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Interannual Variation in CO_2 Effluxes from Soil and Snow Surfaces in a Cool-Temperate Deciduous Broad-Leaved Forest

By

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Key words: Soil CO_2 efflux, open-flow IRGA method, Q_{10} function, seasonal change, AsiaFlux.

Summary

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We estimated the inter-annual variation in soil CO_2 efflux in a cool-temperate oak–birch forest in central Japan. CO_2 effluxes from the soil surface during the snow-free season and from the snow surface during the snow-covered season were measured using an open-flow infrared gas analyzer method from December 1994 to December 1995. Climatic conditions in 1995 were significantly colder than the 22-year mean; this decreased observed values of daily CO_2 efflux and resulting in different temperature response of CO_2 efflux (estimated on the basis of the annual Q_{10} function) compared with the Q_{10} function derived from measured effluxes obtained at the same site and with the same method in normal, warmer years from 1999–2002. This suggests that empirical models such as annual Q_{10} function must be parameterized for the target year before they can be used to estimate annual soil CO_2 efflux, especially during periods of abnormal climatic conditions. Estimated annual values of soil CO_2 efflux from 1994–2002, based on the Q_{10} functions derived from annual datasets for 1995 (an abnormally cold year) and 1999-2002 (normal warm years), ranged from 597 to 793 g C m^{-2} y^{-1}, with a mean ±SD of 713±71 g C m^{-2} y^{-1}. The annual soil CO_2 efflux in 1995, an abnormally cold year, was 16% lower than the mean for the 1994–2002 period, whereas efflux in a warm El Niño year (1998) was 11% higher than the mean. This suggests the presence of a large inter-annual variability in the annual soil CO_2 efflux in this forest.

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Introduction

Cool-temperate deciduous forests are widely distributed throughout eastern Asia, and these forests may act as sinks for atmospheric CO_2 (YAMAMOTO & al. 1999, SAIGUSA & al. 2005). However, the strength of the carbon sink in terms of NEP (net ecosystem production) tends to vary greatly between years (SAIGUSA & al. 2005). The two most important processes that regulate the carbon balance in a forest ecosystem are photosynthesis and soil CO_2 efflux. The relationship between the two (production and decomposition, respectively) determines whether an ecosystem is a sink for, or a source of, atmospheric CO_2, and also determines the strength of the sink or source. It is therefore important to evaluate the inter-annual variation in soil CO_2 efflux to provide insights into the factors that control the large variability in the ecosystem's potential as a carbon sink.

Among the empirical models that have been used to model CO_2 efflux, the "annual Q_{10}" function is thought to be a good choice for estimating the total annual soil CO_2 efflux because it integrates all processes that influence seasonal and annual soil CO_2 efflux (JANSSENS & PILEGAARD 2003, MO & al. 2005). MO & al. 2005 reported large variations in seasonal Q_{10} in the same forest that was used in the present study, and suggested that annual Q_{10} may incorporate not only the temperature response of soil CO_2 efflux, but also seasonal changes in physiological activities induced by changes in root phenology, microbial biomass, and other factors. This raises an important question: Does the temperature response of soil CO_2 efflux in terms of Q_{10} function vary year-to-year? We measured CO_2 efflux from the soil surface during the snow-free season and from the snow surface during the snow-covered season in a cool-temperate oak–birch forest, between December 1994 and December 1995. It was abnormally cold in 1995 and a marked reduction in the net CO_2 sink strength (i.e., NEP) of this forest was observed (SAIGUSA & al. 2005). Our objectives were (1) to examine whether the temperature response of soil CO_2 efflux changed the predictions of the Q_{10} function in an abnormally cold year (1995), and (2) to evaluate the inter-annual variation in soil CO_2 efflux for 1994–2002 on the basis of the Q_{10} functions derived from annual datasets for 1995 (an abnormally cold year) and 1999-2002 (normal warm years).

Material and Methods

The study site is located in the Takayama experimental forest of the Takayama Research Station (TRS), River Basin Research Center (RBRC) of Gifu University. It lies about 15 km east of the city of Takayama, in central Japan (36°08'N, 137°25'E, 1420 m a.s.l.). The 1980–2002 annual mean temperature was 7.2°C, and annual precipitation averaged 2275 mm (data from TRS, ca. 500 m north of the forest). The ground surface is covered with snow from December to April, and the mean annual snowfall is ca. 600 cm. The secondary deciduous broad-leaved forest is primarily dominated by oak (*Quercus crispula*) and birch (*Betula ermanii* and *Betula platyphylla*), with a canopy height of 15 to 20 m. The forest floor is covered with a dense dwarf bamboo (*Sasa senanensis*) community. Further descriptions of the site have been given by MO & al. 2005, NISHIMURA & al. 2004 and SAIGUSA & al. 2005. As this forest is part of the AsiaFlux network of forest sites, the CO_2 flux over the forest has been measured by micro-meteorological methods at a 27-m-tall meteorological tower since 1993 (YAMAMOTO & al. 1999, SAIGUSA & al. 2005). The soil CO_2

orological tower since 1993 (YAMAMOTO & al. 1999, SAIGUSA & al. 2005). The soil CO_2 efflux has been measured by means of the open-flow method in 1995 (the present study), and measurements have been conducted at the same site and with the same method since 1999 as well (MO & al. 2005).

CO_2-efflux measurements

In the survey period, between December 1994 and December 1995, we measured the CO_2 efflux from the soil surface continuously for 24 to 48 h at least twice a month using the open-flow infrared gas analyzer (IRGA) method when the ground was snow-free, and from the snow surface when the ground was snow-covered. The measurement system was the same as that of MARIKO & al. 2000. We used four PVC chambers, each 21 cm in internal diameter and 15 cm in height, for each measurement period. The chambers were distributed with the site as described by MARIKO & al. 2000 at the same locations that were used in the 1999 to 2002 measurements (MO & al. 2005). During flux measurements, the soil temperature at a depth of 1 cm was monitored in each measuring chamber with a thermocouple. Continuous measurement of soil temperature (depth of 1 cm) was carried out near the chamber at 1-h intervals from December 1994 to December 1996.

The temperature response of CO_2 efflux was estimated by means of a Q_{10} function: $F_C = R_{10}Q_{10}^{(T-10)/10}$, where F_C is the measured CO_2 efflux (g C m^{-2} d^{-1}) from the soil or snow surface; R_{10} is the reference CO_2 efflux at 10°C; Q_{10} is the temperature sensitivity of CO_2 efflux (the flux at one temperature divided by the flux at a temperature 10°C lower); and T is the daily mean soil temperature (°C). The Q_{10} function based on annual data sets was used to estimate annual soil CO_2 efflux. The data for soil temperature at a depth of 1 cm used in estimating the annual soil CO_2 efflux for the 1994–2002 period came from different sources: the 1994 dataset was provided by NISHIMURA & al. 2004, the 1995–1996 dataset was obtained during the present study, and the 1997–2002 dataset was provided by MO & al. 2005. SAIGUSA & al. 2005 provides more detailed descriptions on the year-to-year changes in the climate from 1994 to 2002 at the study site.

Results and Discussion

Seasonal change and temperature response of CO_2 efflux in 1995

It was abnormally cold in 1995 compared with the 9- and 22-year mean values (Fig. 1a). On the basis of the air temperature at a height of 25 m (observed at the meteorological tower at the study site), the mean annual air temperature for 1995 was 5.6°C, which makes 1995 the coldest year in the 1994–2002 period (an average of 6.5°C, Table 1). According to records provided by TRS for the 1980–2002 period, 1995 was the second-coldest year of this period (the coldest year was 1993). The abnormally cold weather in 1995 resulted from more than the very cold winter: the low monthly mean temperatures in the spring, early summer, and September were also responsible (Fig. 1a). The annual precipitation of 1995 was close to the mean for the 1994–2002 period, although less rain fell in some months of the growing season (May to October) in 1995 (Fig. 1b, Table 1).

Figure 2a shows the seasonal changes in daily mean air and soil temperature, and the corresponding changes in snow depth. Figure 2b shows the seasonal changes in the daily CO_2 efflux estimated in 1995. In winter, soil surface temperatures remained above 0°C because of the thermal insulation provided by the snowpack. The daily CO_2 efflux from the snow surface ranged from 0.18 to 1.04 g C m^{-2} d^{-1}. In the snow-free season, the daily value of soil CO_2 efflux increased sharply in late spring (e.g., 1.81±0.19 g C m^{-2} d^{-1} on May 11) and peaked in late summer

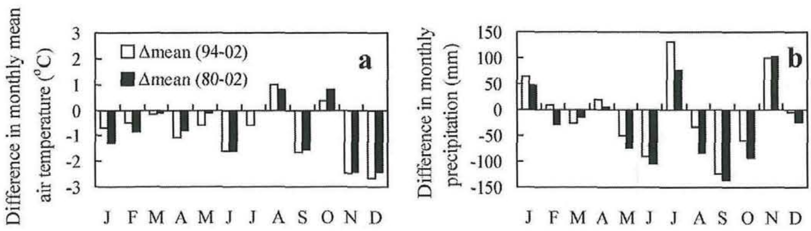

Fig. 1. Difference in monthly mean air temperature (a) and precipitation (b) between 1995 and the mean of 1994-2002 (white block) and 1980-2002 (black block). Air temperature data of 1994-2002 come from the study site, observed at 25 m height on tower. Other datasets come from the Takayama Research Station, ca. 500 m north of the study site.

Table 1. Annual variation of estimated annual CO_2-C efflux, ecosystem respiration (RE) and climate from 1994 to 2002 in Takayama.

Year	CO_2 efflux[1] ($g\ C\ m^{-2}\ y^{-1}$)	RE[1] ($g\ C\ m^{-2}\ y^{-1}$)	Temperature (°C)[3]		Precipitation[3] (mm)
			Air	Soil	
1994	778	735	7.1	8.5	1593
1995	597	706	5.6	7.2	1952
1996	608	699	5.6	7.4	1945
1997	739	716	6.3	8.5	2403
1998	793	819	7.6	9.1	2506
1999	770	746	6.7	8.8	2304
2000	698	756	6.4	8.0	1911
2001	740	750	6.3	8.1	1651
2002	694	746	6.5	7.8	1911
Average	**713**	**742**	**6.5**	**8.2**	**2020**
s.d.	71	36	0.6	0.6	319

1) Estimated by the annual Q_{10} function based on the 1995 dataset (all seasons, Table 2) for 1995 and 1996. The annual Q_{10} function based on the 1999-2002 datasets (all seasons, Table 2) is applied to the other years, however, with a topography correction by reduced 15% of annual value as suggested by JIA & al. 2003 (see details in MO & al. 2005). Values for 1994, 1996, 1997, and 1998 are provided only for the sake of reference, because the annual Q_{10} function was not parameterized for these years.
2) Values are cited by SAIGUSA & al. 2005 estimated by the micro-meteorological methods.
3) Air temperature (25 m) and soil temperature (-1 cm) come from the study site. Precipitation data come from the Takayama Research Station.

(e.g., 4.22±0.56 $g\ C\ m^{-2}\ d^{-1}$ on August 31), then decreased again in the autumn (e.g., 0.72±0.08 $g\ C\ m^{-2}\ d^{-1}$ on November 21). This seasonal pattern resembled that observed in the 1999–2002 period (MO & al. 2005). However, the maximum daily value for soil CO_2 efflux was lowest in 1995: 4.27±0.43 $g\ C\ m^{-2}\ d^{-1}$ in 1995 (observed on September 4), versus more than 6 $g\ C\ m^{-2}\ d^{-1}$ in the 1999–2002 period (MO & al. 2005).

Figure 3 shows that the daily CO_2 efflux was significantly correlated with daily mean soil temperatures in 1995. This indicated that soil temperature was the principle control on the seasonal variation of soil CO_2 efflux in the studied forest in 1995, that was consistent with the results of 1999-2002 (MO & al. 2005). However, the temperature response of CO_2 efflux, in terms of Q_{10} function (Table 2), differed in 1995 (abnormally cold year) compared with that obtained in normal warm years (1999-2002, Mo & al. 2005). For all seasons combined, the 1995 dataset gave a lower R_{10} value (1.63) and a lower Q_{10} value (3.61) than those for the 1999–2002 dataset (R_{10} = 2.05, Q_{10} = 3.79) derived from soil temperature at a depth of 1 cm. For the snow-free season, the 1995 dataset gave a lower R_{10} (1.86) and a slightly higher Q_{10} (2.61) than those for the 1999–2002 dataset (R_{10} = 2.47, Q_{10} = 2.58).

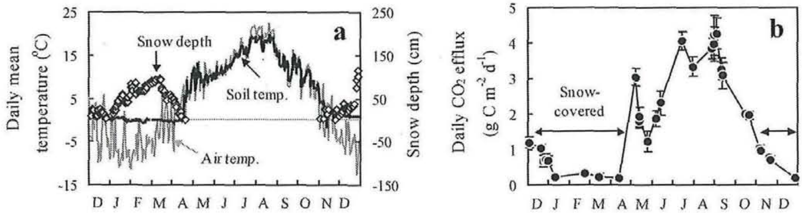

Fig. 2. Seasonal changes in (a) air and soil temperature and snow depth, and (b) daily CO_2-C efflux from Dec. 1994 to Dec. 1995 in Takayama. Air temperature at 25 m height observed on the tower, and soil temperature at 1-cm measured near the study site of efflux. Snow depth data come from the Takayama Research Station. C-efflux measured with the open-flow IRGA method from soil surface (snow-free season) and snow surface (snow-covered season). Error bars in (b) represent the standard deviation (n=4) of efflux.

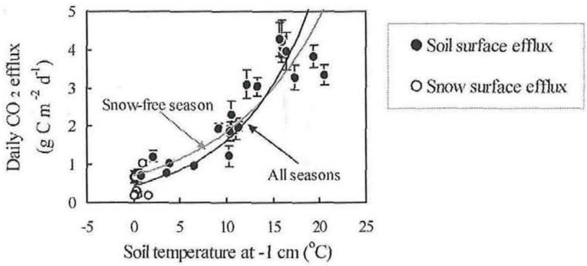

Fig. 3. Relationship of daily CO_2-C efflux and daily mean soil temperature at –1 cm. Error bars represent the standard deviation (n=4). Solid line represents the regression line for all seasons (including snow-covered season), and dash line represents the regression line for snow-free season. The regression equations are shown in Table 2.

Table 2. The regression coefficients for the Q_{10} function derived from various datasets in Takayama. The values for the 1999–2002 datasets are those cited by Mo & al. 2005 and provided for comparison. All regression equations are significant (P<0.001).

Source	Dataset	n	T	R_{10}	Q_{10}	R^2
This study (Fig. 3)	All seasons (1995)	30	Soil temp (-1 cm)	1.63	3.61	0.79
This study (Fig. 3)	Snow-free season (1995)	21	Soil temp (-1 cm)	1.86	2.61	0.84
Mo & al. 2005	All seasons (1999-2002)	60	Soil temp (-1 cm)	2.05	3.79	0.84
Mo & al. 2005	Snow-free season (1999-2002)	52	Soil temp (-1 cm)	2.47	2.58	0.82

Reference respiration (R_0 or R_{10})—the simulated soil CO_2 efflux at a soil temperature of 0 or 10°C—can be an indicator of the volume of soil that is biologically active, and can reflect changes in the size of the microbial population and in the amount and production of roots (WIDÉN 2002). The lower temperatures from April to July in 1995 may have delayed the warming of the deeper soil layers, resulting in a smaller volume of active soil compared with the same period in warmer years, and therefore the lower R_{10} in 1995. Furthermore, the lower R_{10} in 1995 may be partly explained by reduced biological activity of the forest in 1995. Two lines of evidence suggest that the abnormal weather in 1995 may have limited this activity, and especially photosynthesis. One is that the CO_2 uptake rate estimated from tower measurements in June and July of 1995 was 27% lower than during the same period in 1994, and YAMAMOTO & al. 1999 estimated that this decrease was caused by reduced insolation and lower temperatures. The second line of evidence is that the annual NEP and gross primary production (GPP) in 1995 were the lowest values recorded for the 1994–2002 period, based on the results of long-term tower measurements since 1993 (SAIGUSA & al. 2005). The decreased CO_2 uptake may also decrease the physiological activities of roots, because it would reduce the transport of photosynthates to the roots (LARCHER 1995). As a result, the reduced CO_2 uptake may also have induced changes in root growth and other associated biotic factors such as the size of the microbial population, thereby reducing the R_{10}.

MO & al. 2005 reported large variations in seasonal Q_{10} in the forest in the present study, and suggested that annual Q_{10} may incorporate not only the temperature response of soil CO_2 efflux, but also seasonal changes in physiological activities induced by changes in root phenology, microbial biomass, and other factors. It is therefore reasonable to expect that the annual Q_{10} function may differ in an abnormally cold year, especially when the abnormal weather limits the biological activity of the forest, thereby inducing changes in root growth and other associated biotic factors that would influence soil CO_2 efflux. As a result, these changes may modify the value of the function. To sum up all the processes and factors that potentially regulate R_{10} and Q_{10}, it appears that the temperature response of soil CO_2 efflux, as indicated in the annual Q_{10} function, may lead to decreased efflux in an abnormally cold year in this forest. Interestingly, no significant difference in the annual Q_{10} function was found among the four normal warm years from 1999 to 2002 (MO & al. 2005). This may have occurred because the four years had similar annual temperature and precipitation (Table 1), and thus, probably had similar photosynthetic activities. SAIGUSA & al. 2005 reported that the annual GPP for the 1999–2002 period ranged between 944 and 1092 g C m^{-2} y^{-1}, with a coefficient of variation (CV) of 6.2%. However, GPP in 1995 gave the lowest value of 765 g C m^{-2} y^{-1} among the 1994-2002 period, which was 26.1% lower than the mean of 1999-2002 (1035 g C m^{-2} y^{-1}).

The annual Q_{10} function is thought to be adequate for estimating the total annual soil CO_2 efflux, because it integrates all processes that influence seasonal and annual soil CO_2 efflux (JANSSENS & PILEGAARD 2003, CURIEL YUSTE & al. 2004, MO & al. 2005). In our study, the annual soil CO_2 efflux in 1995, as estimated on the basis of the annual Q_{10} function derived from the 1995 dataset, was

597 g C m^{-2} y^{-1} (Table 1). However, using an annual Q_{10} function derived from the datasets for normal (warm) years (here, the 1999–2002 period) may overestimate the annual CO_2 efflux in an abnormal cold year (i.e. 642 g C m^{-2} y^{-1} for 1995) because it overestimated the daily soil CO_2 efflux largely in summer (Fig. 4a). Conversely, using an annual Q_{10} function based on the dataset from an abnormally cold year may underestimate the daily and annual soil CO_2 efflux in normal years (Fig. 4b). These results emphasize that using an empirical model such as the annual Q_{10} function to estimate annual soil CO_2 efflux requires that the model be parameterized for the target year, especially when that year has an abnormal climate. Similarly, the annual Q_{10} function based on an abnormal year's dataset should be applied with caution to estimations in normal years.

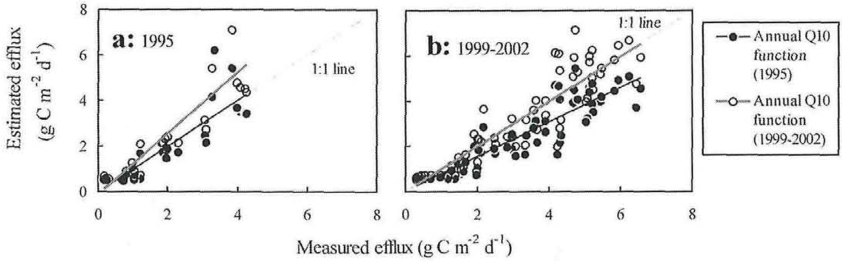

Fig. 4. Relationship between measured and estimated daily CO_2-C effluxes based on the annual Q_{10} function derived from 1995 dataset and by 1999-2002 datasets. (a) 1995 dataset (n=30) of this study, for annual Q_{10} function (1995): slope = 1.01, intercept = -0.04, r^2 = 0.77, and for annual Q_{10} function: slope = 1.33, intercept = -0.12, r^2 = 0.76; and (b) 1999-2002 dataset (n=60) of MO et al. (2004), for annual Q_{10} function (1995): slope = 0.75, intercept = 0.07, r^2 = 0.82, and for annual Q_{10} function: slope = 0.99, intercept = 0.01, r^2 = 0.82. The regression lines are all significant ($P < 0.001$).

Inter-annual variation in soil CO_2 efflux in the 1994–2002 period

Although considerable uncertainties remain in the estimation of annual soil CO_2 efflux using the annual Q_{10} function (MO & al. 2005), we attempted to estimate the year-to-year changes in the annual soil CO_2 efflux for the 1994–2002 period in the studied forest (Table 1). The estimated annual soil CO_2 efflux for the 1994–2002 period ranged between 597 and 793 g C m^{-2} y^{-1}, with a mean value of 713±71 g C m^{-2} y^{-1}. The annual soil CO_2 efflux in 1995, an abnormally cold year, was 16% lower than the mean for the 1994–2002 period, whereas the value in a warm El Niño year (1998) was 11% higher than the mean. These results suggest a large year-to-year variability in annual soil CO_2 efflux in this forest. SAIGUSA & al. 2005 estimated the annual carbon budget components for this forest, including NEP, GPP, and ecosystem respiration (RE), from 1994 to 2002 using flux measurements provided by the micro-meteorological method. They partitioned the annual RE and soil CO_2 efflux on the basis of empirical equations for each parameter as a function of air temperature, and assumed that the temperature dependence of these equations was constant for this forest. However, our findings suggest that the temperature response of soil CO_2 efflux might change in an abnormally cold year, and that this change should be considered when applying empirical models. Our estimation of soil CO_2 efflux matched the annual RE estimated by SAIGUSA & al. 2005 in some years (Table 1); however, estimated values in our study were higher than the annual RE in some years (e.g. 746 and 770 g C m^{-2} y^{-1} in 1999 for RE and soil CO_2 efflux, respectively). The bias between the chamber- and tower-based measurements may result from uncertainties in the estimation of RE (SAIGUSA & al. 2005) as well as uncertainties in the estimation of soil CO_2 efflux. A more comprehensive approach to long-term continuous monitoring of soil CO_2 efflux should be conducted in future studies to permit more detailed discussion of the annual and inter-annual variations in soil CO_2 efflux, and thus provide insights into inter-annual variations in the carbon budget components of the ecosystem.

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