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Effects of environmental factors and soil properties on topographic variations of soil respiration

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Abstract

Soil respiration rates were measured along different parts of a slope in (a) an evergreen forest with mature soil and (b) a deciduous forest with immature soil. The effects of soil temperature, soil moisture, and soil properties on soil respiration rates were estimated individually, and the magnitudes of these effects were compared between the deciduous and evergreen forests. In the evergreen forest with mature soil, soil properties had the greatest effect on soil respiration rates, followed by soil moisture and soil temperature. These results may be explained by different properties of soils that matured under different environments. Thus, we argue that the low soil respiration rates in Plot L of the evergreen forest resulted from soil properties and not from wet soil conditions. In the deciduous forest, soil respiration rates were more strongly affected by soil moisture and soil temperature than by soil properties, which were likely due to the immaturity of the forest soil.

1 Introduction

To estimate carbon uptake in forests, several studies have compared soil respiration rates to tower-based flux measurements (Davidson et al., 2002; Kominami et al., 2003; Sugawara et al., 2005). However, for such comparisons to be scientifically robust, the soil respiration rates must represent as large an area as that represented by the tower-based flux. Such a requirement is problematic because many factors, such as topography, can cause substantial spatial variation in soil respiration rates.

Studies of spatial variation have examined factors along broad scales, ranging from several meters (e.g., Kosugi et al., 2007) to a national scale (e.g., Ishizuka et al., 2006). In Japan, most forested areas involve complex terrain. Therefore, the topographic scale is extremely important for comparisons of soil respiration rates and tower-based fluxes.

Soil respiration rates are affected by environmental factors such as soil moisture and soil temperature (Davidson et al., 1998) and soil properties such as root biomass and porosity, etc. (Hanson et al., 2000; Dannoura et al., 2006). Therefore, both the environment and soil properties can affect topographic variation in soil respiration. During the process of soil maturation, most soil properties, such as the carbon content, soil microorganisms, root biomass, and porosity, develop within the context of topographic variation and result from the specific topographic environment at each location. This maturation process is one cause of the topographic variation in soil respiration. To ensure that soil respiration rates represent as large an area as that represented by tower-based fluxes, estimates of the effects of environmental and soil properties are necessary (Fang et al., 1998).

Spatial variation in soil respiration on slopes has been examined in many forest types, including Japanese cedar forests (Ohashi et al., 2007), Japanese cypress forests (Mitani et al., 2006), mixed Japanese cedar and cypress forests (Tamai et al., 2009), deciduous broadleaf forests (Hanson et al., 1993; Jia et al., 2003), and tropical rainforests (Sotta et al., 2006; Kosugi et al., 2007). The slope heights in these studies varied substantially (between 7 and 70 m), but most studies reported lower soil respiration rates in lower parts of the slopes. Jia et al. (2003), Mitani et al. (2006), and Kosugi et al. (2007) argued that decreased rates of soil respiration on lower slopes are caused by higher soil moisture ratios. Similarly, Tamai et al. (submitted) observed that the soil respiration rates in the wetter, basal part of a 70-m-high slope were lower than those in the middle, upper, and top parts of an evergreen forest. However, Tamai et al. (2009) also reported that soil respiration rates increased dramatically after a rainfall event and when soils were in an extreme wet condition. These results suggest that the lower respiration rate at the basal area of the slope was not the direct result of increased soil moisture, which is in disagreement with Jia et al. (2003). Moreover, in a study of a weathered granitic area of southern Kyoto Prefecture, Tamai et al. (2005a) linked lower rates of soil respiration in areas of elevated topography to greater dryness.

Together, these reports suggest that soil respiration rates are affected by many factors in complicated relationships. Therefore, to understand the mechanisms and rates of soil respiration, estimates must be made of the magnitude of the effects of individual environmental and soil property factors on the spatial variation of soil respiration rates. In a secondary broadleaf forest in northern Japan, Hashimoto et al. (2008) examined the spatial variation of environmental factors, such as the soil moisture ratio, and physical factors, such as the basal area of stems and soil respiration. These authors concluded that the basal area of stems potentially affects soil respiration via the soil moisture ratio. Palmroth et al. (2005) measured soil respiration rates in adjacent pine plantations and hardwood areas in the Duke Forest, North Carolina, USA. They reported that differences in soil respiration rates were more strongly controlled by the effects of soil temperature than by soil moisture or soil properties.

In this study, soil respiration rates were measured along different parts of a slope in (a) an evergreen forest with mature soil and (b) a deciduous forest with immature soil. The effects of soil temperature, soil moisture, and soil properties on soil respiration rates were estimated individually, and the magnitudes of these effects were compared between the deciduous and evergreen forests.

2 Site description

The study sites were located in the Yamashiro Experimental Forest (34°47′ N, 135°51′ E) and the Kahoku Experimental Forest (33°08′ N, 130°43′ E) in Japan (Fig. 1a). The Yamashiro forest is a deciduous forest with immature soil, whereas the Kahoku forest is an evergreen forest with mature soil.

2.1 Yamashiro experimental forest

The Yamashiro Experimental Forest was denuded by heavy logging and remained as bare land until the late nineteenth century, when reforestation and forest rehabilitation occurred. Most of the trees planted at that time have died, and the area is currently covered by deciduous forest dominated by oaks. The mean annual precipitation from 1999 to 2002 was 1449.1 mm, with a mean air temperature of 15.5° C (Goto et al., 2003). The soils are Regosols of sandy loam or loamy sand and contain fine granitic gravel (53% by weight). The soil originates from granite and is classified as immature (Araki et al., 1997). Consequently, the surface soil layer at 5-cm depth has carbon ratios ranging from 38 to 42 mg g^{-1} (Table 1).

2.2 Kahoku experimental forest

The lower and upper areas of the Kahoku Experimental Forest are covered by an approximately 50-year-old Japanese cedar (*Cryptomeria japonica*) forest and a 27 to 50-year-old Japanese cypress (*Chamaecyparis obtusa* Sieb. et Zucc.) forest, respectively. Crystalline schist underlies the watershed. The forest soil is classified as brown forest soil (Cambisol) with a clay loam texture. The mean annual precipitation from 1992 to 2003 was 2160 mm, and the mean annual air temperature was 15.4°C (Kobayashi and Shimizu, 2007). Detailed soil information has been provided by Ishizuka et al. (2006). The carbon ratios of the soil surface layer are larger than in Yamashiro, ranging from 78 to 119 mg g^{-1}. Typically, basal area tends to be larger at sites at lower altitude, although the carbon ratio does not reflect this tendency toward association with slope location (Table 1).

3 Observation methodology

3.1 Yamashiro experimental forest

The Yamashiro Experimental Forest is located in a mountainous area and includes an approximately 10-m-wide valley with a 30-m-high ridge (Fig. 1b). Plot V was located at the bottom of the valley, whereas plot R was on a ridge above the valley (see Table for plot details). The distance between plots was approximately 70 m horizontally and 30 m vertically. Soil respiration (F), soil temperature and the soil moisture ratio were monitored in both plots using automated chamber systems, SS-201A (Rogu Denshi) and HYDRA (Stevens Vitel), respectively.

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An automated chamber system with a closed static chamber of transparent acrylic was used to monitor soil respiration. The inner space of the chamber was 28×13 cm in cross section and 13 cm in height. A stainless steel collar was inserted into the soil at 10 cm 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 July 2004 to June 2005. Throughout the winter (December–March), the automated chamber was closed to take measurements at 30-min intervals and then opened and inactive for 150-min intervals. The active and inactive intervals were 12 and 48 min, respectively, for the remaining months. *F* was monitored by the automated chamber at 1-h intervals in the summer and 3-h intervals in the winter. Analyses were based on the daily average rate.

To investigate spatial variation in the soil respiration rate, measurements were taken around the automated chamber by manually placing an IRGA (GMD-20, Vaisala) enclosed chamber onto eight soil collars set around the automated chamber and inserting it into the soil at 5-cm depth. The inner space of the chamber was a circle of 9.1-cm 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 measurements were 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 other months. The closed times for the automated and manual chambers were 12 or 30 min; these time periods were 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 while below 1300 ppm, after which the rate of increase in CO_2 concentration tended to decrease (Nobuhiro et al., 2003). The CO_2 concentration in the chamber takes much longer than

12 or 30 min to increase to around 1300 ppm in this experimental forest (Nobuhiro et al., 2003). Thus, the closed times of 12 or 30 min did not cause underestimation of F.

3.2 Kahoku experimental forest

In Kahoku, Plots T, U, M, and L were established at the top, upper, middle, and base areas, respectively, of a south-facing slope of approximately 70-m height (Fig. 1c). Detailed plot information is provided in Table 1. The soil respiration was measured for 24 soil colors in each plot using the same manual chamber as in Yamashiro. Measurements were performed once or twice a month from August 2005 to August 2006. The closed time of the manual chamber was 30 min from December to March and 12 min for other months. The soil temperature (S-TMB, Onset, USA) and soil moisture (S-SMA, Onset) at 5-cm depth were also monitored. The soil respiration rates presented in this study correspond to the average rates measured for the 24 soil colors in each plot.

4 Analysis method

The soil respiration rate was calculated from the soil temperature and soil moisture using Eq. (1) (e.g., Tamai et al., 2005b; Palmroth et al., 2005):

$$F_p\left(T_p,\theta_p\right) = a\mathrm{EXP}(bT_p)\left(\frac{\theta_p}{c+\theta_p}\right) \qquad (1)$$

where $F_p(T_p,\theta_p)$ is the soil respiration rate (mg CO_2 m^{-2} s^{-1}), T and θ are the soil temperature (°C) and soil moisture ratio (m^3 m^{-3}) at 5-cm depth, respectively, and a, b, and c are constants. The subscript letter denotes the name of the test plot, with p=R, V, T, U, M, or L.

The magnitudes of the effects of soil temperature, soil moisture, and soil properties on soil respiration rates were estimated individually using Eqs. (2), (3), and (4), respectively:

$$EF(T) = F_c(T_t, \theta_c) - F_c(T_c, \theta_c) \quad (2)$$

$$EF(\theta) = F_c(T_c, \theta_t) - F_c(T_c, \theta_c) \quad (3)$$

$$EF(\text{Soil}) = F_t(T_c, \theta_c) - F_c(T_c, \theta_c) \quad (4)$$

where terms with the subscript c and t refer to parameters for the control and test plot, respectively.

Measured values for T and θ and previously determined values for the constants a, b, and c were substituted into the relevant terms in the right-hand side of Eqs. (2)–(4) to estimate the magnitude of the effect of each parameter on the soil respiration rate. For example, to estimate the effect of soil T on the difference in soil respiration rates between the test and control plots, values of a, b, c, and θ for the control plot were substituted into both terms of the right-hand side of Eq. (2). Only values of T for test and control plots were substituted into the first and second terms, respectively, of the right-hand side of Eq. (2). Equation (4) can estimate the effect of soil properties on soil respiration rate because its parameters, a, b, and c, are thought to represent features of the soil properties (Palmroth et al., 2005). Positive, negative, and larger absolute values calculated using Eqs. (2)–(4) imply accelerated, suppressed, and greater influence, respectively, of each factor on the soil respiration rate.

5 Results

5.1 Yamashiro experimental forest

Figures 2a and 2b present seasonal variation in soil respiration rate (F) at Plots V and R, respectively. Spatial variation in F within each plot was large, with the widest range of values recorded in the manual chamber (approximately 0.35 mg CO_2 m^{-2} s^{-1}). Nevertheless, the soil respiration rate recorded by the automated chamber and the average respiration rate of the data from the manual chamber were almost identical in every case. These results suggest that the value for F measured with the automated chamber can be regarded as the soil respiration rate for each plot.

T_R was slightly higher than T_V in winter, and θ_V tended to be slightly higher than θ_R (Fig. 2d). However, this difference was, in general, very small.

Using the minimum total square difference method to estimate the values for the constants in Eq. (1) for Plots R and V, Eq. (1) can be written as Eqs. (5) and (6), respectively:

$$F_R(T_R,\theta_R) = 0.1111\mathrm{EXP}(0.1000T_R)\left(\frac{\theta_R}{0.6752+\theta_R}\right) \quad (5)$$

$$F_V(T_V,\theta_V) = 0.0424\mathrm{EXP}(0.0878T_V)\left(\frac{\theta_V}{0.1368+\theta_V}\right) \quad (6)$$

The rates of soil respiration for Plots R and V, calculated by Eqs. (5) and (6), respectively, agreed well with the measured soil respiration rates (Fig. 3). The root mean square error between calculated and observed respiration rates and the ratio between the two over the average observed ratio were 0.0002 mg CO_2 m^{-2} s^{-1} and 1.1% and 0.0002 mg CO_2 m^{-2} s^{-1} and 1.1% for Plots R and V, respectively.

5.2 Kahoku experimental forest

First, comparisons were made between T and θ in each of the four plots (Fig. 4e and 4f). The results indicated that measured values for T were almost the same in each of the four plots. However, the measured values of θ differed greatly between plots. Plot L generally had the highest θ values, but fluctuated the least within a narrow range of values for θ_L (0.35–0.45 m^3 m^{-3}). The widest range of θ was recorded at Plot T, in which measured values for θ_T ranged between 0.12 and 0.38 m^3 m^{-3}.

Interestingly, whereas rapid increases in θ_U, θ_M, and θ_L were recorded after a precipitation event, no comparable increases in θ_T were measured, particularly during winter. Kobayashi and Shimizu (2007) attributed repellency in forest soil in the Kahoku Experimental Forest to soil dryness. We also propose soil repellency as the reason for the lack of an observed increase in θ_T following a rainfall event during this study. Indeed, soil moisture differed greatly between the four Kahoku plots.

The relationship between F and T contained a large amount of scatter (Fig. 5). The observed values for F in Plots T, U, and M on 27 June 2006 (the dotted circle in Fig. 5) were much greater than other measured soil respiration rates at $T \approx 22^{\circ}$C. This result can be attributed to elevated values of θ at this time: 328 mm of rain fell between 22 and 26 June 2006, and the aforementioned spurious measurements of F were made the day after this precipitation event, when θ would have been very large. The observed value for F in Plot L on 27 June 2006 (shown as Δ in Fig. 5) was also greater than the other observed rates for Plot L.

Using the minimum total square difference method to calculate constants, Eq. (1) can be rewritten as Eqs. (7), (8), (9), and (10) for Plots T, U, M, and L, respectively:

$$F_T(T_T, \theta_T) = 0.0904\mathrm{EXP}(0.0619 T_T)\left(\frac{\theta_T}{0.4648 + \theta_T}\right) \quad (7)$$

$$F_U(T_U, \theta_U) = 0.0464\mathrm{EXP}(0.1049 T_U)\left(\frac{\theta_U}{0.6935 + \theta_U}\right) \quad (8)$$

$$F_M(T_M, \theta_M) = 0.0357\mathrm{EXP}(0.0969 T_M)\left(\frac{\theta_M}{0.4716 + \theta_M}\right) \quad (9)$$

$$F_L(T_L, \theta_L) = 0.0159\mathrm{EXP}(0.0890 T_L)\left(\frac{\theta_L}{0.1989 + \theta_L}\right) \quad (10)$$

The soil respiration rates calculated using Eqs. (7)–(10) agreed well with the observations within the Kahoku plots (Fig. 6). Seasonal changes in soil respiration rates for Plots T, U, M, and L, calculated with Eqs. (7)–(10), are shown in Fig. 4a–d, respectively. The root mean square error between the calculated and observed rates and the ratio of the two over the averaged observed ratio in the four plots were 0.014 mg CO_2 m^{-2} s^{-1} and 14.6%, 0.014 mg CO_2 m^{-2} s^{-1} and 12.7%, 0.005 mg CO_2 m^{-2} s^{-1} and 9.9%, and 0.017 mg CO_2 m^{-2} s^{-1} and 16.6% for Plots T, U, M, and L, respectively.

6 Discussion

The effects of the soil temperature, soil moisture, and soil properties on soil respiration rate, calculated using Eqs. (2)–(4), are shown in Table 2 and Fig. 7. These calculations were made for 1-year periods from 1 July 2004 to 30 June 2005 in the Yamashiro Experimental Forest and from 16 August 2005 to 15 August 2006 in the Kahoku Experimental Forest. Plots R and M were selected as the control plots in the Yamashiro and Kahoku Experimental Forests, respectively. The results of the study by Palmroth et al. (2005) for pine plantation and hardwood areas in the Duke Forest, North Carolina, are also shown.

The observed features in our experimental forests are summarized in Table 3. Altitudinal differences were around 30 m and 70 m in the Yamashiro and Kahoku forests, respectively. Topographic variability was lower in the pine plantation and hardwood plots of the Duke Forest, with <5% incline in each (Palmroth et al., 2005).

The Yamashiro Experimental Forest, which is dominated by oaks, exhibits little variation in tree species. Conversely, at the Kahoku Experimental Forest, Plots L and M were dominated by Japanese cedar, whereas Plots U and T were dominated by Japanese cypress. In the Yamashiro forest, soils are immature due to heavy past disturbance in this area. In contrast, the soil in the Kahoku forest is brown forest soil with an organized soil structure. The observed variation in soil temperature was very low in both experimental forests, although large variation in soil moisture was recorded in Kahoku, particularly in Plots L and T.

In the Duke Forest, soil respiration rates were affected by the soil temperature, soil moisture, and soil properties, in decreasing order of influence (Palmroth et al., 2005).

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This order of influence was the same as in the Yamashiro forest, with soil temperature having the greatest effect on soil respiration rates. However, estimates of the magnitude of the effect exerted by each parameter using Eqs. (2)–(4) yielded unusually small values for Yamashiro, particularly for *EF*(Soil). This result could explain the low spatial variation in the soil respiration rate observed in Plots V and R at Yamashiro.

Conversely, at Kahoku, soil properties had the greatest effect on soil respiration rates, followed by soil moisture and soil temperature. Perhaps the most remarkable result from the Kahoku study was the very large calculated value for *EF*(Soil). The calculated values for $EF(\theta)$ were as large as in the other two forests. The annual calculated soil respiration rate was almost the same, at 23–26 t CO_2 ha^{-1} $year^{-1}$, in three of the plots at Kahoku, with the exception of Plot L. These results may be due to the effects of $EF(\theta)$ and *EF*(Soil) cancelling each other out in the Kahoku forest. *EF*(Soil) depends on the differences in the parameters a, b, and c in Eq. (1). These parameters are affected by various factors, including Total C, microbial biomass and activity, root biomass and activity, porosity, etc. This study cannot identify which factors are effective. However, each of the soils in four plots in Kahoku has different characteristics. For example, the soil in Plot L includes many fist-sized stones that rolled to the base of the slope and accumulated there. Consequently, the soil volume contributing to soil respiration is small, and the value of *EF*(Soil) is very small in Plot L. The soil in Plot T has repellency properties, which suggests peculiar microbial or root activity. The dominant tree species differ in Plots U and M, indicating that the litter size and conditions different in these two plots. In addition, the microbial species may also differ. Overall, the absolute value of *EF*(Soil) is larger for Kahoku than for Yamashiro and the Duke Forest. By contrast, soil respiration was increased in the wettest conditions after heavy precipitation events in every plot in Kahoku, as shown in Fig. 5. Plot L, which was the wettest, also had the largest basal area of stems in Kahoku. Generally, the above- and underground biomasses of trees are proportional to each other. Therefore, the wet soil conditions do not suppress the soil respiration at Kahoku. The positive and negative values of $EF(\theta)$ and *EF*(Soil) differed from each other in every plot in Kahoku.

Consequently, their effects serve to cancel each other out.

Diversity in tree species and variability in soil moisture were low at the Yamashiro forest. More importantly, the soil structure exhibited minimal variation because of the immaturity of the soil in this area. Thus, *EF*(Soil) values for Yamashiro were very low. By contrast, in the Kahoku forest, tree species, topography, and soil moisture all varied substantially among the study plots, likely because of the maturity of the soil. The forest soil would have matured under specific conditions, individual to each plot. Thus, soil properties in each plot may differ greatly and could explain the large calculated *EF*(Soil) for Kahoku. Thus, we argue that the low soil respiration rates in Plot L were the result of soil properties, not wet soil conditions.

Variation in topography was low in the pine plantation and hardwood areas in the Duke Forest, which could explain why *EF*(Soil) for these areas was smaller than *EF(T)* and $EF(\theta)$.

7 Conclusions

Topographic variation in the soil respiration rate was low in the Yamashiro Experimental Forest, and respiration rates were greatly affected by soil moisture and soil temperature compared to soil properties. These results were likely due to the immaturity of the forest soil.

At the Kahoku forest, calculated soil respiration rates were lower at the base part of the slope than in other parts. We suggest that this pattern can be explained by differences in soil properties rather than elevated soil moisture levels. Calculated annual soil respiration rates were 23–26 $t\,CO_2\,ha^{-1}\,year^{-1}$ in other parts of the slope. Thus, the effects of soil moisture and soil properties in these areas may have cancelled each other out. The effect of soil temperature on the soil respiration rate was small at the Kahoku forest.

To summarize, the topographic variation in the soil respiration rate was caused by different factors in these two forest ecosystems with different vegetation and soil characteristics: one is a deciduous forest with immature soil (Yamashiro) and the other is mostly an evergreen forest with mature soil (Kahoku).

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Table 1. Outline of the observation plots.

Experimental Forest	Plot name	Slope direction	Slope angle	Altitude (m)	Basal area of stem (m^2 100 m^{-2})	Dominant species	Total C ($mg\,g^{-1}$) *1
Yamashiro	V	S 53° W	2°	188	0.131	*Clethra barvinervis*	42
	R	S 52° E	18°	222	0.322	*Ilex pedunclosa*	38
Kahoku	L	S 48° W	43°	166	0.753	*Cryptomeria japonica*	81
	M	S 32° W	32°	184	0.564	*Cryptomeria japonica*	62
	U	S 5° W	22°	213	0.382	*Chamaecyparis obtusa Sieb. et Zucc.*	118
	T	S 17° E	6°	221	3.855	*Chamaecyparis obtusa Sieb. et Zucc.*	79

Table 2. Comparion of the effect on soil respiration by soil moisture ($EF(\theta)$), soil temperature ($EF(T)$) and soil property (EF(Soil)).

Experimental Forest	Yamashiro			Kahoku			Duke (Palmroth et al., 2005)	
Plot	R	V	L	M	U	T	Pine Plantation	Hard Wood
Estimated F_c (tCO_2 ha^{-1} year^{-1})	21.56	21.10	14.42	23.87	25.13	24.79	41.80	51.66
Deifference of F_c from the standard site (tCO_2 ha^{-1} year^{-1})	Standard site	−0.46	−9.45	Standard site	1.27	0.92	Standard site	9.86
Effect of θ (tCO_2 ha^{-1} year^{-1})		1.66	3.89		−1.90	−4.55		2.79
Effect of T (tCO_2 ha^{-1} year^{-1})		−2.10	−1.74		−0.48	−0.54		4.40
Effect of parameters (tCO_2 ha^{-1} year^{-1})		0.20	−9.84		4.41	7.61		2.67

Table 3. Outline of the feature in experimental forest.

Experimental Forest	Variation in topography	Variation in vegetation	Variation in Soil property	variation in soil temperature	Variation in soil moisture
Yamashiro	Remarkable; Altitude difference is ≈30 m	Slight; All plots is covered by deciduous species	Slight; Extremely immature soil	Slight; Fig. 2c	Slight; Fig. 2d
Kahoku	Remarkable; Altitude difference is ≈70 m	Remarkable; Japanese cedar (Plot B, M) Japanese cypress (Plot U, T)	Supposed to be remarkable; matured forest soil	Slight; Fig. 4e	Remarkable in plots B, T Fig. 4f
Duke (Palmroth et al., 2005)	Slight; Slope angle $<5\%$	Remarkable; Hard wood forest and pine plantation			

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Environmental factors and soil properties effects

K. Tamai

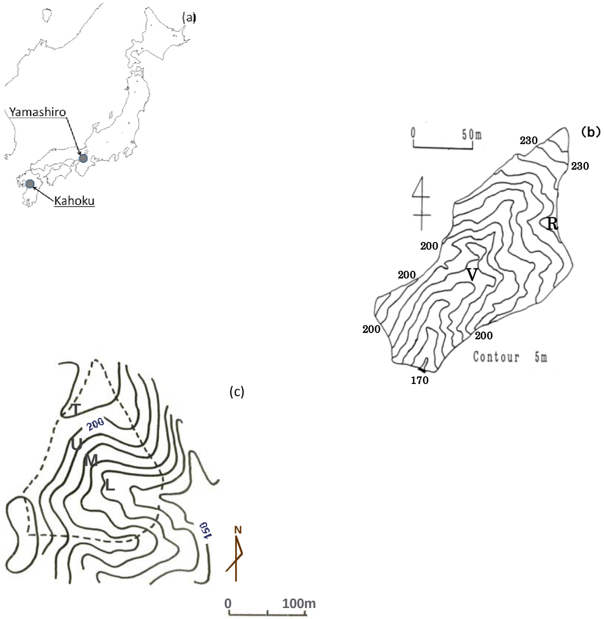

Fig. 1. Location and topography of experimental forest. **(a)** Location. **(b)** Topography of Yamashiro Experimental Forest. R and V indicate the location of Plot R and V, respectively. Numbers show the altitude of contour lines. **(c)** Topography of Kahoku Experimental Forest. T, U, M and L indicate the location of Plot T, U, M and L, respectively.

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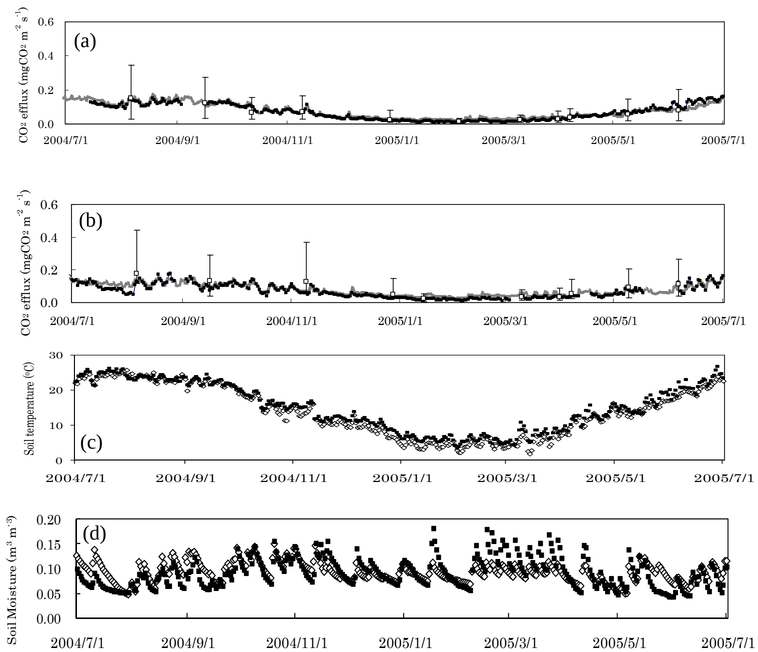

Fig. 2. Seasonal variation of soil respiration, soil temperature and soil moisture ratio in Yamashiro Experimental Forest. **(a)** and **(b)**, soil respirations in Plot V and R, respectively. Black line: Observed soil respiration by automated chamber system. Gray line: calculated soil respiration by Eqs. (5) and (6), respectively. White square: averaged soil respiration by manual chamber system. Bar: the range of maximum and minimum rate by manual chamber. **(c)** and **(d)**, soil temperature and soil moisture, respectively, at 5cm depth. White dot: plot V. Black dot: plot R.

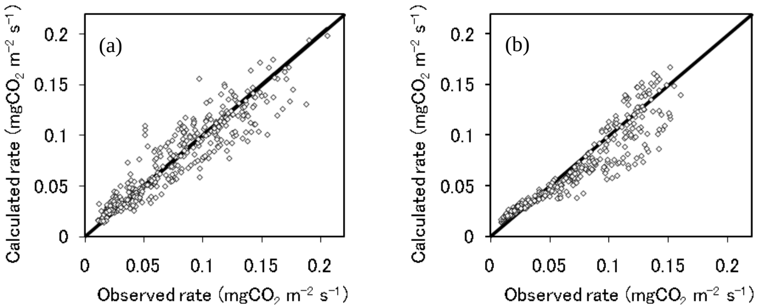

Fig. 3. Comparison of observed and calculated respiration rate in Yamashiro Experimental Forest. **(a)** plot R. **(b)** plot V.

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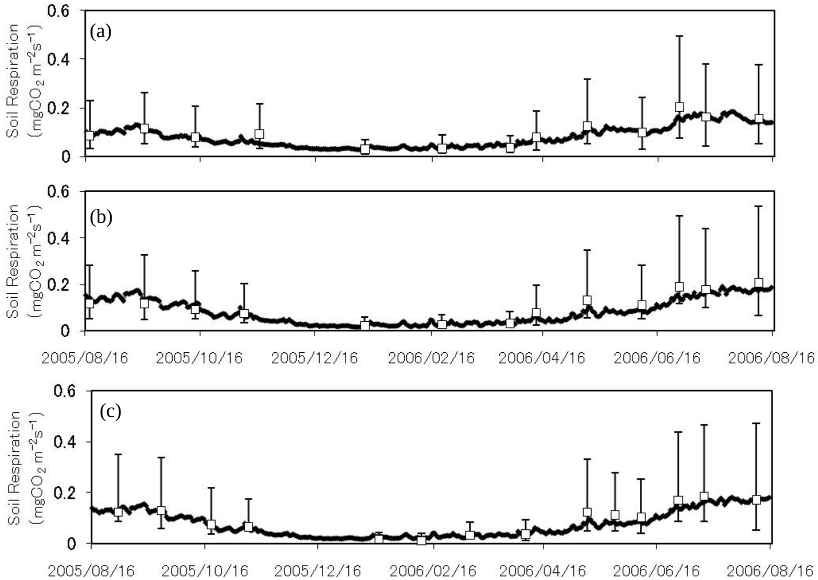

Fig. 4. Seasonal variation of soil respiration, soil temperature and soil moisture ratio in Kahoku Experimental Forest. **(a)**, **(b)**, (c) and **(d)**, soil respirations in Plot T, U, M and L, respectively. Black line: Calculated soil respiration by Eqs. (7)–(10), respectively. White square: averaged soil respiration by manual chamber system. Bar: the range of maximum and minimum rate by manual chamber. **(e)** Soil temperature at 5 cm depth. Gray dot: plot T. Line: plot U. Black dot: plot M. Plus: plot L. **(f)** soil moisture ratio at 5 cm depth. Gray dot: plot T. White dot: plot U. Black dot: plot M. Plus: plot L.

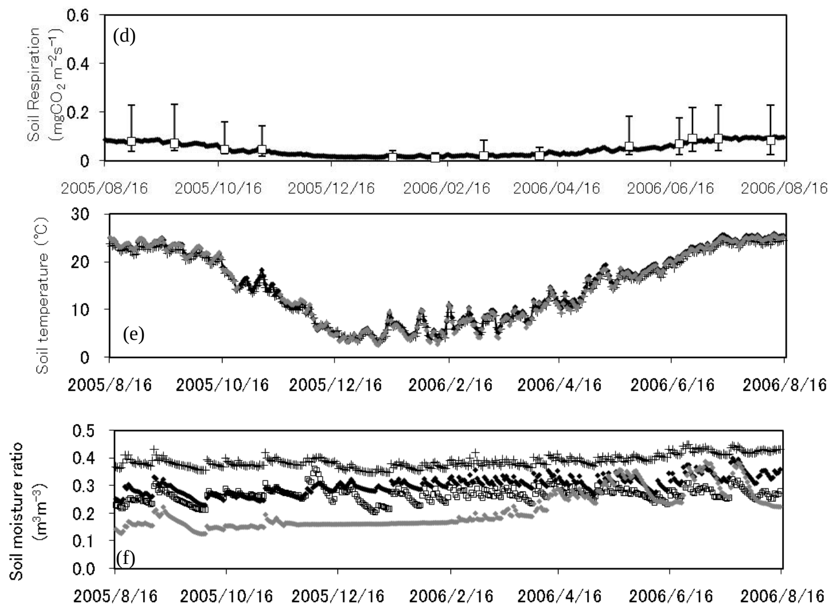

Fig. 4. Continued.

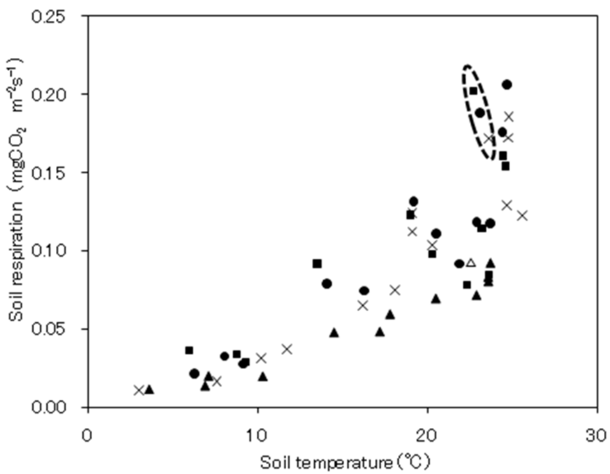

Fig. 5. Comparison between soil respiration and soil temperature in Kahoku Experimental Forest. Black square: plot T. Black circle: plot U. Cross: plot M. Black triangle: plot L. Three points in dotted circle and white triangle were observed on 27 June 2006.

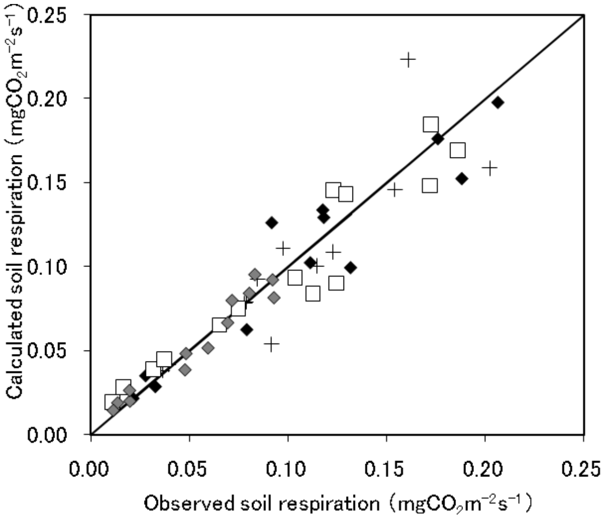

Fig. 6. Comparison of observed and calculated respiration rate in Kahoku Experimental Forest. Cross: plot T. Black diamond: plot U. White square: plot M. Gray diamond: plot L.

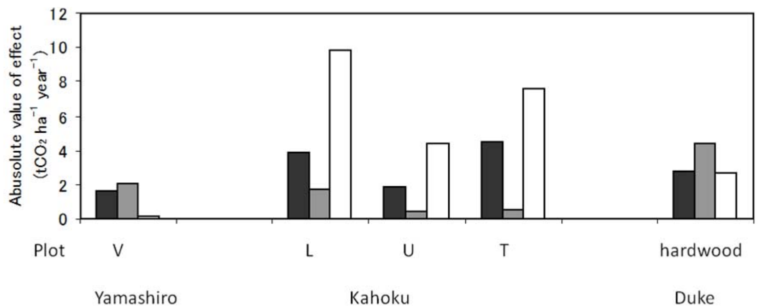

Fig. 7. Comparison of the effect on soil respiration by soil moisture (*EF*(θ)), soil temperature (*EF(T)*) and soil property (*EF*(Soil)). Black block: *EF*(θ), gray block: *EF(T)*, White block: *EF*(Soil).