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Soil CO_2 efflux at timberline on Mt. Fuji

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Abstract: Soil CO_2 effluxes were investigated at timberline on Mt. Fuji. Three study plots along a sequence of vegetation zones (dwarf, tall Japanese larch, and Veitch's silver fir proceeding downward) in the vicinity of timberline were selected for the measurement of soil CO_2 efflux. The results showed differences in the temperature dependence of the soil CO_2 efflux among the three study plots. The highest value ($Q_{10}=4.4$) was derived at the upper plot where the vegetation and soil formation were underdeveloped. Environmental data also showed differences among the three plots in soil temperature and soil water content. The upper study plot was exposed to higher soil temperature and lower soil moisture than the other two plots because of poor vegetation cover and underdeveloped soil formation. The total soil CO_2 efflux during the snow free period from June to October was estimated for the upper, middle, and lower plots as 3.3, 3.0, and 3.7 Mg C ha^{-1} 5 $months^{-1}$. The results suggest that the amount of soil CO_2 efflux does not always correspond to vegetation and soil development.

key words: soil CO_2 efflux, vegetation type, timberline, soil temperature, Q_{10}

Introduction

Alpine timberline is characterized by an abrupt transition in species composition of vegetation within a short distance compared to the lowland treeline progressing toward higher latitude (Tranquillini, 1979; Sveinbjörnsson, 1992; Körner, 1999). Indeed, we can observe a sequence of vegetation zones from timberline downward such as dwarf conifers, deciduous broad-leaved trees, and evergreen conifers within a few hundred meters on a slope of Mt. Fuji in central Japan (Masuzawa, 1985). The difference in such vegetation reflects the difference in the successional stage of the vegetation on the slope after the eruption in 1707 as well as the change of soil characteristics with the transition of the above ground vegetation (Masuzawa, 1985). It is believed that the difference in vegetation structure has influenced carbon dynamics in the timberline ecosystem.

The net carbon exchange of a terrestrial ecosystem is the result of a delicate balance between uptake (photosynthesis) and loss (respiration), and shows strong diurnal, seasonal, and annual variability (Valentini *et al*., 2000). If the vegetation structure

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changes with environmental change, the carbon dynamics of the ecosystem will be influenced greatly. Investigating the carbon dynamics of each vegetation type could lead to evaluating the carbon cycle in the ecosystem at timberline. Although the carbon dynamics in cold regions are affected by the environmental changes from global warming, there are very few reports on the carbon dynamics at timberline (Monson *et al.*, 2002). The aim of this study was to evaluate the CO_2 efflux from the soil surface near timberline with respect to the difference in vegetation as the first step for evaluating the carbon dynamics for the timberline ecosystem.

We investigated the soil CO_2 efflux at and near timberline on the southeastern slope of Mt. Fuji. A series of three different vegetation zones (predominated by dwarf trees, tall Japanese larch, and Veitch's silver fir) ranging over a few hundred meters in vertical distance were selected for the measurements.

Materials and methods

Study site

Mt. Fuji (3775.6 m asl) in central Honshu is the highest mountain in Japan (35°21′ N, 138°43′E). Timberline ranges from *ca.* 2350 m above sea level (asl) on the southeastern slope to 2800 m asl on the northwestern slope. The slope is covered with scoria, which is volcanic ejecta, characterized by its porous shape and blackish color. Vegetation on the slope was destroyed by the Hoei volcanic eruption in 1707. The vegetation has been recovering and is progressing through the vegetational succession (Masuzawa, 1985).

The timberline forest on Mt. Fuji mainly consists of dwarfed Japanese larch (*Larix kaempferi*). The larch grows from the upper limit of the forest downward. The height of the tree increases gradually with decreasing elevation. Alder (*Alnus maximowiczii*) and Erman's birch (*Betula ermanii*) grow along with the larch. Veitch's silver fir (*Abies veitchii*) takes the place of Japanese larch at lower elevation. *Rhododendron brachycarpum*, hemlock (*Tsuga diversifolia*), and spruce (*Picea jezoensis* var. *hondoensis*) are also observed in the lower forest.

The study site is located on the outer slope of the second Hoei parasitic crater (*ca.* 2350 m asl), which is located in the middle of the southeastern slope of the mountain (Fig. 1). Masuzawa (1985) has reported the detailed structure of the vegetation at the study site.

Three study plots (A, B, and C) were set for measuring soil CO_2 efflux and environmental factors (50 m, 120 m, and 220 m from the marginal ridge of the crater) in this study (Fig. 1). A distinct treeline was observed around plot A. The upper area was dominated by herbaceous perennials (*Polygonum cuspidatum*, *P. weyrichii* var. *alpinum*, *Carex doenitzii*, *Artemisia pedunculosa*, etc.). The vegetation at plot A mainly consisted of dwarf *Larix kaempferi*, *Alnus maximowiczii*, and *Betula ermanii.* Scoria soil was accumulated on the floor. Plot B mainly consisted of tall *Larix kaempferi.* The soil surface was fully covered with several kinds of herbaceous perennials and mosses. The vegetation cover on the forest floor was established on a thin (less than 5 cm) organic layer. A scoria layer can be seen by removing the vegetation cover and the organic matter layer. The vegetation at plot C was dominated by *Abies veitchii, Rhodo-*

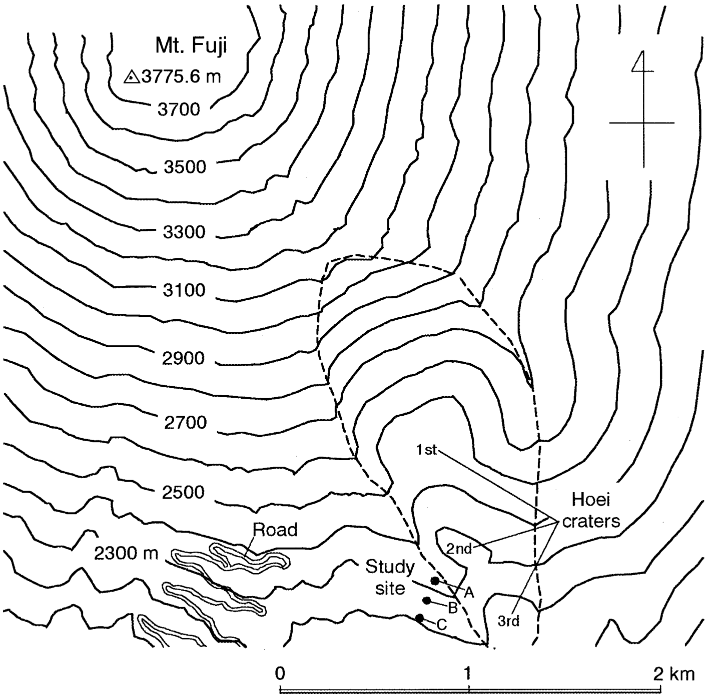

Fig. 1. Study site on Mt. Fuji. The study site is located on the outer slope of Hoei crater. Three study plots for measuring soil CO_2 efflux and environmental factors are shown as solid circles (plots A, B and C).

dendron brachycarpum, *Tsuga diversifolia*, and *Picea jezoensis* var. *hondoensis* were also growing. The forest floor was mainly covered with mosses and herbaceous perennials, and the thickness of the organic matter layer was similar to that at plot B.

The mean annual air temperature at the study site could be estimated by using the environmental lapse rate (0.55℃hm^{-1}), although the air temperature was not monitored in this study. The mean annual air temperature at the Mt. Fuji Meteorological Observatory (3772 m asl) near the summit of Mt. Fuji was −5.9℃ in 2002 (Japan Meteorological Agency). The mean annual air temperature at the study site (2350 m asl) can be estimated at 1.9℃. Uchida *et al.* (2000) estimated the mean annual air temperature for 30 years (1961 to 1990) as 1.2°C at 2400 m on the northwestern slope from data of meteorological stations at Kawaguchiko (Lake Kawaguchi) and the summit of Mt. Fuji. The annual precipitation at the Gotenba meteorological station (35°18′N, 138°59′E and 458 m asl), which is the nearest station on the same slope as the study site, was 2749 mm in 2001 and 2518 mm in 2002 (Japan Meteorological Agency).

Environmental factors

Simultaneously with measurement of the soil CO_2 efflux, soil temperature at 5 cm depth was measured by a data logger with a thermister sensor (Hioki E.E. Corporation, 3633-20 Temperature Logger). The soil water content was measured as a volumetric percentage (%) based on the principle of time domain reflectometry (TDR). The measurement was also carried out just after each air sampling using a water content sensor (Campbell Scientific Inc., HydroSense CS-620) with a 12 cm probe rod.

The seasonal variation of the soil temperature at 5 cm depth was monitored at intervals of 30 min during the snow free period in 2002 at each study plot by a data logger with a thermister sensor (Hioki E.E. Corporation, 3633-20 Temperature Logger). The measurements were carried out from May 30 to November 9, 2002. The temperature data from every hour (from June to October) were used for calculating the daily soil CO_2 efflux at each plot.

Soil CO_2 efflux

Soil CO_2 efflux, the total of the root respiration and heterotrophic respiration, was measured by using the closed chamber (CC) method (Mariko *et al*., 1994; Bekku *et al*., 1995, 1997; Koizumi *et al*., 1999). The flux of CO_2 is calculated from eq. (1):

$$F_{soil}=a(V/A)(\Delta C/\Delta t), \tag{1}$$

where F_{soil} is the soil CO_2 efflux (mg CO_2 m^{-2} h^{-1}), V is the volume of air within the chamber (m^3), A is the area of the soil within the chamber (m^2), $\Delta C/\Delta t$ is the time rate of change of the CO_2 concentration in the air within the chamber (μl CO_2 $l^{-1}s^{-1}$), and a is a constant for unit conversion.

A gray polyvinyl chloride (PVC) cylinder (15 cm in height, 21 cm in internal diameter) was placed at a depth of *ca.* 5 cm over one week prior to the sampling at each measuring plot. A PVC lid was placed on its top just before the first air sampling. A rubber-capped needle was fitted onto an air sample port on top of the lid. The air in the chamber was aspired through the needle into an evacuated vial (5 m*l* volume) five times (0, 30, 60, 120, and 300 s after the lid closing). Then the concentration of CO_2 in the air samples was determined by a gas chromatograph with a thermal conductivity detector (GL Sciences Inc., GC390) in the Yamanashi Institute of Environmental Sciences. The concentration of CO_2 was plotted against time. The data points that could be fitted with a high correlation coefficient by linear regression (Mariko *et al*., 1994; Koizumi *et al*., 1999) were used to calculate soil CO_2 efflux.

Air was sampled at five points in each study plot between 1000 and 1400 hours. The five measurement points were set at random so that the distance between points was at least 1 m. The measurements were carried out on September 14 and October 20 in 2002 and on May 30, August 21, and November 9 in 2003.

F_{soil} calculated from eq. (1) was plotted against soil temperature. Then the data points for the three study plots (plots A, B, and C), which could be fitted by a first-order exponential equation (Epron *et al*., 1999a; Fang and Moncrieff, 2001):

$$F_{soil}=\alpha e^{\beta T}, \tag{2}$$

where α and β are the model parameters to be determined, and T is the soil temperature being monitored (℃), were used to calculate soil CO_2 efflux (mg CO_2 m^{-2} h^{-1}). β is related to the Q_{10} parameter, which means the temperature dependence of soil CO_2 efflux. The value of Q_{10} is the factor by which the respiration rate differs for a temperature interval of 10°C, and is defined as:

$$Q_{10} = (F_{T+10})/F_T, \quad (3)$$

where F_T and F_{T+10} are CO_2 effluxes at temperatures of T and $T+10$ (Winkler *et al.*, 1996). For the first-order exponential equation, which assumes Q_{10} is a constant over the temperature, the Q_{10} value can be calculated as:

$$Q_{10} = e^{10\beta}, \quad (4)$$

where β is the same parameter as in eq. (2).

Daily soil CO_2 efflux is calculated as the sum of hourly soil CO_2 effluxes per day calculated from eq. (2) and the hourly soil temperature. Monthly soil CO_2 efflux was calculated as the total of daily soil CO_2 effluxes per month.

Results and discussion

The mean soil temperatures during the snow free period (from June to October) were 12.0°C, 10.6°C, and 10.4°C at plots A, B, and C (Fig. 2). The maximum (minimum) soil temperatures at plots A, B, and C were 30.1 (0.2)°C, 18.6 (0.7)°C, and 19.5 (−0.6)°C during the same period (Fig. 2). Soil volumetric water contents were significantly lower in plot A than in plots B and C (Table 1). These environmental data suggest that study plot A was exposed to higher temperatures and severe drought during the growing season of the vegetation compared to the other two plots (B and C).

Soil CO_2 effluxes calculated from eq. (1) are scattered as shown by the data points in Fig. 3. The temperature dependence of soil CO_2 effluxes was derived from the five

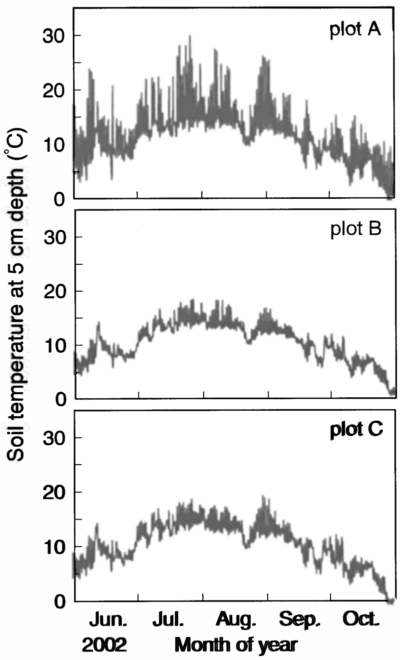

Fig. 2. Soil temperature at 5 cm depth on the three study plots (plots A, B and C). Each data series is shown as a sequence of hourly temperatures during the snow free period (from June to October in 2002) at the study site.

Table 1. Soil volumetric water contents measured at three study plots (A, B and C) on the southeastern slope of Mt. Fuji. Each measurement was carried out just after air sampling for the determination of soil CO_2 efflux. Data are means of five replications. SD is shown in parenthesis. Values with the same suffix letter are not significantly different in each measuring date at the $P < 0.05$ level (Bonferroni/Dunn test).

Plot	Soil volumetric water content (%)			
	Sep. 14, 2001	Oct. 20, 2001	May 30, 2002	Aug. 21, 2002
A	6.4[a] (1.1)	6.7[a] (2.1)	10.7[a] (0.6)	9.4[a] (1.3)
B	17.8[b] (2.8)	17.7[b] (2.5)	22.7[b] (4.0)	18.6[b] (4.8)
C	22.4[b] (5.9)	17.7[b] (3.1)	21.7[b] (3.8)	13.0[a] (1.9)

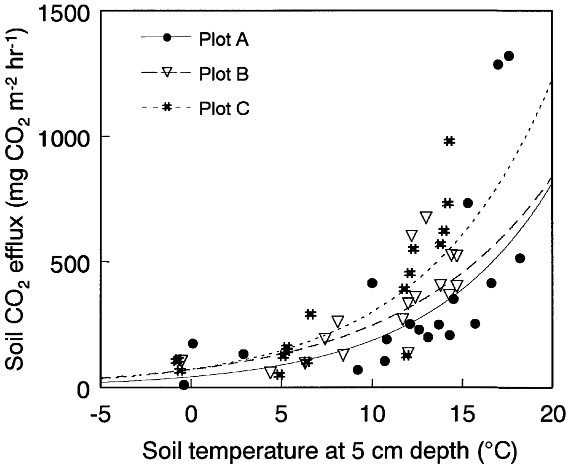

Fig. 3. Relationship between soil CO_2 efflux and soil temperature at 5 cm depth. Data presented by the same symbol are from the same study plot (plots A, B and C from the outer edge of second Hoei crater downward). Each data series is shown as the aggregate of data collected on September 21 and October 20 in 2001, and May 30, August 21 and November 9 in 2002. The solid line is the first-order exponential regression line for plot A ($F_{(x)} = 42.683\ e^{0.1474x}$, $R^2 = 0.58$); the broken line, at plot B ($F_{(x)} = 72.986\ e^{0.1222x}$, $R^2 = 0.66$); the dotted line at plot C ($F_{(x)} = 73.433\ e^{0.1409x}$, $R^2 = 0.70$).

measurement times throughout the year. Model parameter α for the fitted curve for eq. (2) was calculated at 42.7, 73.0, and 73.4, while parameter β was calculated at 0.147, 0.122, and 0.141 at plot A ($R^2 = 0.58$, $n = 19$), B ($R^2 = 0.66$, $n = 18$), and C ($R^2 = 0.70$, $n = 17$) as shown in Fig. 3. The temperature coefficients, Q_{10} values at plots A, B, and C, calculated from eq. (4), were 4.4, 3.4, and 4.1, (Fig. 3).

Calculated monthly soil CO_2 effluxes were 373 (at plot A), 304 (at B), and 402 g CO_2 m^{-2} month^{-1} (at C) in July (Fig. 4a). The highest peaks in monthly soil CO_2 effluxes were observed in July at all study plots. Considering the vegetation succession, higher soil CO_2 efflux is expected at lower study plots in proportion to the amount of

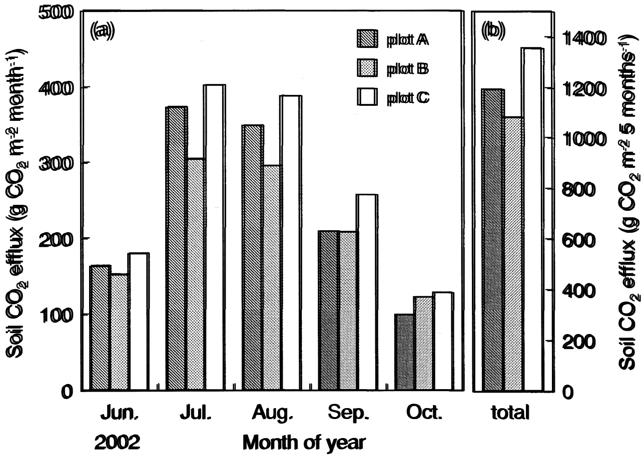

Fig. 4. Soil CO_2 effluxes. (a) Calculated monthly soil CO_2 effluxes for three study plots (plots A, B and C from the outer edge of Hoei second crater downward) on the southeastern slope of Mt. Fuji. Data were calculated by using a first-order exponential regression model (eq. (2) in the text). Mean hourly soil temperatures were applied to the model. (b) The total of monthly soil CO_2 effluxes from June to October in 2002.

organic soil formation. Yet, there were not any conspicuous gradients in monthly soil CO_2 efflux among the three study plots in this study. Plot A showed higher values all through the period, especially in summer, than we had expected.

In order to compare the level of soil CO_2 effluxes among the three plots, the amount of monthly soil CO_2 effluxes during the snow free periods (from June to October) were calculated. The values were 1192, 1081, and 1355 g CO_2 m^{-2} 5 $month^{-1}$ (3.3, 3.0, and 3.7 Mg C ha^{-1} 5 $months^{-1}$) at plots A, B, and C (Fig. 4b). Raich and Schlesinger (1992) reviewed the annual soil CO_2 effluxes for various vegetation types. The mean values were 60 g C (220 g CO_2) m^{-2} yr^{-1} in tundra ($n=11$), 322 g C (1180 g CO_2) m^{-2} yr^{-1} in boreal forests ($n=16$) and woodlands, and 681 g C (2497 g CO_2) m^{-2} yr^{-1} in temperate coniferous forests ($n=23$). Although there were differences in the lengths of the snow free period, the results of this study are equivalent to values in boreal forest and smaller than those in temperate coniferous forest.

Comparing the characteristics of soil CO_2 efflux among the three study plots, the amount of soil CO_2 efflux for the snow free period at plot A showed a relatively high value of 1192 g CO_2 m^{-2} 5 $months^{-1}$ (Fig. 4b), although the vegetation was thinner than at the other plots. This was caused by the high Q_{10} value of 4.4 (Fig. 3) and higher temperature on the soil surface during the snow free period (Fig. 2). Although the climate at timberline is cold, there is a tendency for the soil surface to be heated by solar radiation. This may result from the poor vegetation cover at plot A. Direct radiation could reach the surface soil consisting of scoria, and its blackish color is thought to enhance the temperature increase in the surface soil (Masuzawa *et al.*, 1982, 1991; Anisuzzaman *et al.*, 2001, 2002). The biomass and activity of decomposers in soil may be influenced by this characteristic. Uchida *et al.* (2000) suggest that the temperature difference resulting from the altitudinal difference acts on the microbial growth rate, influencing the temperature dependence of the decomposition rate in soil.

Previous studies have shown that the Q_{10} value is higher in ecosystems associated with low soil temperatures on a global scale (Lloyd and Taylor, 1994; Valentini *et al*., 2000; Bekku *et al*., 2003). The results in this study are comparable with the values of 3.4 in Arctic areas (Bekku *et al*., 2003). The existence of plant roots is thought to be an important factor that affects the Q_{10} value (Boone *et al*., 1998; Borken *et al*., 2002). Respiration of plant roots is a significant component of soil CO_2 efflux (Thierron and Laudelout, 1996; Epron *et al*., 1999b; Högberg *et al*., 2001). The proportion of the contribution of root respiration to total soil CO_2 efflux has been reported by many researchers and varies with vegetation (e.g. Epron *et al*., 1999b; Högberg *et al*., 2001; Rey *et al*., 2002). At timberline where soil is underdeveloped, it is thought that the contribution of roots to soil CO_2 efflux is important. It is expected that the biomass of the roots and the distribution of root respiration be investigated in order to clarify the mechanism of the carbon cycle at timberline.

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