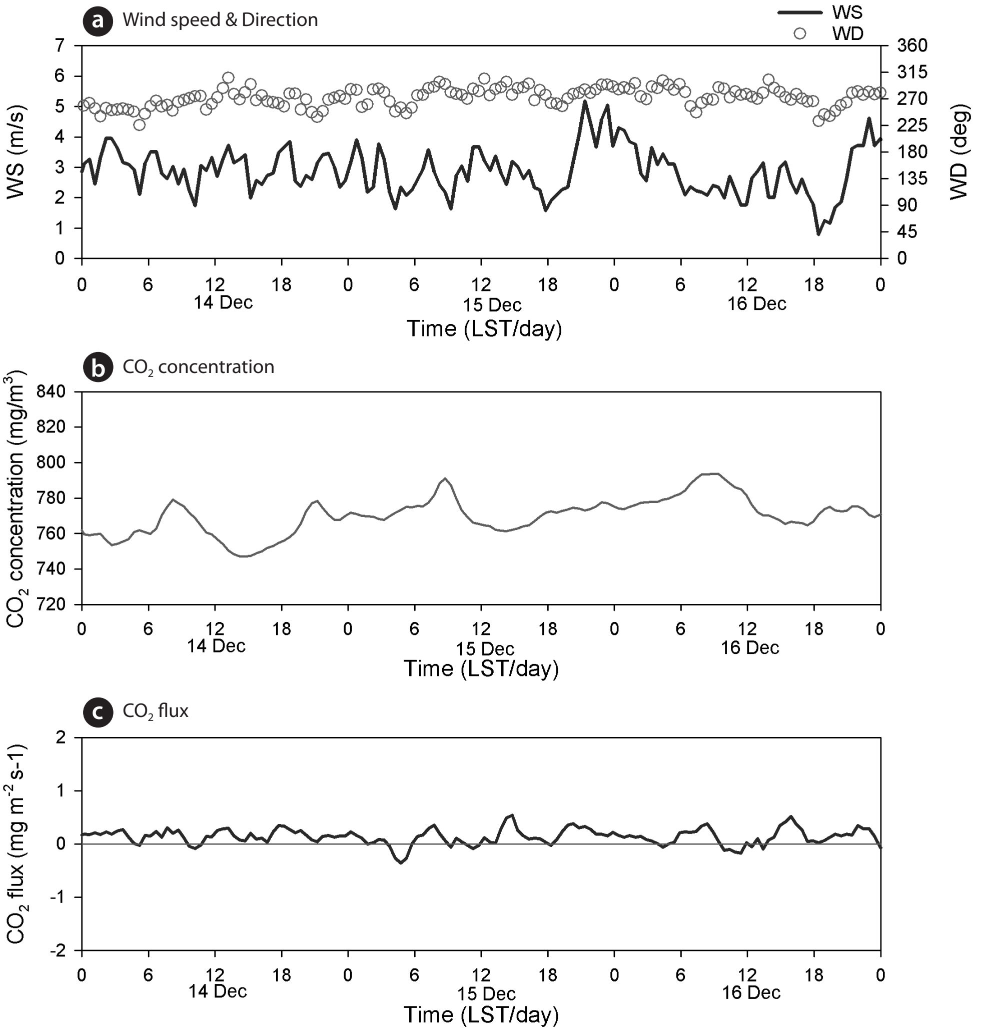

Fig. 4. Time series of (a) wind speed (WS, thick line, m/s) and direction (WD, open circle, deg), (b) CO_2 concentration (mg/m^3) and (c) CO_2 flux (mg m^{-2} s^{-1}) during the winter period from 14 to 16 December 2009.

tively. The rates of soil CO_2 efflux fluctuated within the narrow range from 0.053 to 0.069 mg CO_2 m^{-2} s^{-1}, and the daily mean rate of soil CO_2 efflux was 0.058 mg CO_2 m^{-2} s^{-1} during this period. However, the values of SWC (%) did not change significantly. During the summer period (Fig. 7), the soil temperatures at 5 and 10 cm depths fluctuated by 15.9-19.5°C and 17.0-19.5°C, respectively. The soil CO_2 efflux rate varied from 0.150 to 0.169 mg CO_2 m^{-2} s^{-1}, and their daily mean value (0.159 mg CO_2 m^{-2} s^{-1}) was larger than that in the winter season. However, the mean amplitude of this value (0.015 mg CO_2 m^{-2} s^{-1}) was similar to that seen during the winter period (0.01 mg CO_2 m^{-2} s^{-1}), reflecting small changes in soil temperature under the tree canopy closure and cloudy days during this summer period. In the cool-temperate deciduous forest of central Japan, Mo et al. (2005) reported that when the crown canopy of forest was closed, the diurnal variation in the rate of soil CO_2 efflux was minimal, and followed the small daily changes in soil temperature. Liang et al. (2004) also showed that the range of diurnal variation in the soil CO_2 efflux, photosynthetic active radiation, and soil temperature was greater on sunny days than on cloudy days. The soil CO_2 efflux and environmental factors (air and soil temperatures, and soil moisture content) were measured continuously during the experimental period from April to July of 2010 (Fig. 8). The daily mean values in soil CO_2 efflux and soil temperature increased profoundly from spring to summer. The seasonal pattern in the rate of soil CO_2 efflux strongly followed the seasonal pattern in soil temperatures. The daily mean values in the rate of soil CO_2 efflux increased moderately in the spring (range, 5.2 to 9.0 g CO_2 m^{-2} day^{-1} in April), and increased

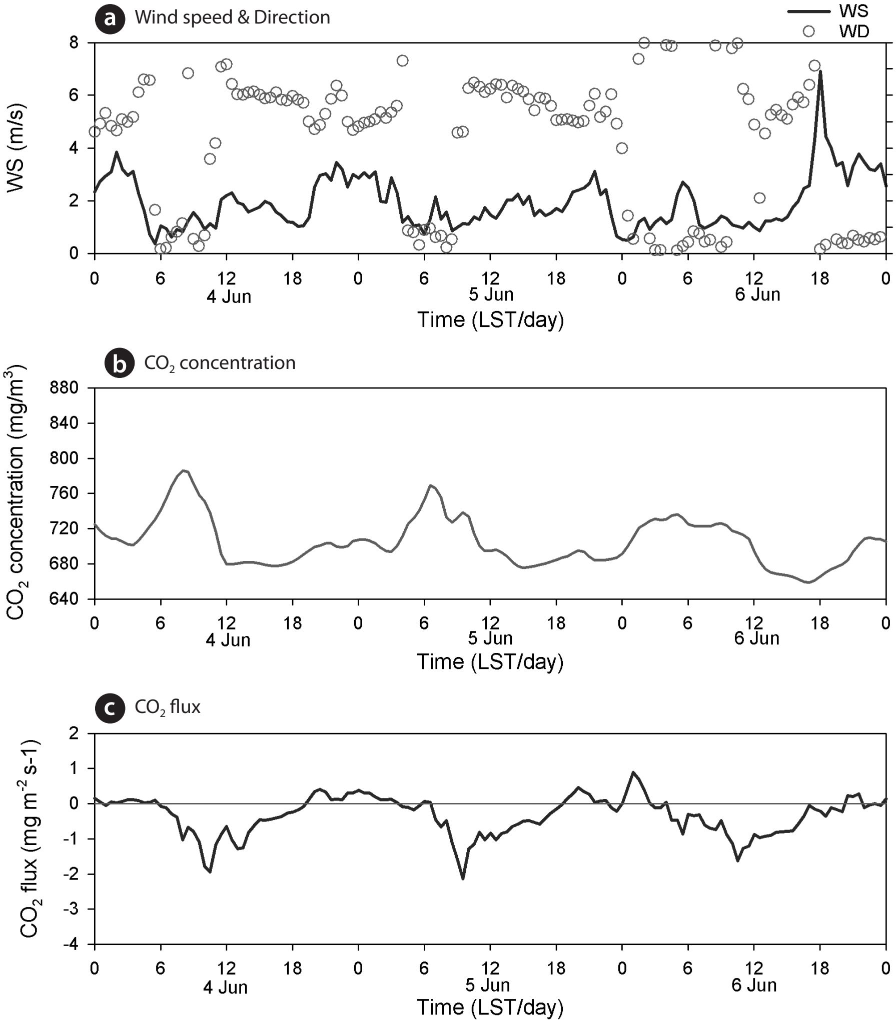

Fig. 5. Time series of (a) wind speed (WS, thick line, m/s) and direction (WD, open circle, deg), (b) CO_2 concentration (mg/m^3) and (c) CO_2 flux (mg m^{-2} s^{-1}) during the summer period from 4 to 6 June 2010.

sharply in summer (range, 18.6 to 37.7 g CO_2 m^{-2} day^{-1} in July). The relation of soil CO_2 efflux to the temperatures was described well by an exponential function (Fig. 9). In the experimental periods, the temperature functions derived from the daily mean soil temperature at different depths accounted for approximately 76-88% of the soil respiration variability, and the daily mean rate of soil CO_2 efflux was most strongly related to soil temperature at 5 cm depth. The Q_{10} values for soil CO_2 efflux varied in range from 2.12 to 3.26, and increased with increasing the soil depth. In the study site, the values of SWC (%) at 15 cm depth had no discernible seasonal trends (range, 17 to 25%), and there were no exponential relationships between soil CO_2 efflux and SWC (data not shown). Similarly, Liang et al. (2004) and Mo et al. (2005) determined that the relation of soil CO_2 efflux to soil moisture was neither clear nor significant in cool-temperate regions, despite being an important environmental factor for the prediction of annual soil respiration rates. However, the continuous results obtained in our study site showed that the higher diurnal variations in soil CO_2 efflux and SWC actually occurred on days with rainfall. Additionally, Inglima et al. (2009) demonstrated that the precipitation pluses in soil CO_2 efflux can enhance heterotrophic respiratory activities during the drought period, reflecting the rapid decomposition of organic materials accumulated in the drying soils.

In this study, atmospheric CO_2 was highly sequestered by the *Q. mongolica* forest stands during the summer period (Fig. 5). The maximum value of total carbon uptake (i.e., NEE) during this period was -8 g CO_2 m^{-2} day^{-1}. The estimated negative (-) value for NEE denotes the net CO_2 transport from the atmosphere to ecosystems. At the same time, the rate of soil CO_2 emission was 6.9 g CO_2 m^{-2} day^{-1} in our study site (Fig. 7). The amplitude of flux variations in NEE was approximately 14% larger than that in soil CO_2 efflux. Gross ecosystem exchange (GEE; g CO_2 m^{-2} day^{-1}) was expressed as follows: GEE = NEE - R_{soil} (Shibata et al. 2005). The GEE corresponds to the net flux of photosynthesis and respiration for aboveground vegetation. Goulden et al. (1996) mentioned that the value of GEE was associated with modest changes in the length of the growing season. Compared with the results reported by Shibata et al. (2005) regarding the estimations for cool-temperate deciduous forests based on flux tower measurements, both GEE (-15 g CO_2 m^{-2} day^{-1}) and NEE in our study site (NSETS) exhibited the lowest values (i.e., largest CO_2 uptake) during the growing season. These results are also consistent with those reported during the growing season in the world wide CO_2 flux network (Baldocchi et al 2001, Falge et al. 2002). However, several uncertainties in applying the eddy covariance techniques over the forest ecosystem remain, most notably the difficulties inherent to measuring CO_2 flux due to the irregu-

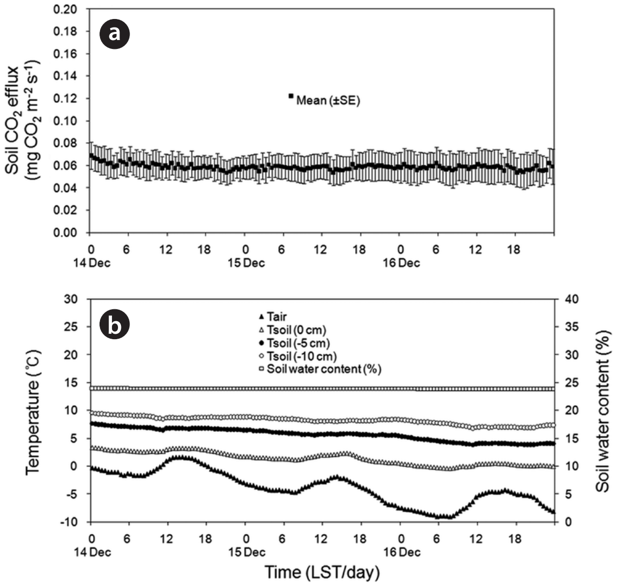

Fig. 6. Diurnal variations in soil CO_2 efflux (a) and environmental factors (air and soil temperatures and volumetric soil water content) (b) during the winter period from 14 to 16 December 2009. Vertical bars show the standard error (SE) of the data.

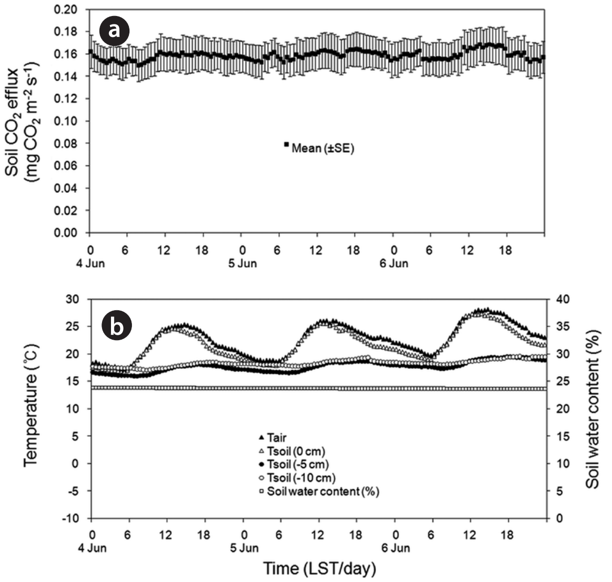

Fig. 7. Diurnal variations in soil CO_2 efflux (a) and environmental factors (air and soil temperatures and volumetric soil water content) (b) during the summer period from June 4 to 6 of 2010. Vertical bars show the standard error (SE) of the data.

lar canopy surface and the drainage flow of CO_2 across the stream valley in the forest ecosystem (Feigenwinter et al. 2008). Moreover, it may underestimate respiration at night in calm winds (Baldocchi et al. 2001). Additionally, Shibata et al. (1998) demonstrated that the effects of nitrogen deposition on carbon sequestration must be investigated more clearly to confirm whether the input of nitrogen from the atmosphere enhances carbon uptake in the forest. As for our study site, the forest ecosystem of *Q. mongolica* is located in the central part of Seoul, and receives elevated amounts of atmospheric nitrogen and CO_2. The atmospheric carbon balance might be affected by the anthropogenic emission, as from the flux source of urban area. It was pointed out byHaszpra et al. (2005), the NEE calculated in the source area isshiftedto more carbon loss, and the real CO_2 uptake by the vegetation is somewhat higher than calculated. Although the *Quercus mongolica* forest in our study site has a large value of carbon uptake in the growing season with the foliation, it is difficult to reach a definite conclusion on the basis of the results in a short-term flux observation of the ecosystem. Therefore, further long-term continuous observations and analyses are required to confirm the obviously results for CO_2 sink or source at forest sites, due to a large inter-annual variation in the NEE of forest ecosystems (Haszpra et al. 2005, Kominami et al. 2008, Mizoguchi 2009).

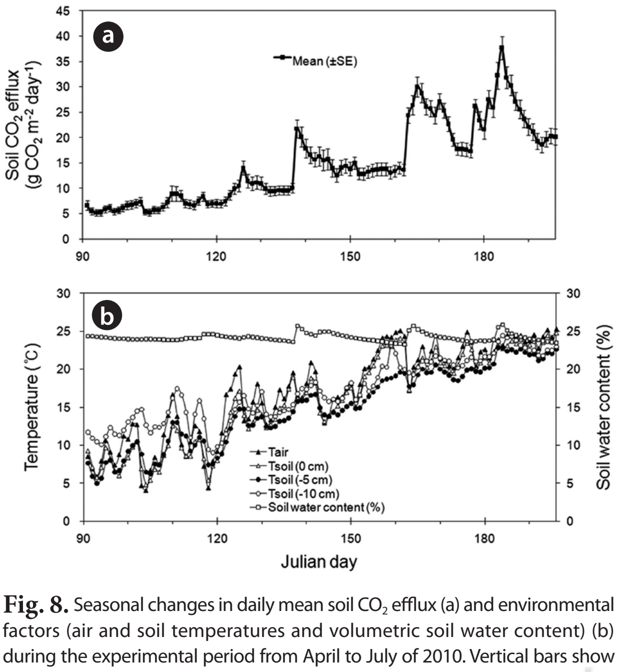

Fig. 8. Seasonal changes in daily mean soil CO_2 efflux (a) and environmental factors (air and soil temperatures and volumetric soil water content) (b) during the experimental period from April to July of 2010. Vertical bars show the standard error of the data.

We found that the AOCCS is a useful tool for both short-term and long-term measurements of soil CO_2 efflux on the forest floor, and can provide high quality data regarding the diurnal and seasonal variations in soil CO_2 efflux with a high temporal resolution and the capturing environmental variables. In further studies, the CO_2 flux values measured continuously and steadily for a long-term at the NSETS can provide us with a greater understanding of net CO_2 exchanges in the forest ecosystem. Consequently, it has become possible to evaluate the seasonal and annual variations in carbon budgets in the *Q. mongolica* forest type predominating in cool-temperate regions of the Korean peninsula.

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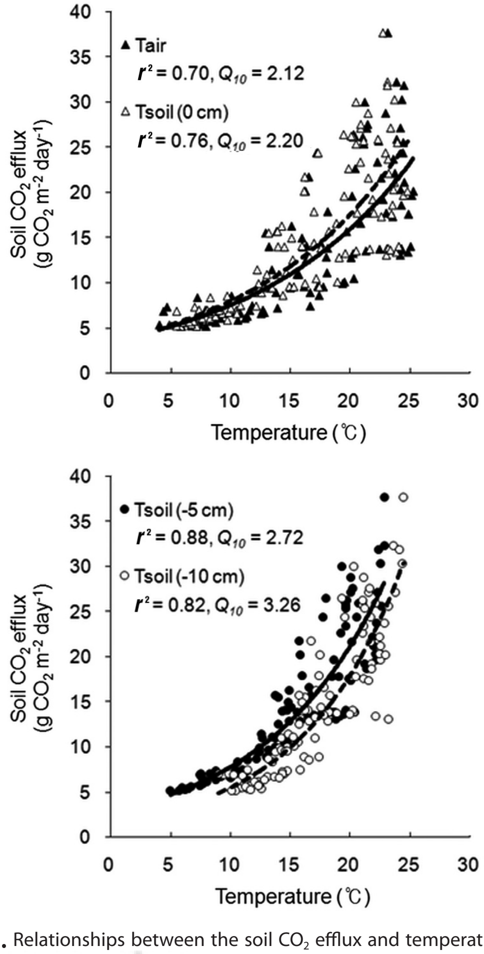

Fig. 9. Relationships between the soil CO_2 efflux and temperatures (air and soil) during the experimental period from April to July of 2010.

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