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Characteristics of CO_2 flux over a forest on complex topography

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ABSTRACT

The CO_2 flux over a mixed forest of evergreen and deciduous broad-leaved trees on complex topography was measured by using an eddy covariance method. To evaluate the CO_2 flux over such a forest and to ascertain the effect of topography, the eddy covariance measurement was conducted at the top of each of two meteorological towers erected in a basin (1.6 ha). The CO_2 flux measured by the eddy covariance method was also evaluated by comparing it with the CO_2 flux from leaf photosynthesis and soil respiration as continuously measured by automatic chamber methods on the forest floor and in the foliage. The daily variations in the daytime CO_2 flux values measured at the two towers were each quite similar. However, for the night-time CO_2 flux values, there was about 36% difference between the towers, even though the flux was measured in the same basin. The CO_2 flux as measured by eddy covariance and including CO_2 storage change (F_n) was 60% lower than that estimated by the chamber methods (F_{chm}). The CO_2 flux as measured by using the relation between F_n and soil temperature at 2 cm depth obtained only under conditions of low stability ($U^* \geq 0.25$ m s^{-1}) was 32% lower than F_{chm}.

1. Introduction

Estimation of Japan's carbon balance requires information on the capacity of its forests to take up carbon. The eddy covariance method is commonly used to measure the CO_2 flux in forests. However, in forests situated on complex topography, such as are commonly found throughout western Japan, the accuracy of the eddy covariance method for measuring the CO_2 flux needs to be evaluated.

For night-time measurements in particular, it is uncertain whether the eddy covariance method is reliable, because reliable measurement of flux requires adequate mixing of the air in the ecosystem with the air above the ecosystem (Goulden et al., 1996b). When low wind speeds and high air stability are common at night, sufficient mixing of air is often inhibited. Under such conditions it is important to measure the change in CO_2 stored within the ecosystem to estimate ecosystem respiration (Wofsy et al., 1993; Jarvis, 1994; Ruimy et al., 1995; Baldocchi et al., 1997; Goulden et al., 1996a; Black et al., 1996). However, even when CO_2 storage is taken into account, uncertainty still persists about the accuracy of measurements of night-time respiration. Goulden et al. (1996b) found that even when measurements of night-time CO_2 flux included storage and were made only while there was substantial turbulent air movement, they were still consistently lower than scaled chamber measurements of component respiration rates and were variable. Lavigne et al. (1997) compared night-time respiration as measured by eddy covariance methods and scaled chamber methods at six coniferous boreal sites; the night-time eddy covariance measurements correlated poorly with the scaled chamber estimates of ecosystem respiration and were consistently lower than the scaled chamber predictions.

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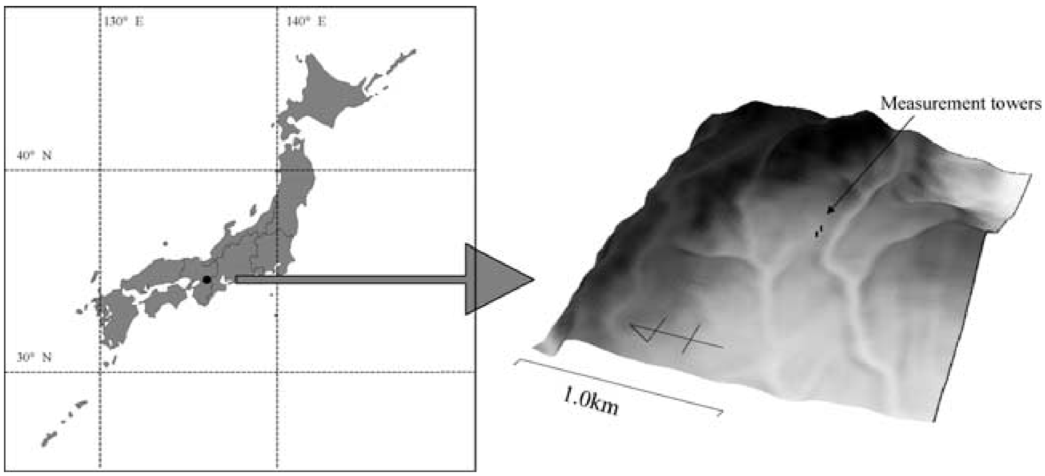

Fig. 1. Location of measurement site.

In this study, we used the eddy covariance method to measure CO_2 flux on two towers [one erected in a valley and the other on a ridge in the same basin (1.6 ha)], and compared the two measurements. We evaluated the CO_2 flux by comparing the data obtained at the two towers with the CO_2 flux measured using chamber methods on the forest floor and in the foliage.

2. Site

Observations were conducted in the Yamashiro Experimental Watershed, located in a hilly and mountainous region of western Japan (lat 34°47′N, long 135°51′E) (Fig. 1, left). The meteorological towers were set up at an altitude of about 220 m asl. The total basal areas of evergreen and deciduous species in the basin are 6.3 and 13.3 m^2 ha^{-1}, respectively. The tree density is 5953 stems ha^{-1}, with deciduous broad-leaf species such as *Quercus serrata* and evergreen trees such as *Ilex pedunculosa* coexisting; the average canopy height is 12 m. Geologically, the site features weathered granites; the soil layer is generally thin, immature and sandy.

3. Methodology

3.1. CO_2 *flux over the forest on the ridge and in the valley*

Two meteorological towers each equipped with an eddy covariance system using a closed-path CO_2 analyzer were erected in the Yamashiro Experimental Basin to measure the CO_2 flux above the forest and to examine the effects of the complex topography on the measurements (Fig. 2). The first tower, 35 m high, was erected in a valley, while the other, 26.5 m high, was situated along a ridge. The difference in elevation from the valley to the ridge is about 25 m and the horizontal distance between the two towers is about 60 m. The eddy covariance sensors were mounted at the top of each tower, and other meteorological variables were measured at various heights. Figure 3 schematically illustrates the eddy covariance system. The eddy covariance measurement was conducted with a three-dimensional ultrasonic anemometer (model DAT-600-3TV, Kaijo, Tokyo, Japan) and a closed-path CO_2 gas analyzer (model LI-6262, LI-COR). The sampling frequency was 10 Hz. The sampled air was drawn into the gas analyzer installed at the bottom of the tower. The distance from the air inlet to the gas analyzer was about 29 m. The delay time was from 9.6 to 10.2 s under a suction of about 9.6 L min^{-1}; the flow rate to the sample cell of the analyzer was maintained at 2.0 L min^{-1} with a mass flow controller (SEC-400, STEC, Kyoto, Japan). The residual air was released from an exhaust port placed just after the pump (subsampling method). Water vapor in the sample air was removed by an air dryer (MD gas dryer, ZBJ02502-72P, Perma-pure, Thomas River, NJ, USA). This air dryer has a high-polymer membrane tube permeable only to water vapor. The sample air is passed through the membrane tube, and dry air is passed along the outside of the tube; as a result, the water vapor moves in the direction of the reduced water vapor pressure,

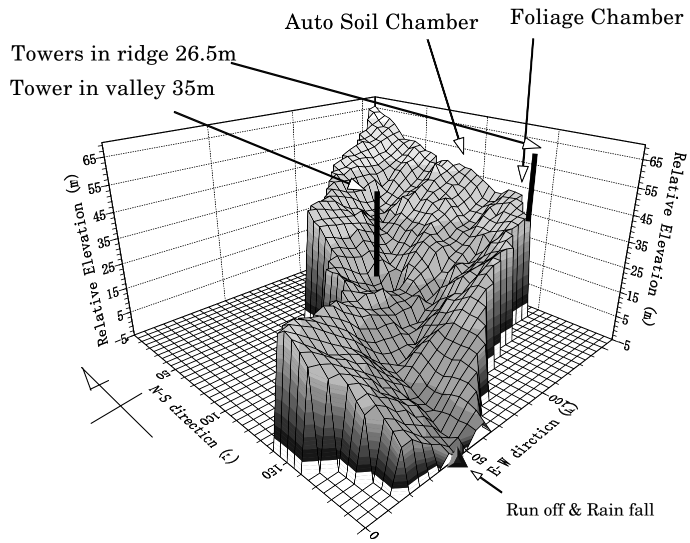

Fig. 2. Elevation map of measurement basin. (Similar geographical features spread out besides the basin.)

namely, from the inside to the outside of membrane tube. The water vapor in the sample air can thus be removed at high speed. Although the chance to measure water vapor flux is lost, dehumidification has the advantage of allowing CO_2 flux to be calculated without the WPL correction (Webb et al., 1980), and also avoids the hazard of dew formation in the sample cell. The flow rate before the sample cell and the humidity and temperature of the sample air at the outlet of the sample cell were monitored with a flow meter and a thermo-hygrometer (HMP-230, Vaisala). The reference cell in the closed-path CO_2 gas analyzer was filled with pure N_2 gas at a flow rate of 0.02 L min^{-1}. Calibration of absolute CO_2 concentration was carried out once a day from 23:45 to 24:00 by using two kinds of standard gas (1, 400 ppm CO_2, 80% N_2, 20% O_2; 2, 0 ppm CO_2, 80% N_2, 20% O_2). CO_2 flux was calculated at 30 min intervals. Almost similar measurement system was evaluated by open-path eddy covariance measurement system (Yasuda et al., 2000).

In this study, we used eddy covariance flux data from 1 January to 31 December 2001 for the ridge measurements and data from 25 April to 19 June 2001 for the valley measurements.

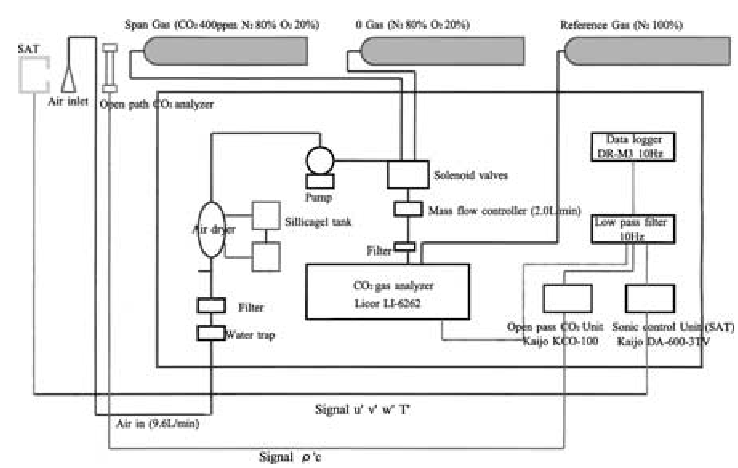

Fig. 3. Scheme of eddy covariance measurement.

3.2. *Storage inside the canopy*

Vertical profiles of CO_2 concentration on the ridge were obtained from air samples taken at eight different heights and pumped through Teflon-lined tubing to an infrared gas analyzer. Calibration of absolute CO_2 concentration and dehumidification were carried out by the same methods as used for the eddy covariance measurements. Vertical profiles from successive 20 min measurement periods were subtracted from each other to measure the changes in CO_2 storage within the canopy over these periods. Our CO_2 flux measurements obtained by the eddy covariance method at 26.5 m on the ridge tower, $F_{\text{eddy(ridge)}}$, and the vertical CO_2 concentration profiles provide a direct measurement of $\text{NEE}_{\text{(ridge)}}$,

$$\text{NEE}_{\text{(ridge)}} = F_{\text{eddy (ridge)}} + \frac{\mathrm{d}C_{\text{(ridge)}}}{\mathrm{d}t}$$

where $c(z)$ is the CO_2 concentration at height z and

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\int c(z)\,\mathrm{d}z$$

is the rate of change of CO_2 concentration between 0 and 26.5 m.

We did not measure the CO_2 storage in the valley in 2001; furthermore, to compare the NEE at a ridge and valley, evaluation of the rate of drainage flow is necessary. Therefore, in this paper we compare only the CO_2 flux at a ridge and valley.

3.3. *CO_2 flux from the forest floor*

The CO_2 flux from the forest floor was measured by using an automatic infrared gas analyzer (IRGA) enclosed-chamber method (Fig. 4). This is an unattended method that raises and lowers a chamber from the soil automatically. The chamber contains an IRGA (GMD 20, Vaisala) to measure the CO_2 concentration. The CO_2 flux from the forest floor was calculated from the increase in CO_2 concentration in the chamber. Nobuhiro et al. (2000) verified the usefulness of enclosing an IRGA in a soil chamber, and determined that the flux rates measured using this chamber method were almost equal to those measured by the closed-flow method with an LI-800 IRGA gas analyzer (LI-COR), over a wide range of CO_2 flux. Using the IRGA/enclosed-chamber method, we measured seasonal and spatial variations in soil respiration from 2000 to 2001 at eight points in the Basin. With the soil respiration data obtained using the automatic chamber method and the measurements of spatial variations in soil respiration, we estimated the mean soil respiration at 30 min intervals from 15 February to 31 December 2001.

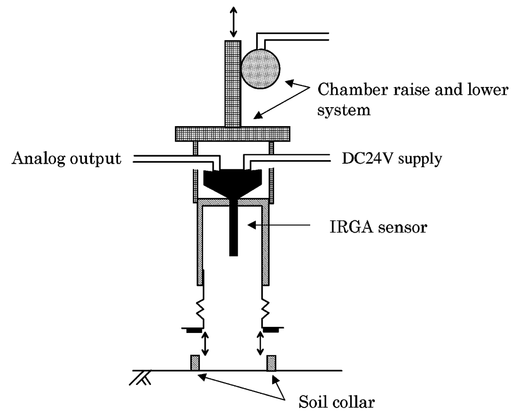

Fig. 4. Method of automatically determining soil CO_2 flux.

3.4. *CO_2 flux in the foliage*

CO_2 flux from the foliage of *Quercus serrata* was measured by using an automated foliage chamber method (Miyama et al., 2001). This is an unattended method that automatically opens and closes a chamber enclosing some foliage. A pump system circulates air between the chamber and a CO_2 gas analyzer (LI-800, LI-COR) that measures the change in CO_2 gas concentration. The CO_2 flux from or into the foliage was calculated from the rate of change in the CO_2 concentration in the chamber. In this study, we used 30-min-interval CO_2 flux data from the foliage of *Quercus serrata* from 26 May to 26 November 2001.

4. Results and discussion

4.1. *Daily variations in CO_2 flux over the ridge and valley*

Figure 5 shows an example of CO_2 flux measured at both the ridge and the valley, and the tendency of the daily variation roughly shows a good relation in the daytime. Therefore, no great changes were seen between the daily variations in CO_2 flux obtained at locations with different geographical features in the local area during the daytime. However, during the night-time, although the respiration rate was occasionally about 0.3 mg m^{-2} s^{-1} at both sites, there were

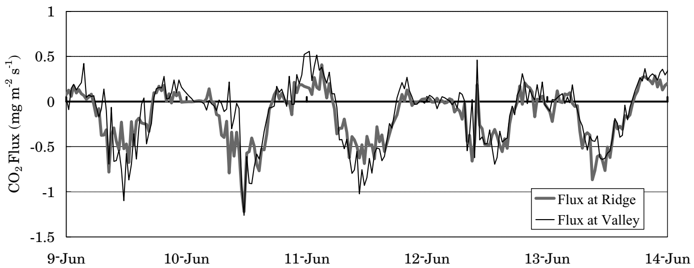

Fig. 5. Daily changes in CO_2 flux measured on the ridge and in the valley using the eddy covariance method.

days when the night-time flux barely reached a positive value. The night-time flux was small when the wind speed was small and the temperature difference between the ridge and the valley was large. We suspected that there is a downward airflow from the ridge to the valley at this time. However, the conditions under which this phenomenon occurs are a subject for future work. As this tendency for night-time flux not to reach a positive value is generally larger on the ridge than in the valley, night-time CO_2 flux measured on the ridge was generally smaller than that in the valley. Table 1 shows the averaged daily amounts of the positive values and the negative values of the CO_2 flux in the valley and on the ridge from 25 April to 19 June 2001. The average positive value, which corresponds to the night-time data, on the ridge was about 36% smaller than the value in the valley, although the average negative values, which correspond to the daytime data, were very close for the ridge and the valley. The total CO_2 flux on the ridge was about 28% smaller than in the valley.

4.2. *Eddy covariance measurements of night-time ecosystem CO_2 flux on the ridge*

Following the method of Wofsy et al. (1993), we plotted storage-corrected night-time eddy covariance

Table 1. *Average daily amounts of the positive values and the negative values of the CO_2 flux in the valley and on the ridge from 25 April to 19 June 2001*

	Total daily CO_2 flux ($g\ m^{-2}\ d^{-1}$)	Daily sum of positive values of CO_2 flux ($g\ m^{-2}\ d^{-1}$)	Daily sum of negative values of CO_2 flux ($g\ m^{-2}\ d^{-1}$)
Ridge	−10.8	4.69	−15.49
Valley	−8.43	7.31	−15.74

fluxes on the ridge against soil temperatures at 2 cm depth (T_s). Data for the 9 h between 20:00 and 05:00 were selected to analyze night-time ecosystem respiration. Figure 6a indicates all data and Fig. 6b indicates data for when air was well mixed for the cases $0.35 > U^* \geq 0.25$ m s^{-1} and $U^* > 0.35$ m s^{-1}. Eddy covariance fluxes above the forest were often negative when air was not well mixed, and even when $U^* \geq 0.25$ m s^{-1}, eddy covariance fluxes were negative at times and the correlation coefficient was low ($|r| = 0.623$). Accepting only above-forest data for which $U^* \geq 0.25$ m s^{-1}, which was 20% of the night-time data in 2001, we obtained the following average relationship (Fig. 6b):

$$F_n = 0.0278 \exp(0.076 T_s),$$

where F_n is the night-time ecosystem respiration on the ridge in mg CO_2 m^{-2} s^{-1}, and T_s is in °C.

Furthermore, accepting only data for which $U^* \geq 0.35$ m s^{-1}, we could obtain steeper equation:

$$F_n = 0.0157 \exp(0.114 T_s),$$

but available data were only 9% of night-time data in 2001.

Table 2 shows the contributions of eddy covariance flux (F_{eddy}) and storage (F_{stor}) to the estimates of night-time net ecosystem exchange of CO_2 (F_n). Lavigne et al. (1997) observed that F_{stor} explained approximately 50% of F_n on average in three coniferous boreal sites when air was not well mixed. However, in our site, the contribution of F_{stor} to F_n was about 28% under conditions when air was not well mixed, and F_{stor} made negligible contributions (0.6%) to F_n when air was well mixed. However, even in cases of high stability, the increased CO_2 storage during the night and the negative CO_2 flux due to consumption of stored CO_2 in the morning was not remarkable. This was mainly

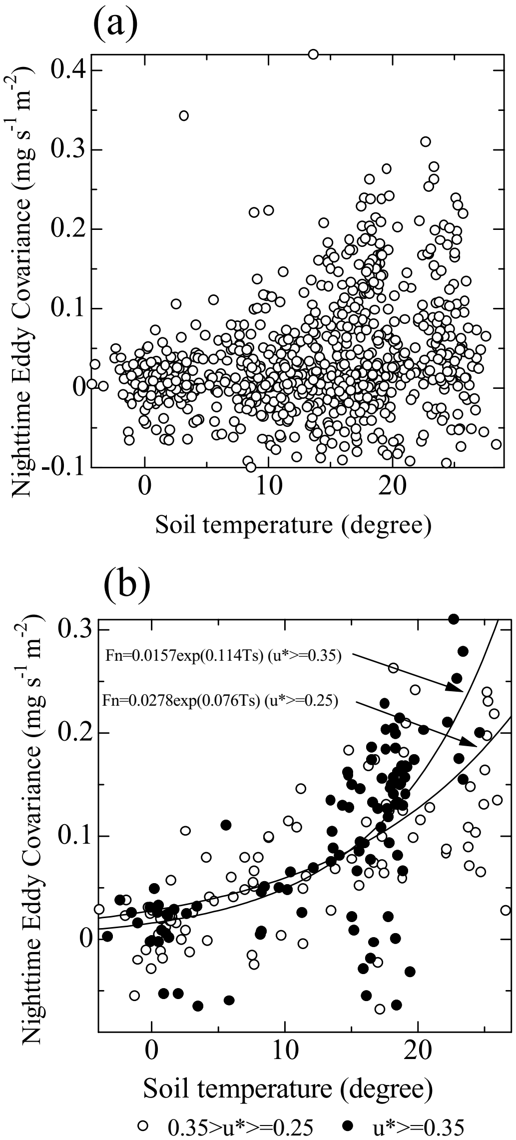

Fig. 6. Relationship between storage-corrected nighttime eddy covariance fluxes on the ridge and soil temperature at 2 cm depth (T_s). (a) All data, (b) under conditions of $0.35 > U^* \geq 0.25$ and $U^* \geq 0.35$ m s^{-1}.

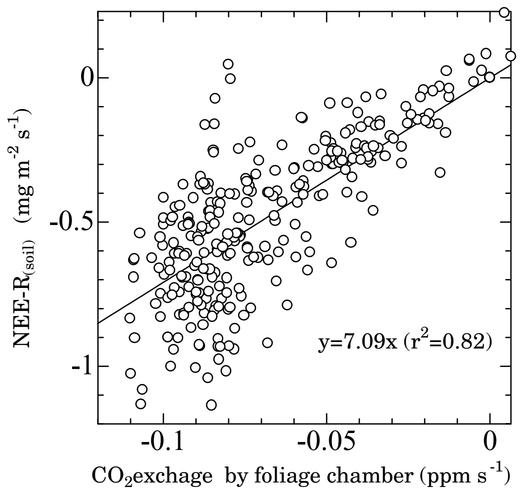

Fig. 7. Relationship between the rate of CO_2 flux minus soil respiration and CO_2 flux from foliage of *Quercus serrata*.

because, even on very calm nights (almost no wind), the difference in CO_2 concentration between the top of the tower (26.5 m) and inside the canopy (3.1 m) was almost always less than 20 ppm. We suspected that was caused by horizontal advection.

4.3. Comparison of CO_2 flux estimated by the eddy covariance method and the chamber methods in night-time

To evaluate the CO_2 flux from the forest as calculated by the eddy covariance method and by the chamber method at night-time, we assumed the following equation:

$$F_c \fallingdotseq F_{(sol)} + F_{(fol)},$$

where F_c is the net ecosystem flux of CO_2, $F_{(sol)}$ is soil respiration, and $F_{(fol)}$ is foliage respiration.

Because we did not have accurate data on spatial variations in the CO_2 flux from foliage, we could not estimate the mean CO_2 flux from foliage at our measurement site by using only the data obtained from the foliage chamber measurements. However, because

Table 2. *Contributions of CO_2 flux measured by the eddy covariance method* (F_{eddy}) *and storage* (F_{stor}) *to estimates of night-time net ecosystem exchange of CO_2* (F_n) *from 1 January to 31 December 2001*

	F_n (mg s^{-1} m^{-2})	F_{eddy} (mg s^{-1} m^{-2})	F_{stor} (mg s^{-1} m^{-2})	Contribution of storage to NEE
$U^* \geq 0.25$ m s^{-1}	0.079	0.078	0.0005	0.5%
$U^* < 0.25$ m s^{-1}	0.028	0.02	0.0079	28%

the relation between the rate of CO_2 flux using the eddy covariance method minus soil respiration and the CO_2 flux obtained by the foliage chamber method has reasonable linearity for daytime data (Fig. 7), we assumed the following equations to estimate the night-time CO_2 flux from foliage by using the daytime CO_2 flux from foliage and the daytime eddy covariance measurements:

$$F_{(\mathrm{fol})} = D_{(\mathrm{fol})} \frac{\sum (F_{\mathrm{daytime(eddy)}} - F_{\mathrm{daytime(sol)}})}{\sum D_{\mathrm{daytime(fol)}}},$$

$$F_{(\mathrm{chm})} = F_{(\mathrm{fol})} + F_{(\mathrm{sol})},$$

where $F_{(\mathrm{fol})}$ is the mean CO_2 flux from the foliage in the measurement site, $F_{\mathrm{daytime(sol)}}$ is the CO_2 flux at the forest floor in the daytime, $F_{\mathrm{daytime(eddy)}}$ is the CO_2 flux estimated by eddy covariance measurements over

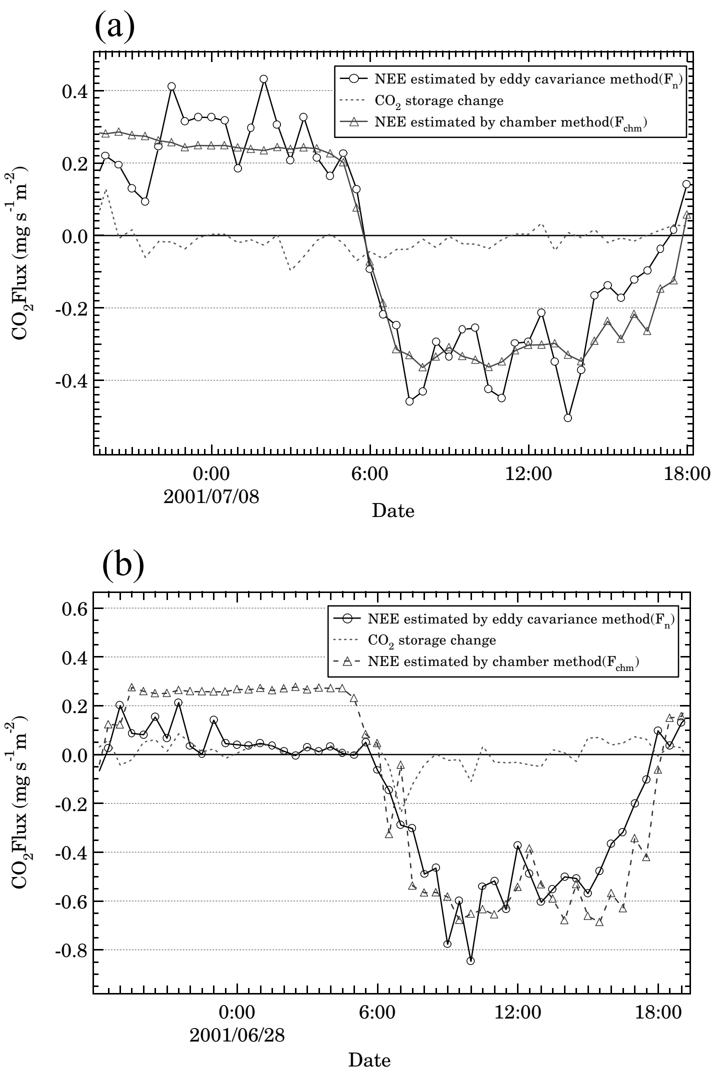

Fig. 8. Daily variations of CO_2 flux estimated using the eddy covariance method including CO_2 storage, change in storage of CO_2 and CO_2 flux estimated by chamber methods. (a) Under conditions of high wind speed and low stability; (b) under conditions of low wind speed and high stability at night.

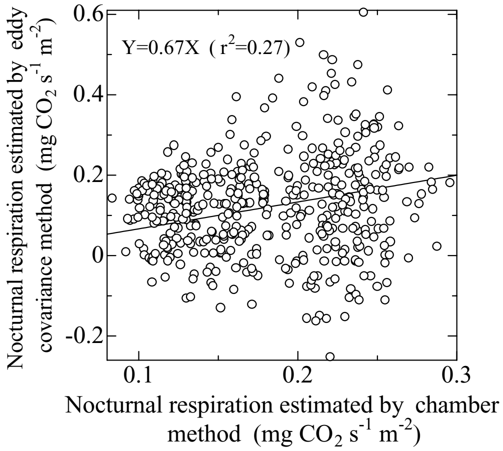

Fig. 9. Relationship between night-time ecosystem respiration estimated by the eddy covariance method including CO_2 storage and by chamber methods ($U^* \geq 0.25$ m s^{-1}).

forest in the daytime, $D_{(fol)}$ is the CO_2 flux measured by foliage chamber, $D_{daytime(fol)}$ is the CO_2 flux measured by foliage chamber in the daytime, and $F_{(chm)}$ is the CO_2 flux estimated by chamber methods.

In these equations, we assumed that the amount of the CO_2 flux from the foliage and forest floor is equivalent to that over the forest measured using the eddy covariance method during the daytime.

Figure 8 shows examples of the daily variations in CO_2 flux estimated using the eddy covariance method and including CO_2 storage, change in CO_2 storage, and CO_2 flux estimated by the chamber methods. The example in Fig. 8a is under conditions of high wind speed and low stability, and the example in Fig. 8b is under conditions of low wind speed and high stability at night. In both cases, the variations in CO_2 flux using the two methods were well correlated for daytime values. In both examples, the patterns of CO_2 accumulation as determined by each method, increasing from morning to noon, correlated well with each other. On the other hand, during the night, the CO_2 flux measured by the eddy covariance method was much smaller than that measured by the chamber methods when the wind speed was small. Furthermore, the variance of the CO_2 flux as measured by the eddy covariance method was generally larger than that of chamber method, and often showed negative values. Figure 9 shows the relation between night-time ecosystem respiration estimated by the eddy covariance method including CO_2 storage and that estimated by the chamber methods when $U^* > 0.25$ m s^{-1}. The value of the coefficient in the relationship $F_n = bF_{chm}$ was lower than 1 ($b = 0.67$) and the correlation was poor ($r^2 = 0.27$). This is similar to the results of Lavigne et al. (1997), for which b ranges from 0.58 to 0.80 and r^2 from 0.06 to 0.27.

Table 3 shows the average night-time CO_2 flux measured by the eddy covariance method (F_n), that estimated by using soil temperature at 2 cm depth (T_s), and the relation between F_n and T_s obtained in section 4.2 (F_{ts}) and that estimated by chamber methods (F_{chm}) using data from 25 May to 26 November 2001. F_n was 60% lower than F_{chm}. In other studies that have compared F_n and F_{chm}, Goulden et al. (1996b) observed that F_n was 35% lower than F_{chm} in a temperate, deciduous forest, and Lavigne et al. (1997) observed that F_n was 20–40% lower than F_{chm} at six coniferous BOREAS sites. Compared with these results, the results of our eddy covariance measurements were very small. The CO_2 flux as measured by using the relation between F_n and T_s obtained only under conditions of low stability ($U^* > 0.25$ m s^{-1}), F_{ts}, was 32% lower than F_{chm}. We examined the possibility that the night-time ecosystem CO_2 flux was underestimated owing to advective losses or to the same environmental conditions that make eddy covariance measurements and storage measurements difficult at night. However, the likely reason is because ecosystem CO_2 flux estimated by chamber methods (F_{chm}) greatly depends on the

Table 3. *Average night-time CO_2 flux measured by the eddy covariance method (F_n), average night-time CO_2 flux estimated by using the soil temperature at 2 cm depth (T_s) and the relation between F_n and T_s obtained in section 4.2 (F_{ts}), and average night-time CO_2 flux estimated by chamber methods (F_{chm}) using data from 25 May to 26 November 2001*

	F_n, eddy covariance method at ridge	F_{ts}, estimated using soil temperature	F_{chm}, estimated by chambers	F_{sol}, soil respiration	F_{fol}, foliage respiration
Mean night-time respiration (mg s^{-1} m^{-2})	0.071	0.121	0.178	0.145	0.034

values of soil respiration, and at our site, relative soil respiration varied within the range 50–160% (data not shown). To evaluate ecosystem CO_2 flux with greater accuracy, additional studies are needed to measure the spatial variations in CO_2 flux from foliage and woody tissue and to measure CO_2 storage in the valley, as well as to estimate CO_2 flux by using biomass inventory data.

5. Conclusion

To evaluate CO_2 flux over a forest situated on complex topography, the CO_2 flux measured at two meteorological towers erected in the same basin were compared. Furthermore, to evaluate the underestimation of night-time ecosystem CO_2 flux using the eddy covariance method, CO_2 flux using the eddy covariance method was evaluated by comparing the calculated values with the CO_2 flux due to leaf photosynthesis and soil respiration, as were continuously measured by using soil and foliage chamber methods. Night-time CO_2 flux measured by eddy covariance including CO_2 storage change was 60% lower than CO_2 flux estimated by the chamber methods even after accounting for CO_2 storage. This result shows the possibility that the night-time ecosystem CO_2 flux was underestimated owing to advective losses. However, CO_2 flux estimated by chamber methods greatly depends on the spatial variations in CO_2 flux from soil and foliage. Therefore, to estimate mean ecosystem CO_2 flux by chamber methods more accurately, measurements of the spatial variability of each component over a wide area are needed. Night-time ecosystem respiration accounts for a large fraction of the daily net carbon uptake, so accurate estimations are required to estimate net ecosystem exchange correctly.

6. Acknowledgements

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