落葉樹林における土壌呼吸に地形の及ぼす影響

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Topographical Effects on Soil Respiration in a Deciduous Forest —The Case of Weathered Granite Region in Southern Kyoto Prefecture—

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Abstract

We monitored soil respiration at a valley bottom and a ridge above that valley in an experimental forest and quantitatively estimated the effect of topography on soil respiration. Compared to the valley bottom, the ridge showed a lower rate of soil respiration in summer and a higher rate in winter; the seasonal difference was caused by soil drying in summer and soil warmth in winter. Both the valley bottom and ridge had annual soil respiration rates of approximately 6.2 tC ha^{-1} $year^{-1}$. However, the annual value for the ridge included the estimated respiration acceleration due to warm soil temperature (0.68 tC ha^{-1} $year^{-1}$) and deceleration caused by soil drying (0.62 tC ha^{-1} $year^{-1}$).

Key words: Soil moisture ratio, Soil respiration, Soil temperature, Weathered granite.

1. Introduction

Previous studies, such as those by Davidson *et al.* (2002), Kominami *et al.* (2003, 2005), and Sugawara *et al.*, (2005), have compared soil respiration rates to tower–based flux measurements to estimate the amount of carbon uptake of a forest. However, in such comparisons, the soil respiration rate must represent as large an area as that represented by the tower-based flux, even though soil respiration varies spatially due to many factors. Topography is one of the factors affecting the spatial variation of soil respiration.

Studies on the spatial variation of soil respiration on slopes have been performed in many forest types, including Japanese cedar forest (Ohashi *et al.*, 2007), Japanese cypress forest (Mitani *et al.*, 2006), mixed Japanese cedar and cypress forest (Shimono *et al.*, 1989), deciduous broadleaf forest (Hanson *et al.*, 1993; Jia *et al.*, 2003), and tropical rainforest (Sotta *et al.*, 2006; Kosugi *et al.*, 2007). The slope heights in these studies varied widely between 7 and 120 m, and most of the studies reported that soil respiration rates were lower on the lower parts of the slopes. Jia *et al.* (2003), Mitani *et al.* (2006), and Kosugi *et al.* (2007) noted that a higher soil moisture ratio is one of the reasons for decreased soil respiration on lower slopes.

In the weathered granite region of Japan, forests have undergone excessive harvesting and litter collection for more than 1,000 years. While these areas have revegetated over the past 130 years, resulting in the current forest coverage, the forest soils are immature and contain very little organic carbon. Contrary to previous studies such as those by Jia *et al.* (2003), Mitani *et al.* (2006), and Kosugi *et al.* (2007), Tamai *et al.* (2005a) reported that soil respiration was lower in areas of higher topography due to drier soil in deciduous forests of the weathered granite region.

To address this issue, we examined the effect of soil temperature and moisture on the difference in soil respiration between ridge and valley bottom locations in a deciduous forest in the weathered granite region of Japan.

2. Site description

The observations took place in the Yamashiro Experimental Forest in southern Kyoto Prefecture,

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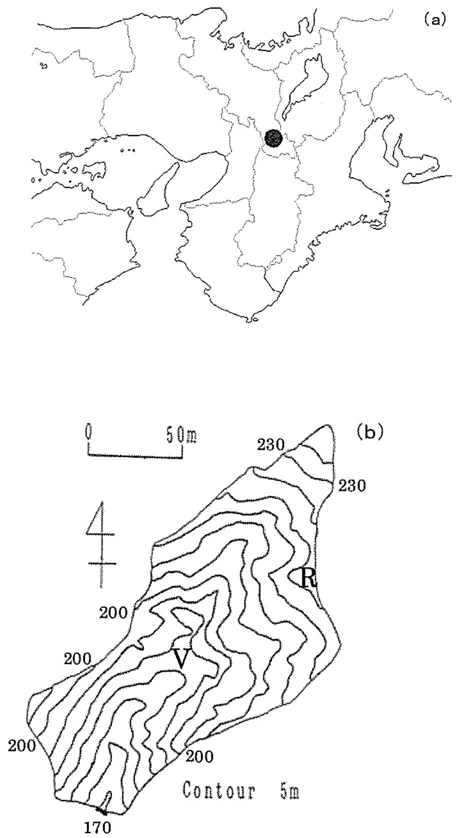


Fig. 1. Location and Topography of the Yamashiro Experimental Forest and plot locations.
(a) Location of the Yamashiro Experimental Forest.
●: Yamashiro Experimental Forest.
(b) Site topography and plot location.
R: Plot R, V: Plot V.
Numbers 170-230:altitude(m).

Japan (Fig. 1(a); 34°47′ N, 135°50′ E). The surrounding and experimental forest had been denuded by heavy logging and remained as bare land until the late 19th century, when reforestation and forest rehabilitation occurred. Most of the trees planted at that time have died, and currently deciduous forest dominated by oaks covers the area. In 1999, Goto *et al.* (2003) determined the total basal area and aboveground biomass of stems with a diameter at breast height (DBH) greater than 3 cm to be 20.7 m^2 ha^{-1} and 105.05 t ha^{-1}, respectively. The average litter fall from 1999 to 2002 was 5.16 t ha^{-1} $year^{-1}$, with a mean air temperature of 15.5℃, warmth index of 125.6℃ month, and annual precipitation of 1,449.1 mm (Goto *et al.*, 2003). The soils are Regosols of sandy loam or loamy sand and contain fine granitic gravel (53% by weight). The average soil depth is 47 cm (Kaneko *et al.*, 2007).

Tamai *et al.* (2005a) recorded soil respiration for 360 colors of soil in the Yamashiro Experimental Forest and reported that the following equation could be adapted to whole of this experimental forest, regardless of topography:

$$F_c = 0.0566EXP\,(0.0717T_s)\left(\frac{\theta}{0.1089+\theta}\right) \quad (1)$$

where F_c is soil respiration (mg CO_2 m^{-2} s^{-1}), and T_s and θ are the soil temperature (℃) and soil moisture ratio (m^3 m^{-3}), respectively, at 5-cm depth.

3. Methodology

The Yamashiro Experimental Forest is located in a hilly mountainous area and includes an approximately 10-m-wide valley with a 30-m-high ridge (Fig. 1(b)). Plot V was located at the bottom of the valley, while plot R was on a ridge above the valley. Table 1 provides information on plots V and R. The distances between the plots were around 70 m and 30 m, horizontally and vertically, respectively. Soil respiration (F_c), soil temperature (T_s), and soil moisture ratio (θ) were monitored in both plots using an automated chamber system, SS–201A (ROGU DENSHI) and HYDRA (Stevens Vitel), respectively.

The automated chamber system with a closed static chamber of transparent acrylic was used to monitor soil respiration. The inner space of the chamber was 28 cm×13 cm in cross section and 13cm in height. A stainless steel collar was inserted into the soil at 10cm depth, and a motor opened and closed the chamber lid automatically (Tamai *et al.*, 2005b). An infrared gas analyzer (IRGA; GMT222, Vaisala) and thermocouple enclosed in the chamber monitored the CO_2 concentration ratio and air temperature. Nobuhiro *et al.* (2003) and Tamai *et al.* (2005b) verified the accuracy of this type of enclosed IRGA chamber. The soil temperature and soil moisture ratio were monitored simultaneously at 5-cm depth. No plants were present in the automated chamber. Observations were made from May 2004 to June 2005. Throughout the winter (December-March), the automated chamber was closed for taking measurements at 30-min intervals and then opened and inactive for 150-min intervals.

Table 1. Outline of the observation plots.

Plot	Symbol	Slope direction	Slope angle (°)	Altitude (m)	Dominant species	Basal Area (m^2)	Amount of dry litter (g/m^2)
Bottom of Valley	V	S53°W	2	188	*Ilex macropoda Clethra barvineruis*	0.131	911.2
Top on the Ridge	R	S52°E	18	222	*Prunus verecunda Ilex pedunculosa Quercus glanca*	0.322	725.6

Dominant species and Basal area were investigated around 10 m×10 m square around the automated chamber.

The active and inactive intervals were 12 and 48 min, respectively, for the remaining months. Thus, recording periods for the manual chamber were 30 min from December to March and 12 min for the other months. F_c was monitored by the automated chamber at 1-h intervals in the summer and 3-h intervals in the winter. The analysis in this study is based on the daily average rate.

To investigate spatial variations in the soil respiration rate, measurements were taken around the automated chamber by putting an IRGA enclosed chamber manually onto eight soil collars set around the automated chamber and was inserted into the soil at 5 cm depth. The inner space of the chamber was the circle with 9.1cm diameter in cross section and 13 cm in height (Tamai *et al.*, 2005a). No plants were present in the soil collars. The manual chamber observations were performed 11 times at Plot V and 15 times at Plot R. Manual measurement was performed once or twice a day in the afternoon. The closed time of the manual chamber was 30 min from December to March and 12 min for the other months.

The closed times for the automated and manual chambers were 12 or 30 min; these times are relatively longer than those in other studies (e.g., Mitani *et al.*; 2006, Kosugi *et al.*, 2007). However, we confirmed that the CO_2 concentration in the chamber increased linearly until it was less than 1300 ppm, after which the rate of increase in CO_2 concentration tended to decrease (Nobuhiro *et al.*, 2003). It takes much longer than 12 or 30 min to increase the CO_2 concentration in the chamber to around 1300 ppm in this experimental forest (Nobuhiro *et al.*, 2003). Thus the closed time of 12 or 30 min did not cause underestimation of F_c.

4. Results

Figures 2(a) and 2(b) show the observed F_c at Plots V and R, respectively. F_c was calculated by Eq. (1) in $mgCO_2\ m^{-2}\ s^{-1}$. Thus F_c was translated from $mgCO_2\ m^{-2}\ s^{-1}$ to $mgC\ m^{-2}\ s^{-1}$ in this study. Seasonal variations in F_c in both plots were less than 0.05 $mgC\ m^{-2}\ s^{-1}$. The spatial variation within each plot was large, with the widest range observed in the manual chamber (approximately 0.10 $mgC\ m^{-2}\ s^{-1}$). Nevertheless, the rate recorded by the automated chamber and the averaged rate of the manual chamber data were almost identical in every case. This suggests that the F_c recorded by the automated chamber can be regarded as the soil respiration rate in each plot. Moreover, the observed F_c and the F_c calculated using Eq. (1) agreed so well that they are so close in Figs. 2(a) and (b); their close agreement is also shown in Fig. 3. Although overestimation of calculated F_c was recognized in the range below 0.015 $mgC\ m^{-2}s^{-1}$, the root mean–square errors (RMSEs) were very small, i.e., 2.3×10^{-4} mgC $m^{-2}s^{-1}$ and 2.83×10^{-4} mgC $m^{-2}s^{-1}$ for plots V and R, respectively. The ratios of these RMSEs to the total observed rate were 1.3 and 1.4%, respectively. Moreover, the dot distributions in Figs. 3(a) and (b) are almost the same even in the smaller range of $F_c<$ 0.015 $mgC\ m^{-2}s^{-1}$. Such good agreement demonstrates that Eq. (1) could be adopted successfully for plots V and R. The good agreement can be attributed to the fact that soils in the experimental forest were immature Regosols of sandy loam or loamy sand. Because this soil structure has not fully developed yet, effects other than soil temperature and moisture might be much smaller than in other forests.

The automated chamber was malfunctioning for 58 days in Plot V and 19 days in Plot R during May 2004 and April 2005, respectively. When F_c values calculated by Eq. (1) were substituted for F_c in those cases, the annual respiration rate was 6.20 tC ha^{-1} $year^{-1}$ in Plot V and 6.23 tC ha^{-1} $year^{-1}$ in Plot R.

In summer (June–September), the plots had nearly equal T_s values. However, in winter, Plot V had a lower T_s value than Plot R (Fig. 2(c)). Plot R had lower θ values than Plot V (Fig. 2(d)). Evapotranspiration caused the low soil moisture ratio in summer, especially on the ridge where higher head than other

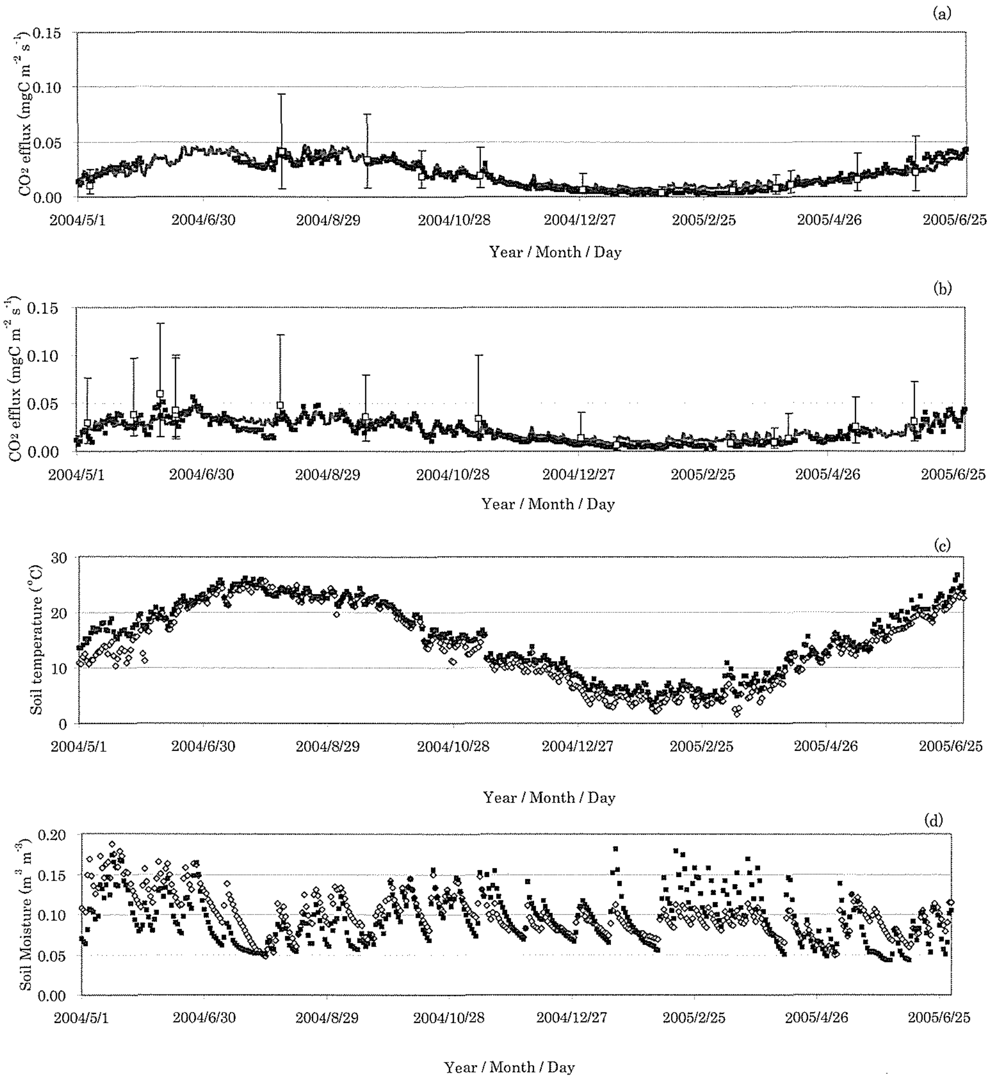
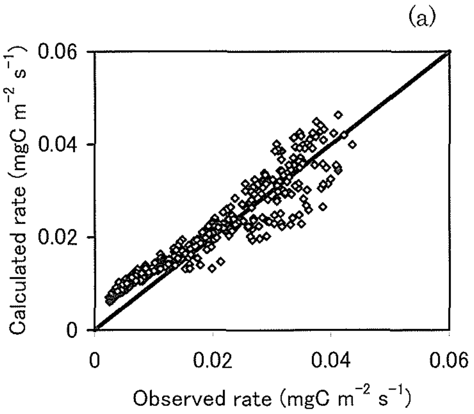


Fig. 2. Seasonal fluctuations in soil respiration, soil temperature, and soil moisture ratio:
(a) F_c fluctuation at Plot V;
Black square: Soil respiration observed by the automated chamber.
Dark line: Soil respiration calculated by Eq. (1).
White square: Averaged soil respiration from the manual chamber observations (bar shows the observed range).
(b) F_c fluctuation at Plot R;
Black square: Soil respiration observed by the automated chamber.
Dark line: Soil respiration calculated by Eq. (1).
White square: Averaged soil respiration from the manual chamber observations (bar shows the observed range).
(c) Soil temperature at 5-cm depth;
White diamond: Plot V, Black square: Plot R.
(d) Soil moisture ratio at 5-cm depth.
White diamond: Plot V, Black Plot R.



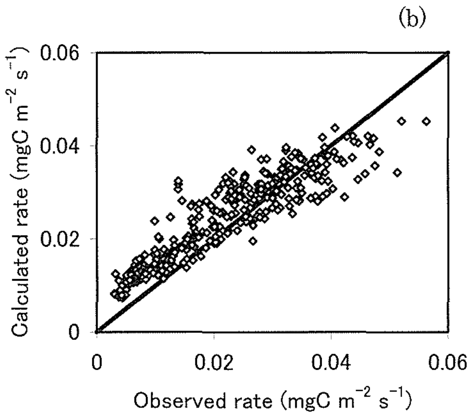


Fig. 3. Comparison of observed and calculated soil respiration rates.
Thick line: isometric line.
(a) Plot V
(b) Plot R

locations is necessary among the total water head to hold the soil moisture.

5. Discussion

5.1. Difference in soil respiration rates between Plots V and R

Figure 4 shows the average difference ($\Delta F = F_{cv} - F_{cr}$) in soil respiration rates between Plots V and R over 5 to 6 days, where F_{cv} and F_{cr} indicate the soil respiration rate in plots V and R, respectively. A white dot indicates that the zero line is not crossed by the standard deviation range. These cases are defined as "recognized difference cases," and the causes of these differences are discussed below.

From November 2004 to March 2005, most of the white dots scatter in the range of −0.005 to 0.000 mgC m^{-2} s^{-1}, indicating that the soil respiration rate in Plot R was slightly higher than that in Plot V. However, from July to September 2004, most of the white dots scatter in the positive area, indicating that the soil respiration rate in Plot V was greater than that in Plot R. The maximum difference of 0.015 mg C m^{-2} s^{-1} was large, considering that the maximum soil respiration rate was about 0.05 mgC m^{-2} s^{-1} (Figs. 2(a) and 2(b)).

5.2. Effects of soil temperature and moisture

The effects of T_s and θ on ΔF_c were estimated by Eq.(2) and (3), respectively.

$$\mathrm{EF}(T_s) = \mathrm{F}(T_{sv}, \theta_r) - F(T_{sr}, \theta_r) \quad (2)$$

$$\mathrm{EF}(\theta) = \mathrm{F}(T_{sr}, \theta_v) - F(T_{sr}, \theta_r) \quad (3)$$

where F (T_{sp}, θ_p) is the rate calculated by Eq. (1), using T_s and θ values in plots V and R. The subscript p denotes Plot V or Plot R.

Figure 5 shows ΔF, EF(T_s), and EF(θ) for the data indicated by white dots in Fig. 4. In winter, between the ↔ in fig.5, the value of ΔF was closer to that of EF(T_s) than to EF(θ). However, EF(θ) fluctuated in synchrony with ΔF, whereas EF(T_s) was almost constant. This indicates that soil respiration in Plot R was higher because T_s in Plot R was higher and that the fluctuation of ΔF on a 5-6 days scale was influenced by a fluctuation of soil moisture ratio on 5-6 days scale.

Except during winter, ΔF was often closer to EF(θ), as shown by ↓ symbol in Fig. 5. Moreover, these values were positive in most cases. These results indicate that the lower soil respiration rate in Plot R in summer was caused by the soil drying on the ridge in this study. This conclusion contradicts previous findings such as reports by Jia *et al.* (2003) and Mitani *et al.* (2006) of lower soil respiration rates in lower topographic locations caused by wetter soil.

5.3. Annual effects of soil temperature and moisture on soil respiration

Here we discuss the annual rates between May 2004 and April 2005. The annual soil respiration rates in plots V and R were almost the same at approximately 6.2 tC ha^{-1} year^{-1}. However, as noted above, differences were recognized between F_c in plots V and R at the shorter time scale. Thus the daily fluctuations of EF(T_s) and EF(θ) are shown in Fig. 6. EF(T_s) was always negative except for a short period in August;

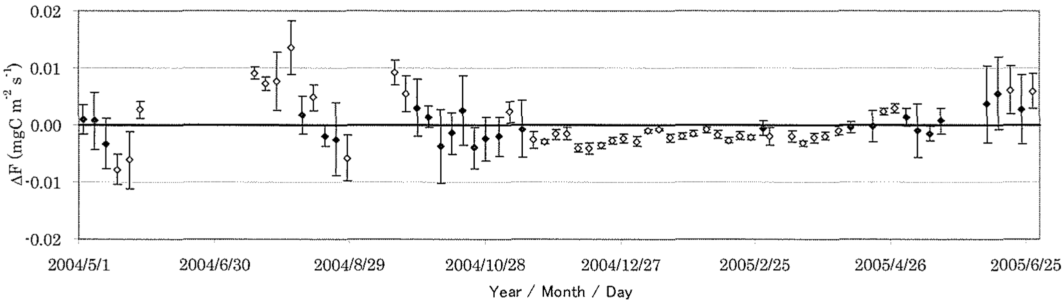


Fig. 4. Seasonal change in the difference in soil respiration between plots V and R.
White diamond: Average difference over 5-6 days with the standard deviation across the zero line.
Black diamond: Average difference over 5-6 days with the standard deviation not to cross the zero line.
Bar: Standard deviation range.

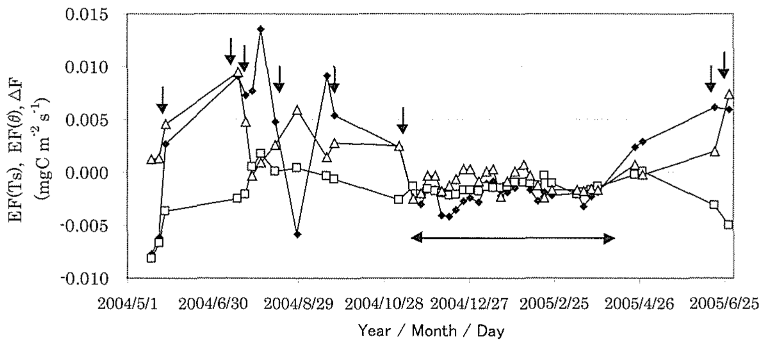


Fig. 5. Effects of soil temperature and soil moisture ratio on differences in soil respiration between the plots.
Black diamond: $\varDelta$F, White square: EF (T_s), White triangle: EF (θ).

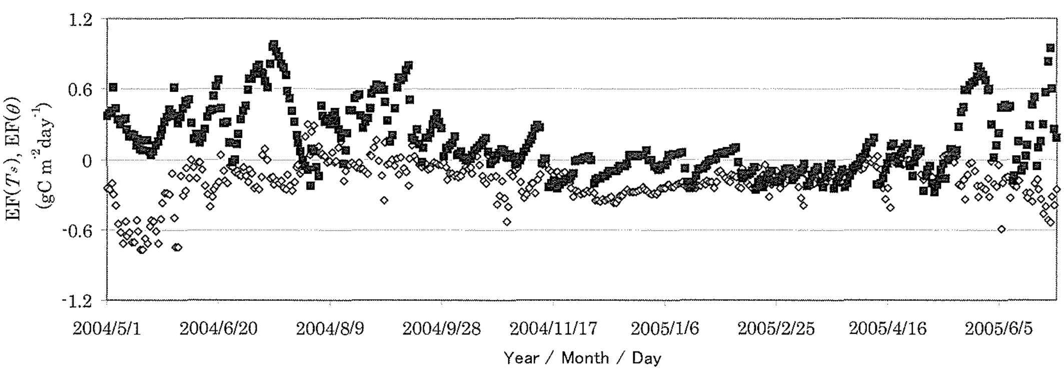


Fig. 6. Seasonal changes in calculated soil respiration differences between the plots, as influenced by soil temperature and moisture.
White diamond: EF (T_s), Black square: EF (θ).

Table 2. Estimated annual effects of soil temperature and soil moisture ratio on the soil respiration differences between the plots.

	Maximum ($gC\ m^{-2}day^{-1}$)	Minimum ($gC\ m^{-2}day^{-1}$)	Sum of Positive rate ($tC\ ha^{-1}day^{-1}$)	Sum of negative rate ($tC\ ha^{-1}day^{-1}$)
EF (T_s)	0.29	−0.77	0.03	−0.68
EF (θ)	0.98	−0.26	0.62	−0.15

however, their effects were supposed to be so small because their absolute values were almost always less than 0.4 gC $m^{-2}day^{-1}$. In contrast, the maximum absolute value of EF(θ) was large at approximately 1.0 gC $m^{-2}day^{-1}$. However, the fluctuation range of EF(θ) was also large, with slightly negative values found in winter. As mentioned above, the fluctuations of EF(T_s) and EF(θ) were too different to compare their effects using their simple annual rates. Thus Table 2 lists the integrated values of negative and positive EF(T_s) and EF(θ), respectively, and their maximum and minimum values.

The integrated value of negative EF(T_s) was −0.68 tC ha^{-1} $year^{-1}$ and that of positive EF(θ) was 0.62 tC ha^{-1} $year^{-1}$. The other two integrated values were small. Thus, low soil moisture ratio in Plot R decreased soil respiration in that plot, while the high soil temperature of that Plot increased the soil respiration there. The annual soil respiration rate in plots V and R were almost the same at approximately 6.2 tC ha^{-1} $year^{-1}$. However, this rate at Plot R includes the effects of acceleration by warm soil temperature (0.68 tC ha^{-1} $year^{-1}$) and deceleration by soil drying (0.62 tC ha^{-1} $year^{-1}$). The values of 0.68 tC ha^{-1} $year^{-1}$ and 0.62 tC ha^{-1} $year^{-1}$ represent about 10% of the annual soil respiration rate. The minimum value of EF(T_s) and the maximum value of EF(θ) reached as large as −0.77 and 0.98 gC m^{-2} day^{-1}, respectively, throughout the year. These differences were large compared to the daily soil respiration rate, indicating that daily differences in the soil respiration rate cannot be ignored.

Thus, our findings suggest that differences in the soil respiration rate caused by soil moisture ratio and temperature amounted to approximately 10% of the annual soil respiration rate. However, Tamai *et al.* (2005a) reported that annual soil respiration rates varied widely from 4.25 to 7.09 tC ha^{-1} $year^{-1}$ in five plots at the Yamashiro Experimental Forest monitored from July 2002 to June 2003. Thus, more test plots and a longer observation period could reveal larger effects.

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References

Davidson, E. A., Savage, K., Verchot, L. V., and Navarro, R., 2002: Minimizing artifacts and biases in chamber-based measurements of soil respiration. *Agric. For. Meteorol.*, **113**, 21–37.

Goto, Y., Kominami, Y., Miyama, T., Tamai, K., and Kanazawa, Y., 2003: Aboveground biomass and net primary production of a broad–leaved secondary forest in the southern part of Kyoto Prefecture, central Japan. *Bull. For. For. Prod. Res. Inst.*, **2**, 115–147 (in Japanese with English abstract).

Hanson, P. J., Wullschleger, S. D., Bohlman, S. A., and Todd, D. E., 1993: Seasonal and topographic patterns of forest floor CO_2 efflux from an upland oak forest. *Tree Physiol.*, **13**, 1–15.

Jia, S., Akiyama, T., Mo, W., Inatomi, M., and Koizumi, H., 2003: Temporal and spatial variability of soil respiration in a cool temperature broad–leaved forest. 1. Measurement of spatial variance and factor analysis. *Jpn. J. Ecol.*, **53**, 13–22 (in Japanese with English abstract).

Kaneko, S., Akieda, N., Naito, F., Tamai, K. and Hirano, Y., 2007: Nitrogen budget of a rehabilitated forest on a degraded granitic hill. *J. For. Res.*, **12**, 38–44.

Kominami, Y., Miyama, T., Tamai, K., Nobuhiro, T., and Goto, Y., 2003: Characteristics of CO_2 flux over a forest on complex topography. *Tellus*, **55B**, 313–321.

Kominami, T., Miyama, T., Tamai, K., Jomura, M., Dannoura, M., and Goto, Y., 2005: Evaluation of nighttime eddy CO_2 flux using automated chamber measurements. *J. Agric. Meteorol.*, **60**, 745–748.

Kosugi, Y., Mitani, T., Itoh, M., Noguchi, S., Tani, M., Matso, N., Takanashi, S., Ohkubo, S., and Nik, A. R., 2007: Spatial and temporal variation in soil respiration in a Southeast Asian tropical rainforest. *Agric. For. Meteorol.*, **147**, 16–34.

Mitani, T., Kosugi, Y., Osaka, K., Ohkubo, S., Takanashi, S., and Tani, M., 2006: Spatial and temporal variability of soil respiration rate at a small watershed revegetated with Japanese cypress. *J. Jpn. For. Soc.*, **88**, 496–507 (in Japanese with English summary).

Nobuhiro, T., Tamai, K., Kominami, Y., Miyama, T., Goto, Y., and Kanazawa, Y., 2003: Development of IRGA enclosed-chamber system for soil CO_2 efflux measurement and its application to a spatial variation measurement. *J. For. Res.*, **8**, 297–301.

Ohashi, M., and Gyokusen, K., 2007: Temporal change in spatial variability of soil respiration on a slope of Japanese ceder (*Cryptomeria japonica* D. Don) forest. *Soil Biol. Biochem.*, **39**, 1130–1138.

Shimono, T., Takeda, H., Iwatsubo, G., and Tsutsumi, T., 1989: Seasonal changes in soil respiration rates from the floor of *Chamaecyparis obtsusa* and *Cryptomeria japonica* plantations. *Bull. Kyoto Univ. For.*, **61**, 46–59 (in Japanese with English summary).

Sotta, E. D., Veldkamp, E., Guimarães, B. R., Paixão, R. K., Ruivo, M. L. P., and Almeida, S. S., 2006: Landscape and climatic controls on spatial and temporal variation in soil CO_2 efflux in an Eastern Amazonian rainforest, Caxiuanã, Brazil. *For. Ecol. Manag.*, **237**, 57–64.

Sugawara, T., Kumagai, T., Ohashi, M., Morooka, T., and Suzuki, M., 2005: Nighttime CO_2 flux over a Bornean tropical rainforest. *J. Jpn. Soc. Hydrol. Water Resour.*, **18**, 64–77.

Tamai, K., Kominami, Y., Miyama, T., and Goto, Y., 2005a: The estimation of time series data for soil respiration based on soil temperature and soil moisture content ratio and its spatial variations in a small mountainous catchment: in the case of weathered granite region in southern Kyoto Prefecture. *J. Jpn. For. Soc.*, **87**, 331–339 (in Japanese with English summary).

Tamai, K., Kominami, Y., Miyama, T., and Goto, Y., 2005b: Temporal fluctuations in the CO_2 efflux on a forest floor—the case of an extremely immature forest soil. *J. Agric. Meteorol.*, **60**, 773–776.

落葉樹林における土壌呼吸に地形の及ぼす影響
—京都府南部の風化カコウ岩地帯における場合—

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要　　約

丘陵状の山地森林小流域における沢底部と尾根部において自動開閉チャンバーによる土壌呼吸量のモニタリング観測を行ない，地形による影響を定量的に評価した。土壌呼吸量は，夏には 沢底部の方が，冬には尾根部の方が多かった。夏には尾根部の土壌が乾燥し，冬には尾根部の地温が高かったためであった。沢底部と尾根部における年間土壌呼吸量は，約 6.2 tC $ha^{-1}year^{-1}$ とほぼ同じであった。しかし沢底部に比べて，尾根部の方が高かった地温による土壌呼吸促進量 0.68 tC $ha^{-1}year^{-1}$ と土壌の乾燥による抑制量 0.62 tC $ha^{-1}year^{-1}$ がほぼ相殺された結果であった。

キーワード：地温，土壌含水，土壌呼吸，風化カコウ岩