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Monitoring soil respiration using an automatic operating chamber in a Gwangneung temperate deciduous forest

Jae-Seok Lee*

Department of Biological Sciences, College of Science, Konkuk University, Seoul 143-701, Korea

Abstract

This study was conducted to quantify soil CO_2 efflux using the continuous measurement method and to examine the applicability of an automatic continuous measurement system in a Korean deciduous broad-leaved forest. Soil respiration rate (Rs) was assessed through continuous measurements during the 2004-2005 full growing seasons using an automatic opening/closing chamber system in sections of a Gwangneung temperate deciduous forest, Korea. The study site was an old-growth natural mixed deciduous forest approximately 80 years old. For each full growth season, the annual Rs, which had a gap that was filled with data using an exponential function derived from soil temperature (Ts) at 5-cm depth, and Rs values collected in each season were 2,738.1 g CO_2 m^{-2} y^{-1} in 2004 and 3,355.1 g CO_2 m^{-2} y^{-1} in 2005. However, the diurnal variation in Rs showed stronger correlations with Ts ($r = 0.91$, $P < 0.001$ in 2004, $r = 0.87$, $P < 0.001$ in 2005) and air temperature (Ta) ($r = 0.84$, $P < 0.001$ in 2004, $r = 0.79$, $P < 0.001$ in 2005) than with deep Ts during the spring season. However, the temperature functions derived from the Ts at various depths of 0, -2, -5, -10, and -20 cm revealed that the correlation coefficient decreased with increasing soil depth in the spring season, whereas it increased in the summer. Rs showed a weak correlation with precipitation ($r = 0.25$, $P < 0.01$) and soil water content ($r = 0.28$, $P < 0.05$). Additionally, the diurnal change in Rs revealed a higher correlation with Ta than that of Ts. The Q_{10} values from spring to winter were calculated from each season's dataset and were 3.2, 1.5, 7.4, and 2.7 in 2004 and 6.0, 3.1, 3.0, and 2.6 in 2005; thus, showing high fluctuation within each season. The applicability of an automatic continuous system was demonstrated for collecting a high resolution soil CO_2 efflux dataset under various environmental conditions.

Key words: automatic continuous measurement system, soil respiration, temperate deciduous forest

INTRODUCTION

Terrestrial ecosystems are some of the most important carbon pools, because they assimilate and store vast amounts of carbon. Thus, estimating CO_2 sequestration by soil is particularly important in global change studies. Soils in terrestrial ecosystems contain more than 1,500 Pg carbon (Raich and Schlesinger 1992, Eswaran et al. 1993) and, hence, play an important role in the carbon cycle between terrestrial ecosystems and the atmosphere. For this reason, various soil types in terrestrial ecosystems have been extensively studied (Schlesinger and Andrews 2000).

Forests are major carbon pools of the terrestrial carbon sink in temperate zones of east Asia. Cool temperate deciduous broad-leaved forest is broadly distributed in this region. Korea also includes temperate deciduous broad-leaved forests, which supply carbon to the soil through various types of litter. Despite that deciduous and mixed forests cover areas of 1.7 × 10^6 and 1.9 × 10^6 ha, respectively, and account for approximately 57% of all Korean

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***Corresponding Author**
E-mail: jaeseok@konkuk.ac.kr
Tel: +82-2-450-3411

forests (Son et al. 2004), there is insufficient information about CO_2 efflux for the forest ecosystem. As a result, analyses of carbon cycle characteristics and parameterization for simulating carbon cycles in mountainous forest ecosystems has been restricted.

Soil respiration rate (Rs) is a very important factor that affects the carbon cycle in temperate forest ecosystems (Raich and Schlesinger 1992, Davidson et al. 1998, Law et al. 1999). Various types of organic matter such as leaves, stems, twigs, trunks, and root litter contribute to the soil carbon content in a forest ecosystem. Stored soil carbon is released into the atmosphere mainly through heterotrophic and autotrophic soil respiration (Schlesinger and Andrews 2000, Lee et al. 2004, Jassal and Black 2006). The mechanism of carbon release from soil is intricately related to various environmental factors.

Previous studies have found that Rs is strongly related to soil temperature (Ts) in various ecosystems (Lee et al. 2002, Wieser 2004, Mo et al. 2005, Suh et al. 2006). A temperature sensitivity factor, Q_{10}, has been derived to describe the Rs rate sensitivity with each 10°C increase in Ts. As higher Q_{10} values indicate higher temperature sensitivity in the absence of moisture stress, this factor is often used in global carbon budget models to simulate ecosystem respiration (Lloyd and Taylor 1994).

The pattern and magnitude of Rs is related to various environmental factors such as water but not Ts. Rs temperature sensitivity exhibits significant differences throughout the ecosystem (Liang et al. 2004), plant phenology (Yuste et al. 2004), topography (Ohashi and Gyokusen 2007, Tamai 2010), and litter accumulation. However, these studies indicate that Rs includes high spatial and temporal variations related to wide environmental complexity, but its dynamics are not well understood.

High resolution Rs data has been employed to accurately determine values and analyze the relationships between Rs characteristics and various events in different environments. Moreover, temporal and diurnal efflux mechanisms, as well as daily and seasonal trends in Rs related to environmental factors, have been considered for their important roles in simulating regional or global carbon cycle dynamics (Guan et al. 2006).

To comprehend the sophisticated parameters used to calculate the ecosystem carbon budget, it is necessary to confirm long-term datasets related to various environmental factors (Mo et al. 2005) based on those obtained in the non-continuous intermittent and short term such as one season or monthly datasets per one growth cycle. This information aids in analyzing high-quality correlations between Rs and environmental factors related to the rates and patterns of soil CO_2 efflux.

Automatic opening/closing chambers (AOCC) are advantageous, because they allow for short-term measurements with minimal disturbance to the surface under study. Furthermore, this system produces high-resolution continuous Rs datasets for an extended time.

To acquire these data, many automatic chambers have been previously used to measure Rs in other countries (Goulden and Crill 1997, Drewitt et al. 2002, Edwards and Riggs 2003, Liang et al. 2004, Suh et al. 2006, Joo et al. 2011). Continuous soil CO_2 efflux data have been accumulated over the long-term in various forest ecosystems in many other countries. However, many studies were restricted in the evaluation such as annual soil respiration or simple seasonal changes using a portable measurement system in a Korean ecosystem (Son and Kim 1996, Lee and Moon 2001, Pyo et al. 2003, Kim et al. 2004, 2009).

Some researchers have attempted to introduce an automatic system into the Korean ecosystem. Suh et al. (2006) reported on a newly developed automatic measurement system using on electric motor. Lee et al. (2009) showed that Rs is significantly correlated with soil and air temperatures (Ta) but not with soil water in an apple orchard. Joo et al. (2011) reported that the amplitude of flux variations in the net ecosystem exchange is approximately 14% larger than those in soil CO_2 efflux in a cool-temperate *Quercus mongolica* forest on Mt. Nam.

The AOCC system carries several restrictions, although it can create high resolution datasets. For example, a sustainable electrical power supply and some level of electrical skill for maintaining the system are required. For these reasons, automatically measured datasets are severely restricted in the Korean temperate vegetation zone. As a result, more sophisticated analyses, using high resolution Rs datasets, are relatively rare in Korean ecosystems. Soil carbon flux data must be collected to evaluate and predict the carbon cycle in Korean temperate forests.

In this study, we examined the applicability of an automatic continuous measurement system in a Korean deciduous broad-leaved forest. We estimated the seasonal and annual amount of soil CO_2 efflux and its characteristics based on a full growth season of data collected with automatic continuous measurements including the winter snow season.

MATERIALS AND METHODS

Study site

The study area was Gwangneung Experimental Forest (37°45'25.37" N, 127°9'11.62" E 340 m a.s.l) of the Korea Forest Research Institute. This is a well-preserved, cool temperate forest located in Kyenggido Province in the west-central portion of the Korean peninsula. The vegetation included old-growth, mixed deciduous broad-leaved forest protected from forest management activities, human disturbance, and civilian access (Lim et al. 2003). This cool temperate deciduous broad-leaved forest is dominated by *Quercus serrata*, *Carpinus cordata*, and *C. laxiflora* with approximate ages of 80-200 years. The tree volume in the Gwangneung Forest is about 550 m^3/ha, and the stand biomass is approximately 225 t/ha (Chae 2011). The bulk density and porosity of the surface soil layer (0 to 0.05 m) were 0.86 (± 0.08) and 0.66 (± 0.04) g/cm^3, respectively. The soil is sandy loam or loam, with 46% sand and 8% silt in the surface layer and 50% sand and 13% silt in the subsurface layers (Lim et al. 2003). A 30 m × 30 m study plot was set on the northeastern slope. The average diameter at breast height (DBH) was 16.7 cm, with a range of 2-65.4 cm above 2 cm, and the biggest DBH was 65.4 cm from a *Q. serrata*.

Description of the soil chamber system

The AOCC system was developed based on the open-flow method and could be used for four seasons. During waiting status, the lid was positioned vertically allowing snow, rain, leaves, and twigs to drop into the soil surface and allowed normal drying and wetting of the soil surface in the chamber. This system provides a high quality Rs dataset related to various environmental factors for short and long-term based measurements with good time resolution (Suh et al. 2006).

The AOCC system is composed of three main parts that include a chamber system in addition to pumping and timer systems. To avoid air stagnation zones, the chamber is shaped as a long octagon with dimensions of 20 (length) cm × 30 (width) cm × 12 (height) cm. The dimensions of the chamber were selected to exclude small plants that could lead to underestimating CO_2 levels as a result of photosynthesis during the daytime.

Applying DC current to the motor opens and closes a 0.5-cm-thick acrylic lid. Two limit switches attached to the top frame cut power to the motor and lock the lid in a vertical position. The pump system consisted of an air pump (GD-6EA; Enomoto, Tokyo, Japan), a mass-flow meter (RK-1250; Kofloc, Tokyo, Japan), an air filter (TPF2000; TPC Inc., Seoul, Korea), a water trap (Perma Pure dryer, SWG-A01-18; Asahi Glass Engineering Co., Ltd., Chiba, Japan), and two infrared gas analyzers (IRGAs, LI-820; Li-Cor, St. Lincoln, NE, USA) to measure the CO_2 concentration at the air inlet and outlet. The IRGAs were calibrated with pure nitrogen gas (zero) and two span gas of 1,507 μL/L (summer) and 507 μL/L (winter) at least once every 2 weeks. After calibration, differences in CO_2 concentration between the IRGAs were within approximately 1 μmol/mol to zero, 961, and 1,601 μL/L.

In our experiment, well-buffered ambient air collected from 30 cm above the soil surface was pumped into the chamber at a rate of 1.8 L/min from a buffer tank with an approximate capacity of 5 L. The pump supplied ambient air at the rate of 0.6 L/min to the IRGA, which was used as a reference CO_2 value for calculating the difference in CO_2 concentrations between the chamber inlet and outlet. This airflow rate was chosen based on LI-820 lab test results, which has a maximum flow rate of 1.0 L/min. Therefore, our selected airflow rate was deemed adequate for IRGA usage.

The timer system was constructed from a timer (H5CR; Omron, Tokyo, Japan) that controlled the opening and closing times of the chamber lid and included relays (G2A; Omron) that divided the electrical power supplied by the DC motor among the chambers. Additionally, the timer system controlled the opening and closing of solenoid valves and data transmission from the IRGA to the data logger terminals (CR10X; Campbell Scientific, Inc., Logan, UT, USA). When the chamber was closed, the absolute CO_2 concentration values at the air inlet and outlet were measured consecutively over a 20-min measurement period (Suh et al. 2006). All CO_2 concentration data were logged in a data logger.

Four chambers were operated to generate continuous Rs datasets. The four chambers were installed considering the kinds of litter supplied from the dominant species on September 15, 2003. The chambers were inserted approximately 4 cm deep from the chamber base into the soil by cutting through the surface litter. Rs was collected in 24 datasets per chamber per day during 15 min per hour for each chamber.

Failed measurements occurred six times over the 2 years due to electrical failure, analyzer trouble, and data logging failure. The main failed measurement period was 64 days from January 15 to March 19, 2005 and when the IRGA was being repaired for 30 days from September 15 to October 15, 2005. During these periods, daily Rs values were calculated using the function from the relationship between Rs and Ts at 5 cm soil depth (Ts5). We collected continuous data for 2 years.

Calculation procedure

Rs (mg CO_2 m^{-2} h^{-1}) was calculated from the difference in the CO_2 concentrations between the chamber's air inlet and outlet by:

$$Rs = a L \rho A^{-1}$$

where a is the difference in CO_2 concentration between the chamber's air inlet and outlet (mol/mol), L is flow rate (L/min), ρ is the density of CO_2 (kg/m^3), and A is the soil surface area (m^2) covered by the chamber base. The constants in this function convert the units to mg CO_2 m^{-2} h^{-1} (Suh et al. 2006).

To collect annual Rs for each year, hourly mean Rs values of the failed measurements were filled by exponential functions derived from all measured Rs of Ts5 for each year and from data seasonally separated from Rs and Ts. Each Rs evaluated in each exponential function was examined for statistical significance. Each season was separated; spring from March to May, summer from June to August, autumn from September to November, and winter from December to February.

Diurnal changes in Rs and Ts were analyzed only during two periods for 10 days in May 19-28 (spring) and July 30-August 8 (summer) in 2005 to estimate the ability of short-term data taking on the continuous measurement system to temporal changes in environmental factors such as rain.

The annual Rs temperature response was estimated based on the exponential function $Rs = R_0e^{KTs}$, where Rs is the daily or hourly mean Rs at a Ts of 0°C; Q_{10}, the temperature sensitivity of Rs; and Ts, the measured Ts5. Q_{10} was calculated by the factor reaction increase for an increase of 10°C ($Q_{10} = e^{10k}$), and k is the daily mean Ts5 (Mo et al. 2005).

Measurement of environmental factors

Ts values were measured at depths of 0, 2, 5, 10, 20, and 30 cm with a T-CC thermocouple (0.32 mm; Ninomiya, Tokyo, Japan). Ts measurements are necessary to estimate annual Rs rates using a temperature-based Q_{10} model. Daily Ts from a temperature logger (HOBO TidbiT v2; Scottech, Hamilton, New Zealand) were used for gap filling instilled at a 5-cm soil depth.

The Ta and air pressure for calculating Rs were measured at a height of 30 cm above the soil surface using a thermocouple and temperature sensor (HOBO Pro RH/Temp; Scottech) installed in the radiation shell. Soil water content (SWC) was measured at depths of 0-30 cm at three points, and precipitation was collected with a rain gauge (RG2-M; Cole-Parmer, Raleigh, NC, USA). All datasets were stored in a data logger (CR10X; Campbell Scientific Inc., Madison, WI, USA).

Statistical analysis

The Rs value distributions were tested for normality, and the data for each year was normally distributed. Correlation analysis and one-way analysis of variance were used to determine the relationship between measured Rs and environmental factors for each year and to test for significant differences among the annual and seasonal Rs values; 1) that the gap was filled with the exponential function derived from the annual (GA) or seasonally separated (GS) daily mean Rs and daily mean Ts collected during each season (spring, summer, autumn, winter), and 2) which was calculated using an exponential function derived from the annual (EA) or seasonally (ES) separated daily mean Rs and daily mean. Therefore, while directly measured Rs were included in GA and GS, EA and ES did not include the measured Rs. Multiple comparisons between annual or seasonal values were tested at the 0.05 probability level.

All statistical analyses were conducted using MinTab Statistical Software (Minitab Inc., State College, PA, USA).

RESULTS AND DISCUSSION

Climate

The annual precipitation was 1,789.1 and 1,745.3 mm in 2004 and 2005, respectively (Table 1 and Fig. 1a). Precipitation was greatest during summer in both study years. The annual mean Ta measured at 0.3 m height above the soil surface was 10.6°C in 2004 and 8.7°C in 2005 (Fig. 1a). The 1 year daily mean Ta ranged from -17.0°C at the end of January to 26.2°C in late June and from -15.1°C at the end of December to 25.8°C at the end of August 2004 and 2005, respectively (Fig. 1a). The annual mean Ts5 was 10.1°C in 2004 and 8.6°C in 2005, respectively (Fig. 1b). The minimum and maximum Ts5 ranged from -1.5°C in March to 23.5°C in early August 2004 and ranged from -3.5°C at the end of January to 24.4°C in mid August 2005, respectively.

Annual and seasonal soil CO_2 efflux rate

Fig. 1b shows the seasonal variation in Rs that was filled with values calculated with an exponential function de-

Table 1. Various values of soil respiration and environmental factor in Gwangneung cool temperate deciduous broad-leaved in 2004 and 2005

	Daily mean Rs (mg CO_2 m^{-2} h^{-1})						*F*-value ($P < 0.05$)							Ts5[**] (°C)	Q_{10}[††]	Precipitation (mm)
	GS[†]	GA[‡]	ES[§]	EA[¶]	Mean	S.D.	GS:GA	GS:ES	GS:EA	GA:ES	GA:EA	ES:EA				
2004																
Spring[*] ($N = 92$)	189.7	168.4	260.6	135.4	188.6	53.0	1.21	14.40	12.10	22.20	3.92	61.89	$F(1.182) = 3.89$	7.7	3.2	290.2
Summer ($N = 92$)	696.1	683.1	699.8	686.3	691.3	7.9	0.26	0.04	0.11	0.72	0.01	0.28	$F(1.182) = 3.89$	19.7	1.5	1,075.3
Autumn ($N = 91$)	321.8	298.1	324.5	279.7	306.0	21.2	0.49	0.01	1.77	0.01	0.40	1.75	$F(1.181) = 3.89$	12.6	7.4	327.2
Winter ($N = 91$)	42.6	41.0	44.3	39.5	41.8	2.1	0.71	1.49	2.92	4.66	0.62	11.25	$F(1.180) = 3.89$	0.5	2.7	96.5
Annual mean or total	312.6	297.7	332.3	285.2	306.9	20.3	0.00	0.82	0.50	0.82	0.01	0.05	$F(1.8) = 5.32$	10.0	3.7 (4.2)	1,789.1
2005																
Spring ($N = 92$)	147.9	146.3	108.0	97.1	124.8	26.1	0.01	6.15	11.50	5.80	11.02	0.91	$F(1.182) = 3.89$	4.9	6.0	162.1
Summer ($N = 91$)	1,035.7	884.1	1,026.9	659.1	901.5	175.8	9.63	0.03	59.89	8.41	26.38	56.22	$F(1.181) = 3.89$	19.1	3.1	1,092.7
Autumn ($N = 91$)	322.8	321.5	359.7	290.9	323.7	28.1	0.00	1.66	1.17	1.66	1.08	5.03	$F(1.180) = 3.89$	12.2	3.0	353.3
Winter ($N = 91$)	25.7	26.5	25.1	27.5	26.2	1.1	0.68	0.60	3.53	3.24	0.93	11.62	$F(1.179) = 3.89$	-1.9	2.6	137.2
Annual mean or total	383.0	344.6	379.9	268.7	344.0	53.2	0.02	0.01	0.30	0.01	0.11	0.18	$F(1.8) = 5.32$	8.6	3.7 (3.0)	1,745.3

S.D., standard deviation; Ts5, Ts at 5 cm soil depth; Rs, soil respiration rate.

[*] Spring, Mar-May; summer, Jun-Aug; autumn, Sep-Nov; winter, Jan, Feb & Dec.

[†] GS: gap was filled with data using exponential function derived from Ts5 and Rs collected in each season (spring, summer, autumn, winter).

[‡] GA: gap was filled with data using exponential function derived from Ts5 and Rs collected for one year.

[§] ES indicates value calculated with exponential function derived from Ts5 and Rs collected in each season (spring, summer, autumn, winter).

[¶] EA indicates value calculated with exponential function derived from Ts5 and Rs collected for one year.

[**] Ts5 indicate daily mean soil temperature at 5 cm depth.

[††] Q_{10} was calculated with exponential function derived from only observed Rs, and parenthesis indicate values derived from observedall annual datasets.

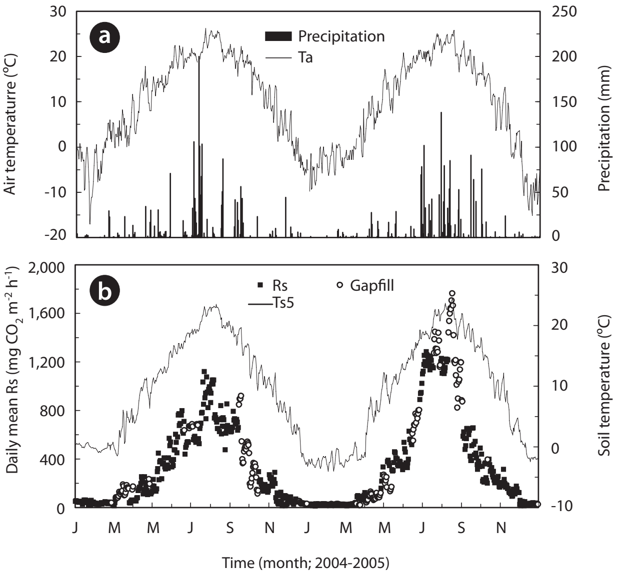

Fig. 1. Seasonal changes and relationships observed during the 2004-2005 study period in a Gwangneung temperate-deciduous forest, Korea, include (a) air temperature (Ta; solid line) and precipitation (vertical bar), (b) soil respiration rate (Rs; black quadrangles, gap filled Rs; white circles) and soil temperature (Ts5; solid line) at 5 cm depth. Air temperature was collected at 0.3 m above the soil surface. Gaps were filled with values calculated from an exponential function derived from the relationship between annually measured Rs and soil temperature at a 5 cm depth (Ts5) for each year.

rived from relationships between measured Rs and Ts5 for each year. Rs was moderate in the winter, from December to March, increasing to a peak of approximately 1,300 mg CO_2 m^{-2} h^{-1} in July, and then decreased in autumn. Rs showed the highest wave patterns during the summer and the lowest during winter. In the winter, Rs was 41.8 and 26.2 mg CO_2 m^{-2} h^{-1} in 2004 and 2005, respectively, and Ts5 was 0.5 and -1.9°C in 2004 and 2005, respectively. Ts clearly increased to 7.7 and 4.9°C during spring in 2004 and 2005, respectively. Furthermore, Ts5 increased to 19.7 and 19.1°C during the respective summers of 2004 and 2005. Rs in spring and summer increased to 173.3 and 684.4 mg CO_2 m^{-2} h^{-1} in 2004, respectively. Additionally, Rs increased to 205.2 and 968.2 mg CO_2 m^{-2} h^{-1} in spring and summer 2005, respectively. However, in the respective autumn seasons in the aforementioned years, Ta decreased sharply to 12.7 and 12.3°C, as did Rs to 310.4 and 311.7 mg CO_2 m^{-2} h^{-1}. These results indicate that the seasonal changing patterns in Rs undoubtedly depended on those of Ts5. This finding was particularly evident at a depth of 5 cm (Figs. 1a and 2a), which was widely used in the exponential functions.

Previous studies have shown that the variation in Rs is strongly related to factors associated with Ts fluctuations (Liang et al. 2004, Joo et al. 2011). Temperature may explain up to 72-96% of the variation in Rs in temperate forests (Rey et al. 2002, Kang et al. 2003, Subke et al. 2003), and that any change in Rs is strongly related to fluctuations in Ts. Furthermore, Rs is strongly correlated with Ts in temperate forests (Mo et al. 2005, Suh et al. 2009, Bahn et al. 2010).

The approximate relationship between Rs and Ts5 is given by Eq. 1 ($r = 0.91$, $P < 0.001$, $N = 275$) in 2004 and Eq. 2 ($r = 0.87$, $P < 0.001$, $N = 215$) in 2005 (Fig. 2a). The approximate relationship between Rs and Ta is given by Eq. 3 ($r = 0.84$, $P < 0.001$, $N = 275$) in 2004 and Eq. 4 ($r = 0.79$, $P < 0.001$, $N = 215$) in 2005.

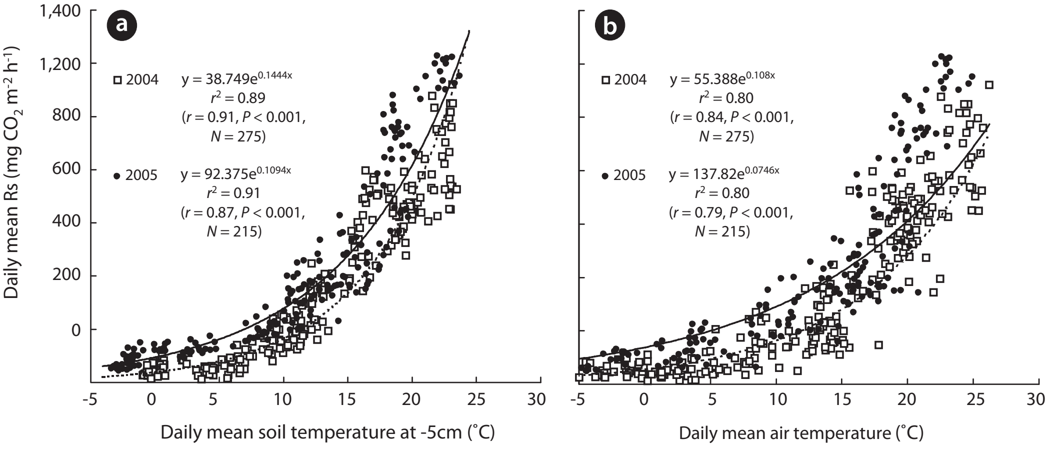

Fig. 2. Exponential relationships between (a) soil temperature (-5 cm), (b) air temperature and soil respiration rate (Rs) in 2004 (white quadrangles) and 2005 (black circles). Datasets used only measured Rs and soil temperature values.

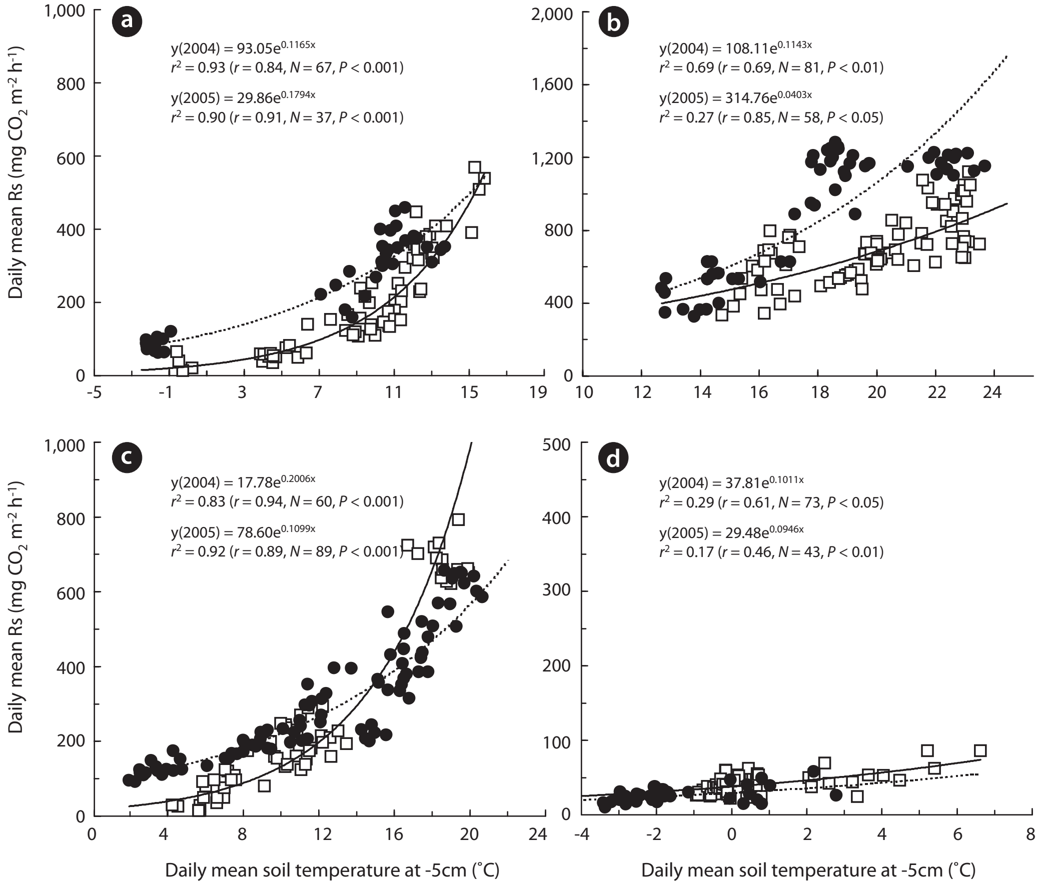

Fig. 3. Relationships between soil respiration rate (Rs) and soil temperature at a 5-cm depth during each season in 2004 (white quadrangles) and 2005 (black circles): (a) spring season from March to May, (b) summer season from June to August, (c) autumn season from September to November, and (d) winter season from December to February. Datasets used only measured Rs and soil temperature values.

$$Rs_{(2004)} = 38.75e^{(0.1444Ts5)} \quad (1)$$
$$Rs_{(2005)} = 92.38e^{(0.1094Ts5)} \quad (2)$$
$$Rs_{(2004)} = 55.39e^{(0.108Ta)} \quad (3)$$
$$Rs_{(2005)} = 137.82e^{(0.0746Ta)} \quad (4)$$

A seasonal analysis revealed that Rs, which is expressed as the daily soil carbon efflux, was significantly correlated with daily mean Ts5 (Figs. 1b, 2a, and 3). In the two measurement years, Ts5 increased from -2.5 to 15.8°C in the spring, and Rs also increased from approximately 13.0 to 568.0 mg CO_2 m^{-2} h^{-1}. Rs was strongly correlated with Ts and Ta in spring (Fig. 3a). These trends are illustrated in Fig. 3a, which shows that r is 0.84 ($P < 0.001$, $N = 67$) in 2004 and 0.91 ($P < 0.001$, $N = 37$) in 2005, respectively. The summer (2004, $r = 0.69$, $P < 0.001$, $N = 81$; 2005, $r = 0.85$, $P < 0.05$, $N = 58$) and autumn seasons (2004, $r = 0.94$, $P < 0.001$, $N = 60$; 2005, $r = 0.89$, $P < 0.001$, $N = 89$), also showed a high correlation between Rs and Ts5 (Fig. 3c). In contrast, the correlation in winter was relatively weaker ($r = 0.61$ in 2004 [$P < 0.001$, $N = 73$], $r = 0.46$ [$P < 0.001$, $N = 43$] in 2005) than that in other seasons (Fig. 3d). The exponential function fit about 29% and 17% of the winter season in 2004 and 2005, respectively (Fig. 3d).

However, the annual Rs value was different according to the gap filling or estimating method, although the difference was not significant. We assumed that the most ideal annual Rs value occurred when the gap was filled with a value calculated with a seasonally separated exponential function based on seasonal data (GS in Table 1).

The annual Rs estimated with EA was 285.2 (2,498.6 g CO_2 m^{-2} y^{-1}) and 268.1 mg CO_2 m^{-2} h^{-1} (2,353.4 g CO_2 m^{-2} y^{-1}) in 2004 and 2005, respectively (Table 1). However, the annual Rs values, with the gap filled with data using the exponential function derived from Ts5 and Rs collected in each season, were 312.6 mg CO_2 m^{-2} h^{-1} (2,738.1 g CO_2 m^{-2} y^{-1}) in 2004 and 383.0 mg CO_2 m^{-2} h^{-1} (3,355.1 g CO_2 m^{-2} y^{-1}) in 2005 (GS in Table 1). In the case of GA, the annual Rs values were 297.7 (2,607.5 g CO_2 m^{-2} y^{-1}) and 344.6 mg

CO_2 m^{-2} h^{-1} (3,018.9 g CO_2 m^{-2} y^{-1}) in 2004 and 2005, respectively. Also, the annual Rs values calculated with ES were 332.3 (2,911.0 g CO_2 m^{-2} y^{-1}) and 379.9 mg CO_2 m^{-2} h^{-1} (3,328.0 g CO_2 m^{-2} y^{1}) in 2004 and 2005, respectively. Although no significant differences were observed between annual values, the seasonal values showed significant difference in some cases.

In the summer of 2005, annual Rs was significantly higher in GS compared with that in GA and EA. GS was significantly lower compared to ES but higher than EA in spring in 2004 ($P < 0.05$).

Although no significant difference was observed between the estimated annual Rs ($P < 0.05$), the range of values showed a minimum of 2,498.6 g CO_2 m^{-2} y^{1} in EA to a maximum of 2,738.1 g CO_2 m^{-2} y^{1} in GS in 2004, and a minimum of 2,353.4 g CO_2 m^{-2} y^{1} in EA to a maximum of 3,355.1 g CO_2 m^{-2} y^{1} in GS in 2004. Therefore, an ideal continuously measured dataset using a more sophisticated measurement system is needed to evaluate accurate seasonal and annual Rs.

Over all, the mean annual Rs was about 2,851.3 g CO_2 m^{-2} y^{1} and ranged from 2,426.0 to 3,229.5 g CO_2 m^{-2} y^{1}, according to calculation or gap filling methods. These values were relatively lower than those reported in a previous study for a Korean temperate forest. Annual Rs in portable temporal measurements sometimes employed presumption absence data in winter or the rainy season. In this study, these findings may have been observed because data were collected for a restricted period under relatively favorable conditions.

Several studies have been conducted on Korean temperate forests. Lee and Moon (2001) estimated an annual mean Rs of 6,964 g CO_2 m^{-2} y^{1} in a *Q. acutissima* forest, Kim (2008) reported an Rs of 3,372.6 g CO_2 m^{-2} y^{1} in a *Q. variabilis* forest, and Chae et al. (2003) showed an Rs of 4,178.5 g CO_2 m^{-2} y^{1} in a *Q. serrata* forest mixed with *C. laxiflora* in Gwangneung Forest. For the same *Quercus* community, Yi et al. (2005) reported various Rs values of 2,487.8-3,582.8 g CO_2 m^{-2} y^{1} in a *Q. mongolica* forest of various ages and *Q. variabilis* for April-November. The overall annual soil CO_2 efflux in Korean deciduous-temperate forests was approximately 2,452.8-6,657.6 g CO_2 m^{-2} y^{1} with a mean of 4,555.2 g CO_2 m^{-2} y^{1}, when it was calculated from Lee et al. (2010).

Raich and Schlesinger (1992) reported that the annual soil CO_2 efflux is 1,943.0-5,133.4 g CO_2 m^{-2} y^{1} in a temperate broadleaf and mixed forests at 34-38° latitude. The medium value of the mean soil CO_2 efflux calculated by Raich and Schlesinger (1992) was 2,374.8 g CO_2 m^{-2} y^{1} in a temperate forest, which was relatively lower than that collected in our study. One explanation for this result is that our study site was an 80-100-year-old forest (Chae et al. 2003, Suh et al. 2006).

In contrast, the temperature sensitivity of Rs, commonly referred to as Q_{10}, has been the general focus of many studies, and Ts is typically a reliable predictor of Rs, except under severe drought conditions (Moncrieff and Fang 1999). The Q_{10} values from spring to winter calculated from each season's dataset were 3.2, 1.5, 7.4, and 2.7 in 2004 and 6.0, 3.1, 3.0, and 2.6 in 2005, showing high fluctuations within each season (Table 1).

However, the Q_{10} calculated with the annual full growth season data was 4.2 and 3.0 in 2004 and 2005, respectively. Annual values between years showed some differences compared to the annual data. When Q_{10} was calculated with only three growth seasons from spring to autumn, without considering the winter season, which is sometimes absent in temporal measurements, the value was the same at 4.03 in 2004 and 2005, respectively, which was higher than the four-season mean.

Q_{10} derived from the exponential functions, referred to as daily Rs, was 4.2 and 3.0 in 2004 and 2005, respectively (Table 1). An exponentially linear relationship between Q_{10} and temperature is generally acknowledged (Bekku et al. 2003, Zhang et al. 2009). A Q_{10} value of 2-4 is considered typical for forest soils in which the temperature ranges from 10-25°C, whereas higher values are observed when the temperature is 0-10°C (Kirschbaum 1995). Moreover, an average Q_{10} of 2.4 for Rs has been suggested (Raich and Schlesinger 1992). In this study, individual values were 4.2 and 3.0 in 2004 and 2005, respectively (Table 1). These values exceeded the previous typical value by 1.2. However, several studies have determined that Q_{10} has annual and seasonal variations. Those studies indicated that the variation in Rs under field conditions is very low at low Ts and high at high Ts (Frank et al. 2002, Jia et al. 2006). Moreover, Q_{10} varies with seasonal changes due to factors such as leaf phenology, root growth, and the microbial population (Mo et al. 2005, Bahn et al. 2010). Therefore, long-term measurements under various environmental conditions are required for a more accurate estimate of Q_{10}. We can understand the Rs mechanism from the available data, including relationships between parameters. Therefore, a temperature sensitivity evaluation is needed that includes winter season datasets.

Diurnal change in soil respiration

The relationship between Ta and Ts at 0, 2, 5, 10, and 20 cm was determined for periods spanning several days in

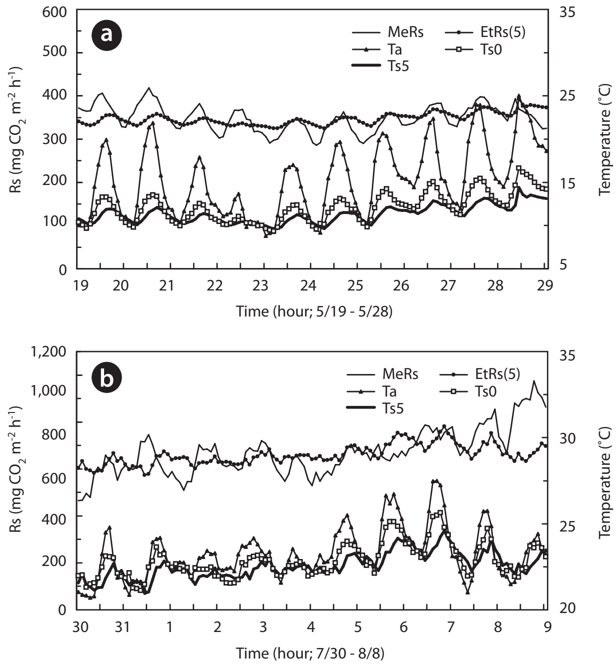

Fig. 4. Diurnal variations in soil respiration rate by measuring Rs (MeRs) and estimated Rs (EtRs[5]), air temperature (Ta), and soil temperature at 0 cm (Ts0) and 5 cm (Ts5) depths: (a) diurnal variations during the spring season, May 19-31, 2005, and (b) in the summer season, July 30-August 9 in the same year.

spring and summer (Fig. 4a and 4b). Rs, expressed as the hourly soil CO_2 efflux, clearly exhibited diurnal variation during some days in the spring (May 19-28) and summer (July 30-August 9) seasons. In the spring, the diurnal pattern of CO_2 efflux fluctuated by about 90 mg CO_2 m^{-2} h^{-1}. However, the value was higher in the summer at approximately 160 mg CO_2 m^{-2} h^{-1}. At that time, Ta and Ts showed clear changes in wave patterns. The range of change was higher in Ta and surface Ts than that in deep soil.

Fig. 5 shows the results for the relationship between Rs, Ta, and Ts at soil depths of 0, 2, 5, 10, and 20 cm in 2005. In the 2005 spring season, the diurnal change in Rs correlated more strongly with Ta ($r = 0.61$, $P < 0.001$) than with deep Ts ($r = 0.26$ at a soil depth of 20 cm) (Fig. 5a-f). However, in the summer season, the Rs correlated weakly with Ta ($r = 0.37$, $P < 0.001$) (Fig. 5g), and the exponential functions derived between Rs and Ts at different depths (0, -2, -5, -10, and -20 cm) revealed that the correlation coefficient showed narrow differences ranging from 0.41 in 0 cm to 0.49 at 20 cm soil depth (Fig. 5h and 5l).

The diurnal Q_{10} based on Ta and Ts was calculated for periods of several days in the spring and summer seasons. The calculated diurnal Q_{10} values were unreasonably low, with an average of 1.40 over the range 1.14-1.50 in the spring and an average of 1.92 over the range 1.35-2.57 in the summer.

The diurnal Rs patterns were nearly regular, producing a wave in both spring and summer seasons (Fig. 4). Additionally, Rs fluctuated with changes in Ta and Ts. Overall, the regression analysis indicated relatively lower correlation coefficient values ($r = 1.1$-1.5 in spring and $r = 1.4$-2.6 in summer) at all hourly temperatures than those at seasonal temperatures; however, these values increased at greater soil depths. In previous studies, Rs showed variations over the course of a day, mainly in response to changes in Ts and to seasonal changes reflecting root growth phenology and litter decomposition (Edwards and Riggs 2003, Suh et al. 2006). Therefore, diurnal changes in Rs may be dependent on factors other than temperature. However, Rs predicted by Ta and Ts, in addition to the observed Rs, showed similar diurnal amplitudes in our study, but the estimated Rs peaks preceded the observed Rs peaks after 3-4 h (Fig. 4). The reason for the time delay is that more or less time is required until the soil respiration source is activated.

The Q_{10} derived from Ta and Ts increased with soil depth (Fig. 4). A similar trend was observed in previous studies. Mo et al. (2005) described that Q_{10} derived from the relationship between Rs and Ts at various depths increased from 3.8 at -1 cm to 5.5 at -50 cm in a temperate forest in central Japan. These researchers suggested that the Ts at -50 cm may not be as effective for predicting Rs in temperate forests as that observed at a more shallow depth (0-20 cm). Savage et al. (2009) reported that the depth at which Ts measurements are performed clearly affects the calculated diurnal Q_{10}, which is used to calculate the regression.

SWC and rainfall events

The relationship between Rs and the SWC was analyzed with 1-year data in 2005, because a soil water sensor was installed that year. Moreover, because Rs and Ts are correlated, CO_2 efflux may be depressed by low temperatures during winter. Therefore, we used only the data for the summer season in our analysis of Rs-SWC relationships. Rs showed a weak correlation with SWC for the summer ($r = 0.28$, $P < 0.05$, $N = 63$). Indeed, a plot of Rs against SWC for 1 year showed a confounding correlation (Fig. 6).

Although Rs showed a clear correlation with Ts ($r = 0.91$, $P < 0.001$ in 2004, and $r = 0.87$, $P < 0.001$ in 2005), the relationship between Rs and SWC and that between Rs and precipitation for the summer season was confounding ($r = 0.28$, $P < 0.05$) (Figs. 6 and 7). Lee et al. (2010) found that Rs seasonality is strongly affected by the pattern of summer rainfall when the soil is warm (> 15°C). However, other studies have found that Rs is not affected by SWC when research is not restricted to the rainy season, particularly during the so-called Jangma in Korea (Joo et al. 2011). Rainfall during the main growth from June to September accounted for 73.0% (1,306.5 mm) and 82.7% (1,266.5 mm)

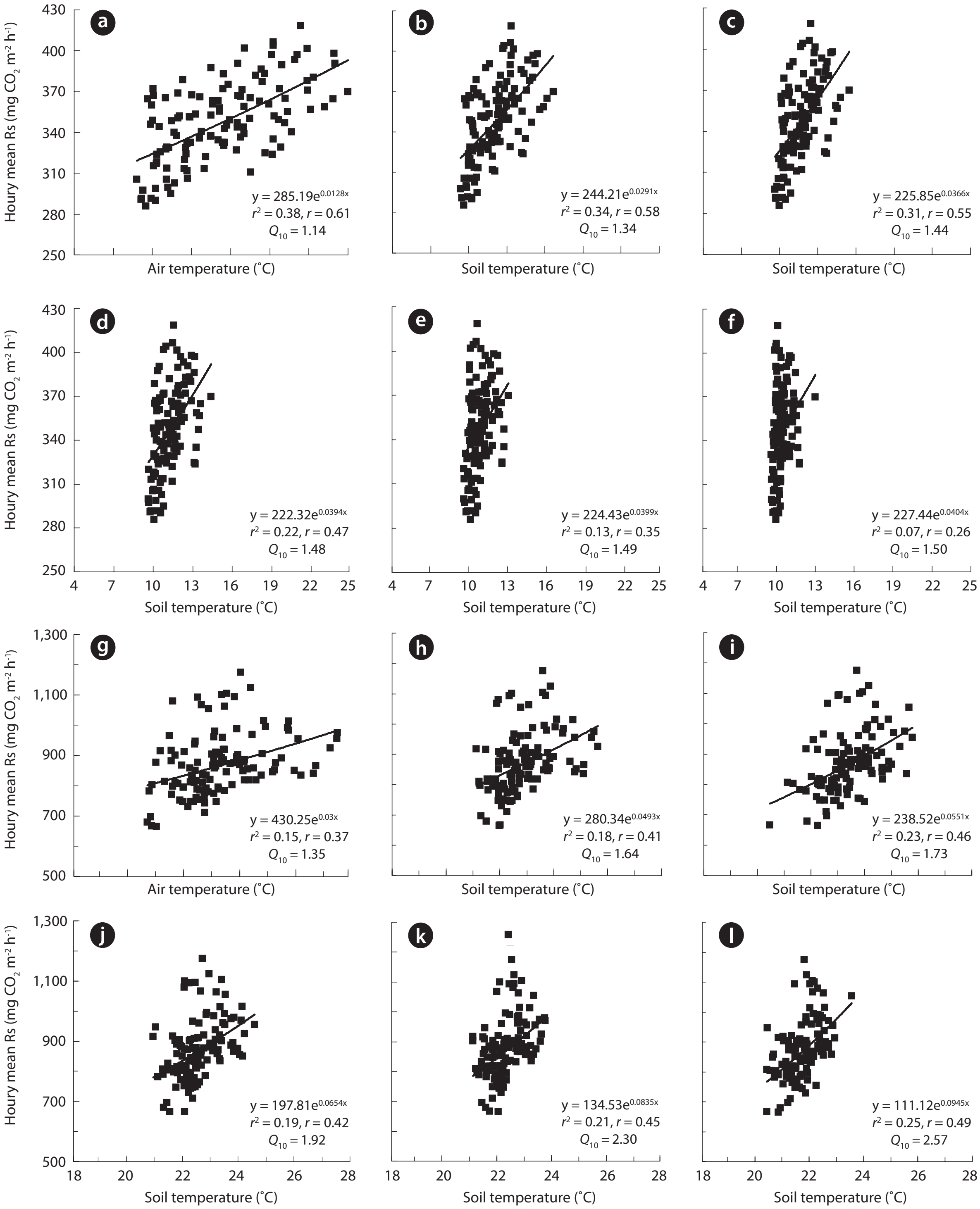

Fig. 5. Relationship between hourly mean soil respiration rate and air (Ta) (a and g) and soil temperatures (Ts) (b-f and h-l) at depths of 0, 2, 5, 10, and 20 cm during the spring season, May 19-31, 2005 (a-f) and in the summer season, July 30-August 9, in the same year (g-l). Soil respiration rate (Rs) was significantly positively correlated with Ta and Ts at each soil depth ($N = 121$, $P < 0.001$).

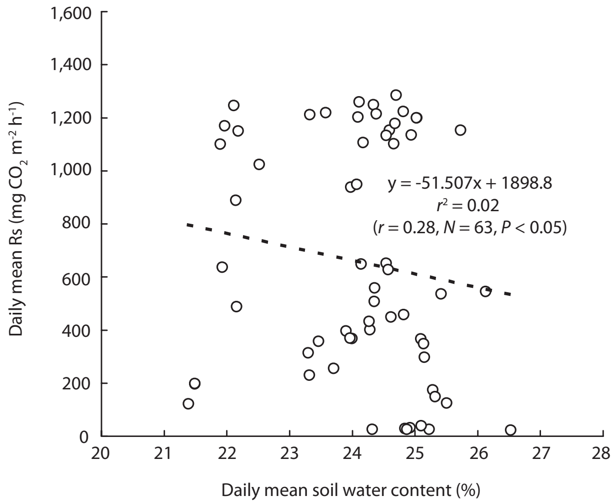

Fig. 6. Relationship between daily mean soil respiration (Rs) and soil water content at a 0-30 cm depth during the summer season in 2005. Mean soil water content was 24.1% during this season.

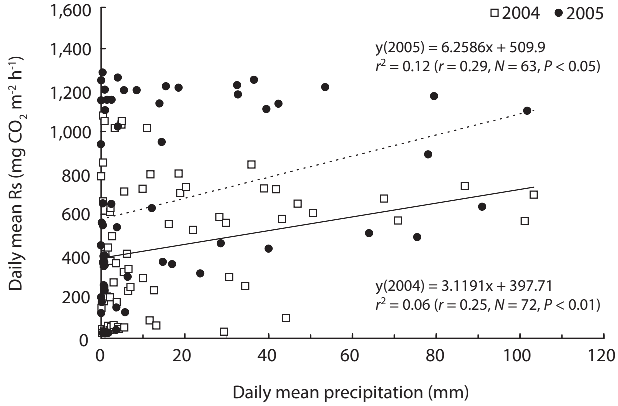

Fig. 7. Relationship between daily mean soil respiration rate (Rs) and precipitation in 2005. Data were selected only for precipitation levels > 0.1 mm.

of the annual rainfall in the study area in 2004 and 2005, respectively (Fig. 1a). From these results, it was determined that the SWC was sustained at an approximate average of 24.1% (Fig. 6), although some SWC data were absent. Therefore, because the study area received sufficient precipitation to provide stress-free moisture conditions, the relationship between Rs and SWC may not have been revealed.

Fig. 7 shows the relationship between Rs and precipitation. Rs showed a confounding correlation with precipitation for the full growth season ($r = 0.25$, $P < 0.01$ in 2004 and $r = 0.29$, $P < 0.05$ in 2005). The reason for the weak correlation may also have been due to the drought-free conditions.

Application of the continuous system for Rs measurements

Functions relating soil CO_2 efflux and environmental factors and the various related parameters helps in understanding and predicting soil carbon cycle evolution. However, the task is daunting, because the material cycle is affected by various environmental factors in the ecosystem. Collecting Rs data is generally restricted by various factors such as weather and field conditions (Son and Kim 1996, Kang et al. 2003, Yi 2003, Moon 2004). In particular, measurements in the winter season are impeded by factors such as a relatively low Rs and working conditions that are harsher than those during other seasons. For these reasons, the annual mean Rs or the total amount of soil CO_2 efflux in this study was inaccurately estimated from the use of exponential functions, or this value could not be calculated because of insufficient data for the winter. However, the AOCC system helped collect data under various environmental conditions. Therefore, use of this system affords more sophisticated results than those obtained by the temporal periodic measurement method (Suh et al. 2006).

Although the AOCC system automatically collects continuous data onsite, field conditions may make accurate data collection difficult. Unpredicted events such as abrupt heavy rain or snow, felled trees, and power failures can result in the absence of data. Data collection frequency (used for elucidating different relationships) collected by the AOCC system under various environmental conditions was higher than that obtained with a portable system, although several accidents occurred when using the system. The characteristics in the annual and seasonal datasets were analyzed by comparing Rs values and environmental factors.

We used the AOCC system to collect adequate continuous data to analyze the relationship between Rs and several environmental factors. The results indicated that normal Rs values under various forest conditions cannot be obtained by intermittent measurement systems. Annual Rs can be underestimated because direct measurements in winter are often restricted by various factors. However, soil CO_2 efflux during the dormant season ranges from 10% to 50% of the total annual Rs (Mariko et al. 2000, Brooks et al. 2005, Schindlbacher et al. 2007, Wang et al. 2010).

A simple instrument such as a manually operated portable system was used to obtain normal values such as magnitudes of annually emitted amounts. However, to understand certain characteristics such as seasonal variations and to estimate annual magnitude for the reference respiration of soil CO_2 efflux in several ecosystems, it is necessary to introduce a parallel continuous measurement system into an existing temporal measurement.

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