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ORIGINAL RESEARCH

Annual Variation of Soil Respiration and Precipitation in a Temperate Forest (*Quercus serrata* and *Carpinus laxiflora*) Under East Asian Monsoon Climate

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Abstract The consequence of changing pattern of precipitation on soil CO_2 emission is poorly understood in montane forest ecosystems under monsoon climate in Asia. In this paper, the results of 3-year field measurements are reported on the annual soil respiration (R_s) from a temperate deciduous broad-leaved forest (*Quercus serrata* and *Carpinus laxiflora*) in Korea, and its interannual variations are examined associated with changing precipitation. Based on biweekly chamber measurements from 2001 to 2004, the annual soil CO_2 emission averaged to be 7.8 t C ha^{-1} with an annual variability of ~20%. The soil temperature explained 22–97% of seasonal variations of R_s each year whereas the water-filled porosity (*WFP*) and precipitation pattern had a major effect on the observed interannual variation. The optimum values of *WFP* during the main growing season depended not only on the amount but also on the intensity and frequency of precipitation. These results indicate that the changes in catchment hydrology can significantly alter the carbon sink/source strength of forest ecosystems in monsoon Asia.

Keywords Soil respiration · Precipitation · Soil temperature · Water-filled porosity · Interannual variability · Temperate forest

Introduction

In terrestrial ecosystems, soil respiration (R_s) is a significant component of carbon cycle (Valentni et al. 2000). Based on extrapolations from biome land area and climate-driven regression models, annual estimates of the global R_s are 70 to 80 Pg C year^{-1} (Schlesinger and Andrews 2000; Raich et al. 2002). More than two thirds of the forest carbon is contained in soils and associated peat deposits, particularly in high-latitude forest and soil respiration comprises ~70% of ecosystem respiration (Dixon et al. 1994; Granier et al. 2000; Janssens et al. 2001).

R_s results from (1) autotrophic respiration (by roots and associated mycorrhizae) and (2) heterotrophic respiration (by microorganism and soil fauna that decompose aboveground litter and belowground detritus and soil organic matter; Fang et al. 1998; Hanson et al. 2000). The decomposition rate of organic matter depends primarily on soil temperature (T_s) and soil water content (*SWC*) (e.g., Singh and Gupta 1977; Meentemeyer 1984; Aerts 1997). The former is well-known as the most important factor controlling soil carbon emission whereas the latter is a good predictor under limiting water conditions (Davidson et al. 2000; Law et al. 2001; Rey et al. 2002) but less important under well-watered conditions (e.g., Swanson and Flanagan 2001).

Recently, more studies have focused on the response of soil CO_2 emission to precipitation events, but the results are conflicting. Several explanations on the mechanism through which precipitation affects the soil CO_2 emission are through (1) an increased activity of microorganism and root respiration with the supplement of soil water from rainfall (Orchard and Cook 1983; Borken et al. 1999; Lee et al. 2002, 2004; Huxman et al. 2004; Casals et al. 2009; Inglima et al. 2009; Kim et al. 2010), (2) a decrease in CO_2 diffusivity with increasing water-filled porosity (Sotta et al. 2004; Lee et al. 2008, 2010), (3) the dissolution of CO_2 in the water in soil pores (Rochette et al. 1991; Ball et al. 1999), (4) an increase of anaerobe with decreasing soil

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porosity (Ito and Takahashi 1997), and (5) a degrading soil quality (e.g., clay content, soil compactness, C, and N) with the deformation of soil surface structure (Ball et al. 1999; Borken and Matznen 2009). The results from previous studies suggest that R_s can either increase or decrease depending on the types of precipitation, vegetation, and climate. On the other hand, some studies have reported optimum ranges of soil moisture (e.g., water-filled porosity of 50–60%; Linn and Doran 1984; Mielnick and Dugas 2000), and mechanisms of drying and wetting were studied for the mineralization and fluxes in soils (Borken and Matznen 2009).

Terrestrial ecosystems in East Asia undergo significant influences of summer monsoon climate such as "Changma" (i.e., an intensive and consecutive rainfall period in June or July) and subsequent typhoons accompanying intensive rainfalls between July and September in Korea. The paucity of field data during such intensive and lengthy rainfall periods would cause the annual estimation of soil CO_2 emission to be "monsoon-biased." Considering the likely changes in pattern of precipitation, a clear understanding of the under East Asian monsoon on soil CO_2 exchange is essential. In this paper, annual soil carbon emission from a typical deciduous broad-leaved forest in montane Korea is presented, and the influence of monsoon climate on its interannual variability is examined. R_s was measured biweekly using closed dynamic chamber systems from October 2001 to September 2004.

Material and Methods

Study Site

The soil chamber measurements were made in a natural temperate deciduous broad-leaved forest dominated by *Quercus serrata* and *Carpinus laxiflora* (80 to 200 years old) in Gwangneung forest in the west-central part of Korean Peninsula (37°45′25.37″ N, 127°9′11.62″ E—340 m a.s.l.; Fig. 1). The average tree height was 18 m with a range from 16 to 25 m. The average DBH was 175 mm with a range of 90 to 380 mm. Tree volume was about 550 m^3 ha^{-1}, and the stand biomass was about 225 tons ha^{-1} in Gwangneung forest. The foliage area index (FAI) measured by leaf area meters (LAI-2000, LI-Cor, Inc., Lincoln, NE, USA) reaches the maximum of 5 to 6 in July–August. The slope angle and slope aspect of the measurement area are, respectively, 13° to 15° and NE–E, representing mean characteristics of the forest site. Parent rock type is granite gneiss and the soil type is brown alfisols with depths ranging from 0.38 to 0.66 m. The bulk density and porosity of the surface soil layer (0 to 0.05 m) are 0.86 (±0.08) g cm^{-3} and 0.66 (±0.04), respectively. Soil texture is sandy loam or loam, with 46% sand and 8% silt in surface layer and 50% sand and 13% silt in subsurface layer (Lim et al. 2003).

Figure 2 shows the variations of annual air temperature and precipitation from 1970 to 2004. Also shown is the hourly air temperature and precipitation during this study period observed at the weather station 2 km apart. The normal (i.e., 30 years average) air temperature and precipitation are 11.5 (±0.6)°C and 1,436 (±363) mm, respectively. Annual air temperature (measured on the tower at 29 m above the ground) during the study period (October 2001 to September 2004) was near normal (11.0°C) with daily averages ranging from −16°C (in December) to 28°C (in July). Typically, "Changma" lasts for a month in June or July with intensive rainfalls, followed by typhoons from July to September, resulting in approximately 70% of annual precipitation during June to September (KMA 1995). In relation to the study period, the total amount of precipitation was near normal (1,524 mm) in 2001, below normal (1,264 mm) in 2002, above normal (1,911 mm) in 2003, and normal (1,466 mm) in 2004. Especially, amount of precipitation during 2004 was concentrated in July only, which was very different from those of the other 3 years. The length of Changma was also different for each year—39, 32, 33, and 24 days in 2001, 2002, 2003, and 2004, respectively.

Field Measurements

R_s was measured biweekly at nine sampling locations in the eco-plot (20×30 m), using a closed dynamic chamber system (LI-6400 with LI-6000-9 soil chamber, LI-COR, Inc., Lincoln, NE, USA). The location of this eco-plot was selected to be within the major footprint area for the tower CO_2 flux measurements. In the eco-plot, the depth of litter layer ranges from 20 to 100 mm, and average depth of litter layer was 51 (±29) mm. The soil texture is silt loam, with 38% sand and 59% silt in the nine sampling location. R_s were measured using PVC collars (80 mm in height, 106 mm in diameter) to minimize disturbance. T_s at 0.1 m depth was measured outside each collar using a soil temperature probe (LI-6000-09TC, LI-COR, Inc., Lincoln, NE, USA). *SWC* at 0 to 0.1 m depth was measured by portable soil water content sensor (Hydro Sense, Campbell Scientific Australia Pty. Ltd., Hyde Park, QLD, Australia). Additional sensors for T_s (TCAV, Campbell Scientific, Inc., Logan, UT, USA) and *SWC* (CS615, Campbell Scientific, Inc., Logan, UT, USA) and a rain gauge (TE 525, Campbell Scientific, Inc., Logan, UT, USA) were also installed around the flux tower for continuous measurements. In 2004, automatic opening/closing chamber (AOCC) systems have been also added for long-term measurements, which produced similar results to those from manual chamber measurements (Suh et al. 2006). Detailed information on

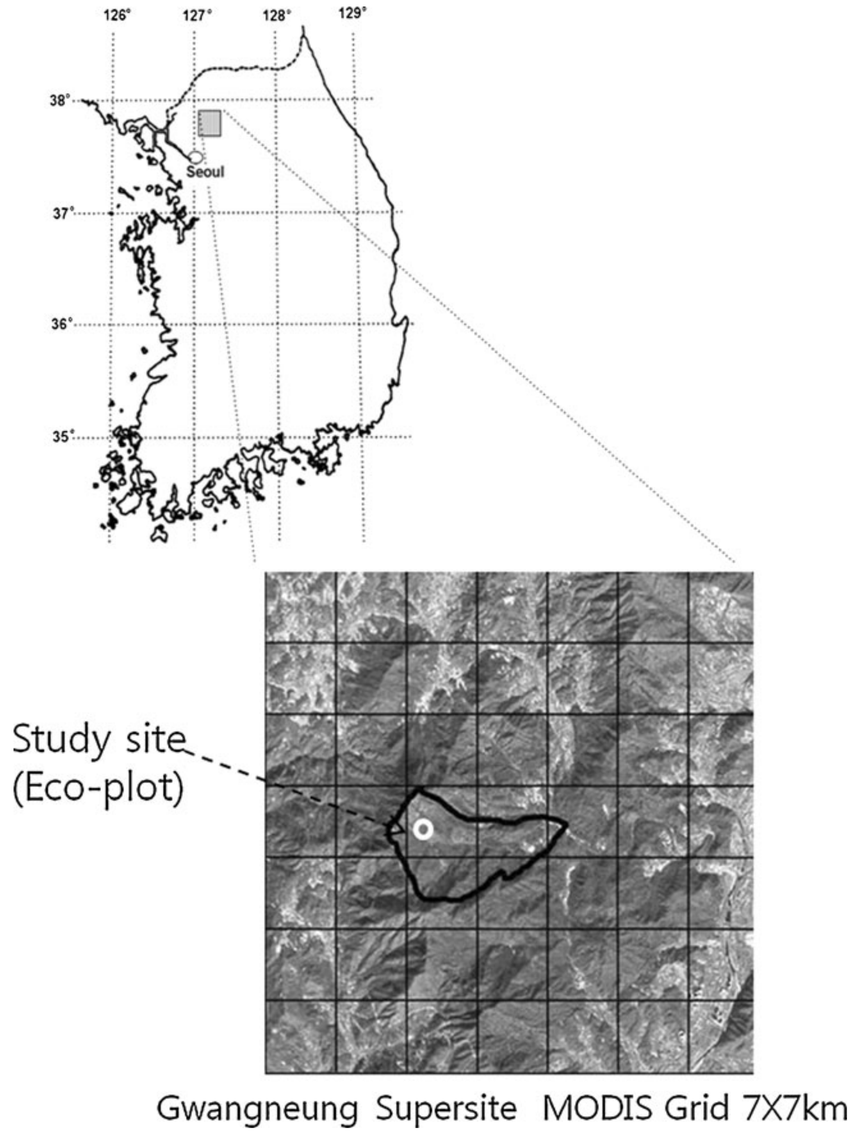

Fig. 1 Map of the location of the study area (modified from Kim et al. 2006)

field operation and calibration of closed dynamic chamber system can be found in Chae et al. (2003).

Gap Filling

To accurately estimate annual soil carbon emission, a gap filling method was used (Falge et al. 2001; Griffis et al. 2003). Daily R_s can be calculated from the fitted equations (Eqs. 1 and 2) that comprise of an exponential function of T_s alone or along with parabolic function of water-filled porosity (*WFP*; defined as volumetric water content divided by soil porosity; Lloyd and Taylor 1994; Mielnick and Dugas 2000). Following Mielnick and Dugas (2000), based on the variable separation method, Eqs. 1 and 2 can be combined as Eq. 3a in a multiplicative fashion. Equation 3a can be rewritten by normalizing the *WFP* term by dividing it by its maximum value such that the *WFP* term ranges from 0 to 1. In Eq. 3b, optimum conditions of *WFP* result in setting the respective factor to 1 and less than optimal conditions reduce it, thus decreasing the R_s (determined by T_s).

$$R_s \approx ae^{bT_s} \tag{1}$$

$$R_s \approx a'(WFP - WFP_{min})(WFP_{max} - WFP)^c \tag{2}$$

$$R_s = \left(ae^{bT_s}\right)\left[a'(WFP - WFP_{min})(WFP_{max} - WFP)^c\right] \tag{3a}$$

$$R_s = \left(ae^{bT_s}\right)f(WFP);\ \text{where} \tag{3b}$$

$$0 \le f(WFP) = \frac{\left[(WFP - WFP_{min})(WFP_{max} - WFP)^c\right]}{[d/(c+1)][cd/(c+1)]^c} \le 1$$

$$\text{and}\quad d = WFP_{max} - WFP_{min}$$

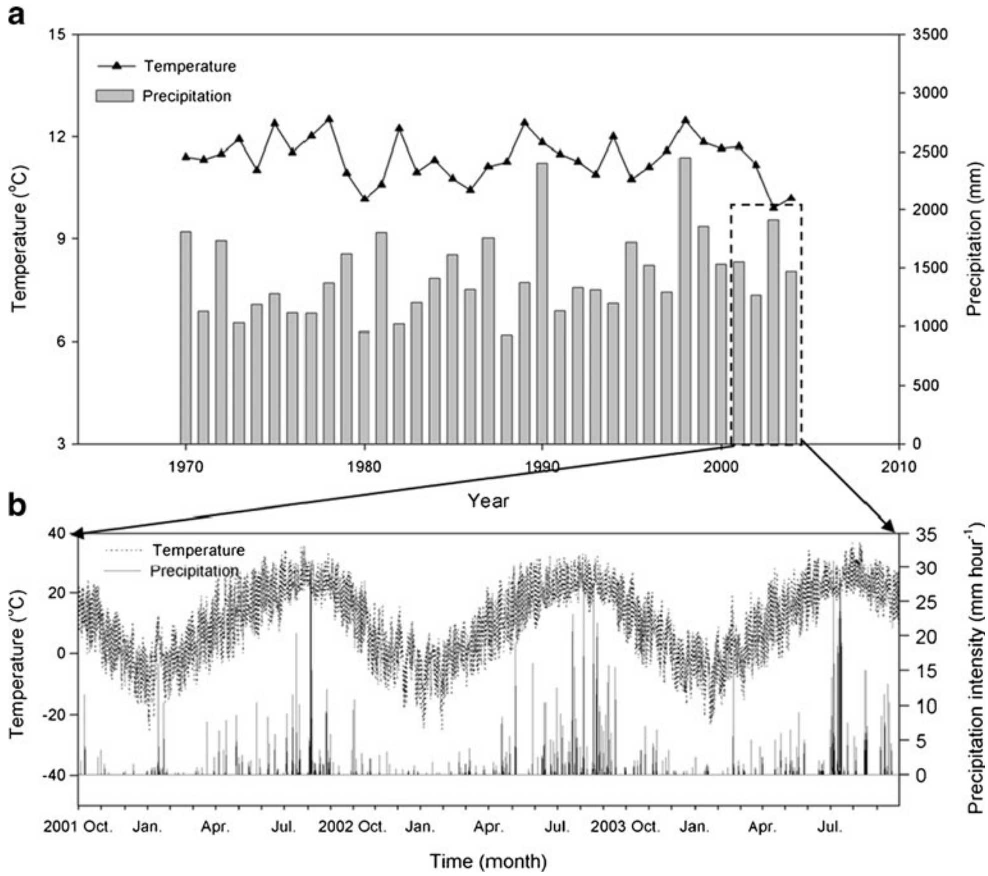

Fig. 2 Annual variation of **a** air temperature and precipitation from 1970 to 2004 and **b** hourly air temperature and precipitation during study period (2001 to 2004) at Gwangneung forest

The coefficients *a*, *a*′, *b*, and *c* were derived from nonlinear least square fittings ($a>0$, $b>0$, $c>0$). Figure 3 shows sensitivity of Eq. 3b to ±25% changes of the coefficients *a*, *b*, and *c*. We used *WFP* of 0.38 for (a) and (b), which is the average, and 25°C for T_s in (c). The relationship between R_s and T_s was evaluated with Eq. 1 using three different methods over the measurement periods. First method was to use whole set of individual values of R_s and T_s of nine locations, second method was to use spatially averaged values of R_s and T_s for nine locations, and third method was to use individual values of R_s and T_s at each location. In addition, the compound effect of T_s and *WFP* on R_s was examined using Eq. 3b. We used T_s at 0.1 m and *WFP* at and 0 to 0.1 m depth obtained from nine measurement locations. Based on actual field observation, WFP_{min} and WFP_{max} are 0.14 and 0.80, respectively. For gap filing, we used daily averages of T_s at 0.1 m and *WFP* at 0 to 0.1 m depth obtained from continuous 30-min measurements near the flux tower.

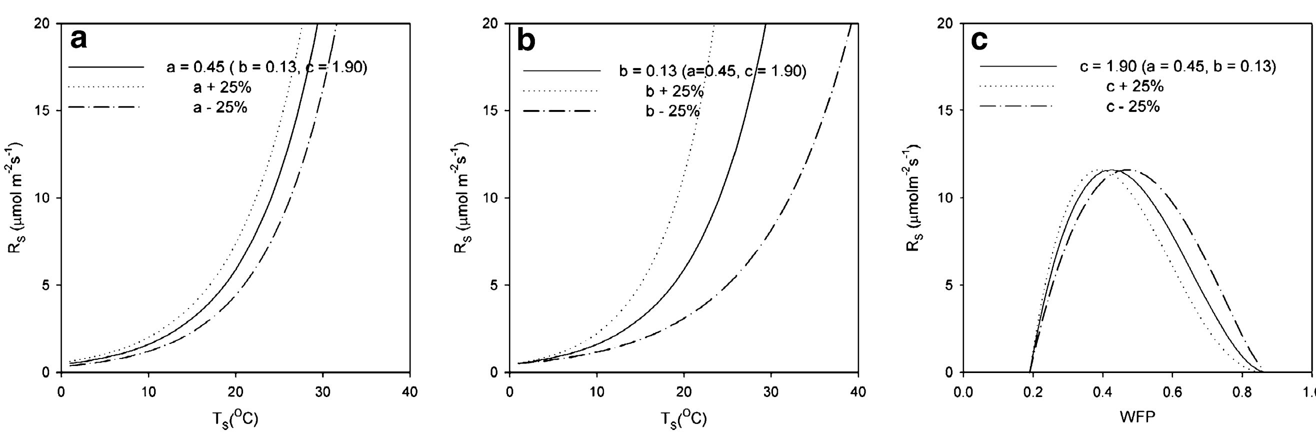

Fig. 3 Sensitivity of Eq. 3b to ±25% changes of the coefficients *a*, *b*, and *c* (*WFP*, 0.38 for **a** and **b**; 25°C for T_s in **c**)

Each year period (from October to September), period I, period II, and period III, was divided into four sub-periods: senescence (October to November), dormancy (December to March), green up (April to May), and main growth (June to September). Then, the relationships between R_s and T_s and *WFP* were evaluated for each period.

Results

Seasonal Variation

Figure 4 shows the seasonal variations of R_s, T_s, *WFP* and solar radiation (*I*) for the 3-year measurement periods. Spatially averaged R_s for nine sample locations ranged from 0.3 to 6.5 μmol m^{-2} s^{-1}. The overall patterns and magnitudes of R_s were similar for the three periods (I, II, and III) and generally followed those of T_s throughout the seasons except for the main growth when the varying effects of soil moisture with changing precipitation played a role, which will be discussed later.

The seasonal variations of T_s showed no significant difference ($p>0.05$) in their magnitudes for the three periods with no phase lags (based on cross-correlation analysis). T_s ranged from −2°C to 23°C with seasonal peaks in late July to early August. The ranges of *WFP* at 0 to 0.1 m layer for the whole study period were from 0.20 to 0.86, which depended on the patterns and types of precipitation encountered during each period (Fig. 4).

The pattern and amount of precipitation were various for three periods. As pointed out earlier, precipitations for the three periods are very different in their total amounts and number of days—1,288 mm and 104 days for period I, 1,867 mm and 127 days for period II, and 1,479 mm and 109 days for period III. Also, period of intensive precipitation for period I and period II was in August, while that of period III was in July. The observed difference was not only the total amount but also the pattern. The size of precipitation intensity was period III>period II>period I and means of those were 2.47, 2.37, and 2.20 mm h^{-1}, respectively. Based on the wavelet power spectrum analysis, the precipitation frequency of the three periods was 1 to 8 days in August for period I, 1 to 2 days in July to August for period II, and 8 to 16 days (with 3 to 5 days of no rain) for period III. Consequently, characteristic of precipitation in period I was small amount, low intensity, and very intermittent rains except August that in period II was large amount and high frequency from July to September and that in period III was normal amount, high intensity, and intensive rains only in July. The seasonal variation of radiation equaled to that of precipitation. Especially, variation of radiation showed extreme fluctuation from June to August.

Gap Filling

Fitting Using Whole Set of Individual Data

T_s alone explained 63% to 73% and T_s and *WFP* explained 58% to 63% of periods I and II of the variation of whole R_s of individual data for each period (Table 1). For the period III, however, T_s explained only about 17% and T_s and *WFP* explained 14% of the variation mainly due to large scatters of R_s at high T_s and the lack of the observed data at low T_s. The relationship between R_s and T_s for the period III was obtained by fitting the averaged *a* from period I and II. The low R^2 values in Table 1 for whole raw data may be attributed to the inherent spatial variability of 30% to 40% among those nine locations. Such spatial variability would depend on the surrounding environmental factors such as T_s. However, the spatial variation of T_s was small, and thus, we attributed the cause of such variation to the differences in litter layer, distribution of root respiration, physical and chemical characteristics of soil, and soil moisture content. Table 1 summarizes the results of nonlinear least squares fittings of the Eqs. 1 and 3b for the periods I to III.

Fitting Using Spatially Averaged Data for Nine Locations

T_s alone explained 90–97% and T_s and *WFP* explained 94% to 95% of periods I and II of the variation of mean R_s for each period (Table 2). The corresponding values of Q_{10} were 3.7 and 3.6, respectively. For the period III, however, T_s explained only about 22% and T_s and *WFP* explained 19% of the variation with Q_{10} of 2.0. R^2 for averaged data for nine locations were above 0.9 for two Eqs. 1 and 3b for periods I and II. We found that R^2 of period II improved when using Eq. 3b.

Fitting Using Individual Data for Each Location

For individual values for each location, the effects of *SWC* on R_s in terms of *WFP* were clearly identified during period II when the encountered ranges (0.26–0.61) of *WFP* were sufficiently wide for the regression analyses due to the highest amount and frequency of rainfalls (e.g., 4, 5, 6, and 8 of location). The consideration of *SWC* improved the performance of the regression model during period II only (Table 3). During period I, T_s predominantly explained >90% of the variation of R_s due to small ranges (0.20–0.47) of *WFP* as a result of the lowest amount of precipitation among the three periods. The coefficients of period III were not derived from Eq. 3b due to lack of data.

Annual Soil Carbon Emission and Its Interannual Variation

Annual carbon emission was calculated using coefficients in Eqs. 1 and 3b of Table 2 because relationship between

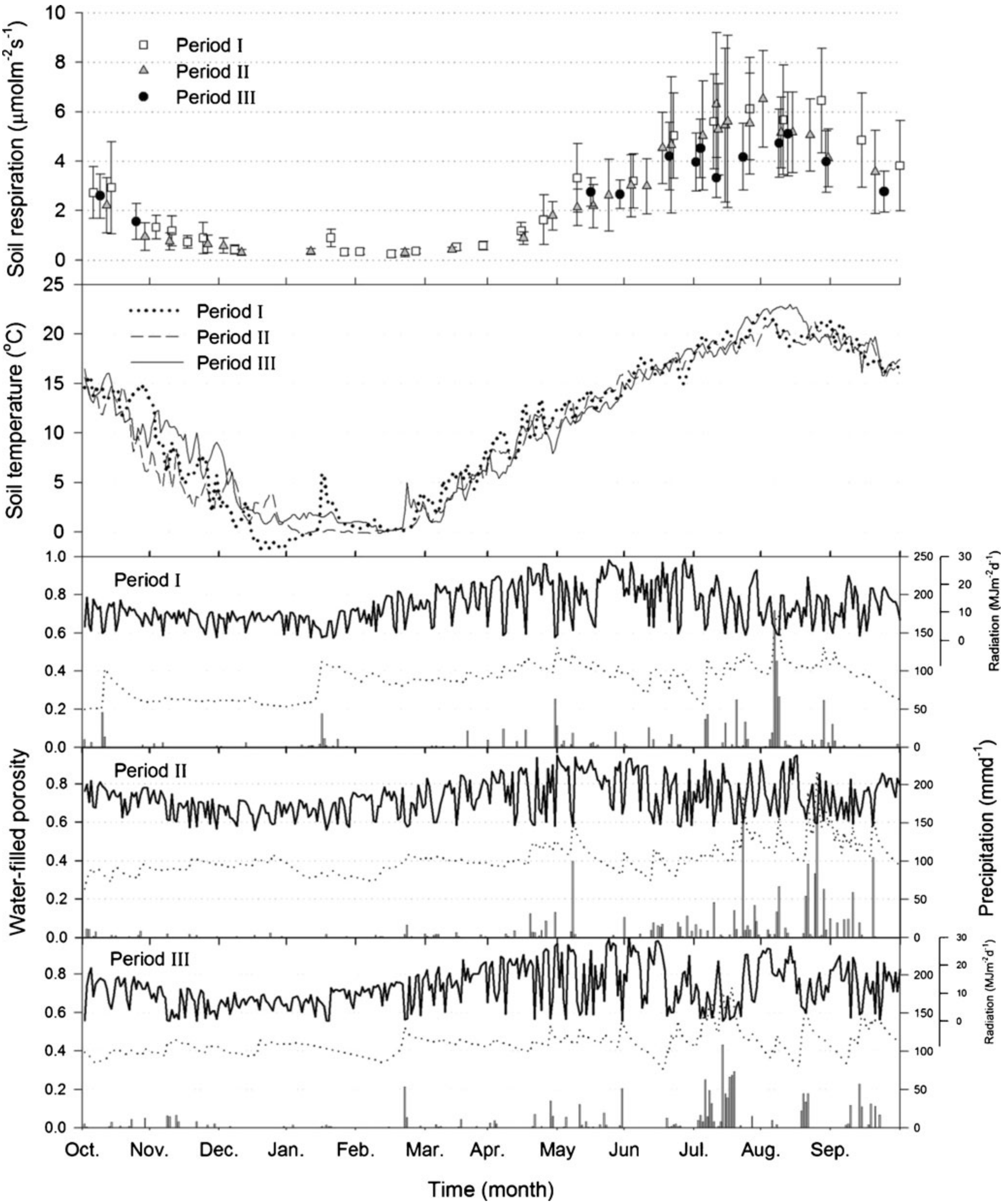

Fig. 4 Seasonal variations of respiration (R_s), soil temperature (T_s), water-filled porosity (*WFP*; *dot line*), precipitation (*vertical bar*), and radiation (*solid line*) from October 2001 to September 2004 (period I: October 2001 to September 2002, period II: October 2002 to September 2003, period III: October 2003 to September 2004)

Table 1 Coefficients for the relationship of whole set soil respiration (R_s) of individual data with soil temperature (T_s) and water-filled porosity (*WFP*) and values of R^2 for each period I to III (numbers in parenthesis are standard errors)

Raw R_s		*a*	*b*	*c*	R^2	*N*
Equation 1	Period I	0.36 (0.05)	0.14 (0.01)		0.73	229
	Period II	0.36 (0.07)	0.13 (0.01)		0.63	258
	Period III	0.36[a] (–)	0.12 (0.00)		0.17	106
Equation 3b	Period I	0.39 (0.09)	0.14 (0.01)	1.97 (0.17)	0.63	183
	Period II	0.46 (0.10)	0.13 (0.01)	1.00 (0.09)	0.58	252
	Period III	0.43[a] (–)	0.15 (0.00)	2.12 (0.22)	0.14	106

[a] Values are averaged *a* from those of period I and II

spatially averaged data explain the most realistically among three methods (Table 4). Annual emissions of soil carbon during period I, period II, and period III were 810 to 914, 838 to 856, and 625 to 626 g C year^{-1}, respectively. However, uncertainty of period III for the annual carbon emission may be considered according to low R^2. Soil carbon emission peaked usually between late July and early August, and soil emission for main growth amounted ~70% of the annual emission. Interannual variation for R_s during the 3-year period was estimated to be 16~19%. Especially, annual carbon emission of period III contributed to large range of variation.

Discussion

Magnitudes of Soil Carbon Emission For the temperate broad-leaved and mixed forests located in 34~38° latitude, the reported range of annual soil carbon emission by *Quercus* spp. is from 530 to 1,400 g C m^{-2} (Raich and Schlesinger 1992). The average annual soil carbon emission of temperate deciduous forest (including mixed forest) is 647± 51 g C m^{-2} (Raich and Schlesinger 1992). In Gwangneung forest, annual soil carbon emission is 625~914 g C m^{-2}, which is greater than the average soil carbon emission reported in the literature. For example, Mo et al. (2005) reported soil carbon emission of 695~770 g C m^{-2} year^{-1} from a temperate deciduous broad-leaved forest in Japan under similar climate conditions, which is slightly lower than those from Gwangneung forest.

Interannual Variation Coefficient of variation (CV) for R_s during the three periods is estimated to be about 16% to 19%. Such annual variability is in the upper range of those (i.e., 1–10%) reported from multi-year observations in other forests (Ohashi et al. 1999; Valentni et al. 2000; Borken et al. 2002; Mo et al. 2005). In particular, soil carbon emission during the period III decreased by 170 to 288 g C m^{-2} year^{-1}, compared to that of the periods I and II.

Effect of Precipitation and Water-Filled Porosity The rainfalls during the main growth accounted for 66% to 75% of the annual rainfall during the study period. Similarly, R_s during the main growth also accounted for 60% to 70% of the annual soil carbon emission. The rainfall amount and number of rainy days during the 4-month period of main growth from periods I to III were, respectively, 750 mm for 39 days, 1,197 mm for 49 days, and 990 mm for 35 days, indicating that period III had the most intensive rainfalls. Probably because of such different patterns and distribution of rainfalls, the relationship of R_s with T_s and *WFP* in period III was not as robust as those in period II. Such

Table 2 Coefficients for the relationship of spatially averaged soil respiration (R_s) with soil temperature (T_s) and water-filled porosity (*WFP*) and values of R^2 for each period I to III (numbers in parenthesis are standard errors)

Mean R_s		*a*	*b*	*c*	R^2	*N*
Equation 1	Period I	0.35 (0.05)	0.14 (0.01)		0.97	25
	Period II	0.41 (0.10)	0.13 (0.01)		0.90	29
	Period III	0.38[a] (–)	0.11 (0.00)		0.22	13
Equation 3b	Period I	0.36 (0.09)	0.14 (0.01)	2.18 (0.30)	0.94	21
	Period II	0.45 (0.09)	0.13 (0.01)	1.33 (0.10)	0.95	29
	Period III	0.41[a] (–)	0.11 (0.00)	1.86 (0.60)	0.19	13

[a] Values are averaged *a* from those of periods I and II

Table 3 Coefficients for the relationship individual soil respiration (R_s) of each location with soil temperature (T_s) and water-filled porosity (*WFP*) and values of R^2 for period I and II (numbers in parenthesis are standard errors)

Individual R_s	*a*		*b*		*c*		R^2	
	Period I	Period II	Period I	Period II	Period I	Period II	Period I	Period II
Equation 1								
1	0.50 (0.12)	0.29 (0.06)	0.13 (0.01)	0.14 (0.01)			0.91	0.94
2	0.30 (0.08)	0.28 (0.06)	0.13 (0.01)	0.15 (0.01)			0.90	0.95
3	0.37 (0.10)	0.45 (0.11)	0.16 (0.01)	0.14 (0.01)			0.93	0.92
4	0.85 (0.24)	1.29 (0.65)	0.11 (0.01)	0.09 (0.03)			0.82	0.49
5	0.40 (0.06)	0.22 (0.07)	0.13 (0.01)	0.17 (0.02)			0.96	0.94
6	0.29 (0.04)	0.27 (0.06)	0.13 (0.01)	0.14 (0.01)			0.96	0.93
7	0.22 (0.05)	0.25 (0.08)	0.13 (0.01)	0.14 (0.02)			0.92	0.87
8	0.24 (0.06)	0.32 (0.11)	0.14 (0.01)	0.12 (0.02)			0.92	0.79
9	0.15 (0.04)	0.22 (0.06)	0.17 (0.01)	0.15 (0.02)			0.95	0.91
Equation 3b								
1	0.60 (0.15)	0.45 (0.09)	0.13 (0.01)	0.12 (0.01)	2.24 (0.29)	1.03 (0.12)	0.93	0.94
2	0.39 (0.14)	0.40 (0.10)	0.13 (0.02)	0.13 (0.01)	4.48 (0.65)	1.32 (0.19)	0.88	0.93
3	0.60 (0.23)	0.78 (0.23)	0.14 (0.02)	0.12 (0.02)	2.03 (0.37)	1.33 (0.15)	0.87	0.88
4	1.10 (0.55)	1.01 (0.50)	0.10 (0.03)	0.13 (0.03)	2.73 (0.58)	2.71 (0.35)	0.63	0.73
5	0.49 (0.18)	0.23 (0.05)	0.12 (0.02)	0.17 (0.01)	1.17 (0.24)	0.93 (0.07)	0.89	0.97
6	0.36 (0.09)	0.32 (0.03)	0.12 (0.01)	0.13 (0.01)	1.36 (0.23)	1.29 (0.07)	0.92	0.98
7	0.18 (0.06)	0.36 (0.12)	0.16 (0.02)	0.12 (0.02)	2.08 (0.23)	0.74 (0.12)	0.92	0.85
8	0.30 (0.12)	0.31 (0.09)	0.14 (0.02)	0.13 (0.02)	1.73 (0.38)	1.57 (0.18)	0.92	0.86
9	0.44 (0.22)	0.36 (0.11)	0.14 (0.02)	0.13 (0.02)	0.85 (0.13)	1.27 (0.29)	0.87	0.90

combination of dry and wet spells, the very characteristics of monsoon climate, restrained R_s by 30% to 50% during main growth less than those of periods I and II.

Considering the potential effect of changing pattern of precipitation (including soil moisture) in monsoon climate of East Asia, it is worth further examining Eq. 3b. Based on the use of Eq. 3b, the optimum values of *WFP* for periods I to III were 0.35, 0.43, and 0.39, respectively. The effect of *WFP* on R_s is clearly seen in period II when the *WFP* data were ample with a wide range of soil moisture content. Furthermore, data from individual collars yielded improved R^2 values when Eq. 1 was replaced by Eq. 3b (e.g., locations 4, 5, 6, and 8 of period II). Similar improvement by the inclusion of *WFP* was also obvious for the mean data during period II.

Mechanism of Reduction in R_s The consecutive, intense rainfalls would block soil pores, disturb CO_2 diffusion, and then restrain the activity of microorganism and dissolution of CO_2 with reduced oxygen supply, causing reduction in R_s. This mechanism is further supported by high FAI, fallen leaves, and litter layers. Forest canopy with high leaf area index would significantly intercept rainfalls and provide slow but steady water flow into the soil without soil evaporation. The litter layers may have hindered soil evaporation and enhanced anaerobic conditions in the soil,

Table 4 Soil carbon emission of each period, soil respiration (R_s; grams of carbon per square meter) and controlling factors, soil temperature (T_s; degree Celsius), water-filled porosity (*WFP*), and precipitation (*P*; millimeters)

Period	I					II					III				
Equations 1 and 3b	R_s		T_s	*WFP*	*P*	R_s		T_s	*WFP*	*P*	R_s		T_s	*WFP*	*P*
Sub-period	914	810				856	838				625	626			
Senescence	109	58	10.4	0.26	91	90	76	8.3	0.35	64	82	87	10.9	0.40	108
Dormancy	60	50	1.7	0.32	92	68	64	1.8	0.37	80	63	66	2.3	0.42	116
Green up	120	120	11.8	0.42	217	119	121	11.3	0.43	236	80	84	10.6	0.45	223
Main growth	625	582	18.7	0.39	750	579	577	18.4	0.47	1197	400	389	19.0	0.47	990

resulting in slowdown of the rate of decomposition. Especially, very wet layer of fallen leaves and litters in turn obstructs gas exchange between soil and the atmosphere. Hence, the distribution of vegetation and the conditions of soil surface in Gwangneung could result in significant suppression of soil carbon emission from the forest floor. Lee et al. (2010) reported same results at Gwangneung forest in the summer of 2006, and they suggested that possibility of suppression of soil carbon was saturation of the soil pore spaces. Recently, Borken and Matznen (2009) studied to evaluate mechanisms, the intensity, duration, and frequency of drying and wetting for the mineralization and fluxes of C and N in terrestrial soils. They suggest that hydrophobicity of organic surface is an important mechanism that reduces C and N mineralization in top soils after precipitation.

Further examination of the annual carbon emission from the forest floor for each period suggests that soil CO_2 emission in period I was determined predominantly by T_s because of relatively low amount and frequency of rainfalls that may have resulted in *WFP* near optimum. However, frequent rainfalls and the consequent short-term changes in soil moisture in period II revealed the effect of soil moisture clearly through positive and negative mechanisms expressed in Eq. 3b. Compared to periods I and II, the amount of rainfall in period III was intermediate, and the amount of total carbon emission was 23% to 32% less than other two periods. The reasons for the decreased R_s in period III that were not explained fully by T_s and *WFP* may be attributed to (1) different patterns of rainfalls and the consequent conditions of *WFP* and solar radiation and (2) potential role of thick layer of litters covering the floor surface. The first reason is mainly caused by the unique rainfall distribution that resulted in dry spells in June and August with wet July of intense and continuous rainfalls. The prolonged 21 days (except 2 days) of rainfalls amounting to 614 mm (42% of total amount in 2004) may have inhibited evaporation from the litter surface, thereby isolating the surface soil layer from the overlying atmosphere through wet litter layer. This is further supported by the different amount of solar radiation. During July of period III, very low amount of solar radiation (1 to 2 MJ m^{-2} day^{-1}) persisted and thus hindered evaporation from litter layer of excess water. The following period from late July to mid August was unusually dry with only about 30 mm rainfall for 25 days. The soil and litter layer dried out under strong solar radiation and the decreasing *WFP* influenced R_s significantly.

Concluding Remarks

The objectives of this study were to quantify the annual soil carbon emission from a typical deciduous broad-leaved forest in central Korea and examine the influence of monsoon climate on its interannual variability. The estimated annual R_s for the 3-year periods varied, depending on the integration methods. It ranged from 625 to 914 g C m^{-2} $year^{-1}$ when estimated as a function of T_s only. However, its variability decreased (626 to 838 g C m^{-2} $year^{-1}$) when R_s was estimated as the function of both T_s and *WFP*. Regardless of the integration methods, the interannual variability in R_s at Gwangneung forest was consistent with an order of ~20%. However, such an interannual variability was not caused by the changes in T_s but associated with altered magnitude, frequency, and duration of the summer rainfalls.

For both individual location data and their spatially averaged data, the effects of *SWC* on R_s in terms of *WFP* were clearly identified during the period II when the encountered ranges of *WFP* were sufficiently wide for the regression analyses due to highest amount and frequency of rainfalls. The consideration of *SWC* improved the performance of the regression model during the period II only. During the period I, T_s predominantly explained >90% of the variation of R_s due to small ranges of *WFP* as a result of the lowest amount of precipitation among the three periods. During the period III, however, the variations of R_s could not be explained by those of T_s and/or *WFP*, implying the potential effect of additional factors. The period III was notable with recurring dry and wet spells, which are the typical characteristics of monsoon climate. The coincidence of the timing of the dry spell and the following excessive rainfalls had significantly affected the annual R_s during this period.

Under varying monsoon climate, understanding of changing characteristics of precipitation is required for a realistic assessment of soil carbon emission. Consequently, both qualitative and quantitative understanding of amount, pattern and persistence of precipitation, the subsequent amount of water contents in the litter and soil layers, and their relationships with microclimate variables (e.g., radiation, temperature, humidity) must precede accurate assessment of R_s. In order to clarify the role of monsoon climate in carbon cycle under different scenarios, the relationship between precipitation and *SWC* needs to be clearly understood by improving the observation of precipitation and by partitioning into intercepted precipitation and throughfall. Understanding of carbon and water exchanges in a complex landscape such as Gwangneung forest requires rigorous theoretical and experimental approaches and interdisciplinary efforts.

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