12.6 INTER-ANNUAL VARIABILITY OF CARBON BUDGET COMPONENTS IN AN ASIAFLUX FOREST SITE ESTIMATED BY LONG-TERM FLUX MEASUREMENT

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1. Introduction

The study site is located in a cool-temperate zone in central Japan, under significant influence of the Asian monsoon. The Asian summer monsoon, often characterized by heavy rains and humid summers, provides abundant water to most ecosystems during the growing season. The Asian winter monsoon affects the amount of snowfall, especially in mountainous regions, which plays an important role in the spring onset of the growing season as well as in the provision of water resources for the upcoming summer.

We investigated the year-to-year variability of the annual carbon budget estimated by a long-term flux measurement extended over ten years. An objective of this study is to present the long-term trend of the CO_2 exchange and to make clear the cause of the year-to-year variability. The focus of the paper is on the inter-annual variability of the annual carbon budget components in relation to the climatic variables and the length of the growing season.

2. Site

The study site, established in 1993, is about 15 km east of Takayama City, in the central part of Japan (36^o 08' N, 137^o 25' E, elevation 1,420 m). Annual precipitation is about 2,300 mm. Vegetation is an approximately 50-year-old secondary deciduous forest, primarily dominated by oak (*Quercus crispula*) and birch (*Betula ermanii*; *Betula platyphylla var. japonica*) (Jia et al., 2002; Muraoka et al., 2003; Ohtsuka, 2003). The canopy height is about 15-20 m. The sub-canopy is dominated by maple (*Acer rufinerve*; *Acer distylum*) and shrubs (*Hydrangea paniculata*; *Viburnum furcatum*). The understory is dominated by a dense evergreen dwarf bamboo (*Sasa senanensis*). A tower 27 m in height is located in a hilly area, and the main wind direction shows a clear diurnal variation from west to southwest in daytime and northeast at night.

3. Method

3.1 *Meteorological measurements*

The downward and upward radiation for short wave (MR21, EKO Japan) and long wave (MS201, EKO) and the air temperature and humidity (HMP 233, VAISALA) are measured on the tower. Wind direction and mean wind speed are measured at 26 m and 10 m in height by combined wind vane and fan anemometers (MA-110, EKO). The soil water content (CS615, CAMPBELL) and soil heat flux (MF81, EKO) are measured under the forest floor. Photosynthetic Active Radiation (PAR) is measured (IKS27, KOITO, Japan) above and below the canopy. The Plant Area Index (PAI) of the tree canopy has been estimated near the tower since 1995 by an optical sensor for PAI measurement (Plant Canopy Analyzer, LAI-2000, LI-COR) (Yamamoto et al., 1999) and also by a transmittance of PAR assuming constant extinction coefficient k (=0.83) (Saigusa et al., 2002).

3.2 *Flux measurements and carbon budget estimation*

The CO_2 flux above the canopy has been measured since September 1993 by an aerodynamic method using the vertical gradient of CO_2 concentration dC/dz and the diffusion coefficient K over the canopy (Yamamoto et al., 1999).

$$F_C = K\,\frac{dC}{dz} \quad . \qquad (1)$$

The value of K was calculated based on the mixing length theory in and above the canopy (Watanabe and Kondo, 1990) by the mixing length L and the vertical gradient of the mean wind speed du/dz as follows.

$$K = L^2\left|\frac{du}{dz}\right| \quad . \qquad (2)$$

The mean CO_2 concentration has been continuously measured since 1993 at different heights in and above the canopy (27, 18, 8.8, and 5.8 m) with high precision using calibrated standard gases (Murayama et al., 2003). The vertical gradient of the CO_2 concentration was calculated by the hourly mean CO_2 concentration at two heights over the canopy (27 m and 18 m), and the gradient of wind speed was estimated by the hourly mean wind speed measured at 26 m and 10 m. The CO_2 flux was estimated by the aerodynamic method every hour.

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In 1999, the CO_2 flux by the aerodynamic method was intensively compared with that by the eddy covariance method in order to validate the CO_2 flux estimated by the aerodynamic method. The mixing length was estimated by the inter-comparison and classified by the wind speed and solar radiation as described by Yamamoto et al. (1999). The values of mixing length were listed in Table 1.

Table 1 Values of mixing length for each atmospheric stability category (u, mean wind speed; S, solar radiation).

	S > 500 Wm^{-2}	20 < S < 500 Wm^{-2}	S <20 Wm^{-2}
0 < u < 3 m s^{-1}	4.2 m	3.9 m	4.3 m
3 < u m s^{-1}	3.7 m	3.8 m	5.2 m

The fluxes of sensible heat, water vapor, and CO_2 have been measured continuously since July 1998 by the eddy covariance method at 25 m on the tower using a three-dimensional ultrasonic anemometer (DAT-600, KAIJO, Japan) and a closed-path infrared gas analyzer (LI-6262, LI-COR). The coordinate rotation for the vertical wind speed normal to the mean wind direction was applied. The time lag required to draw air down was determined every half hour, and spectral correction was applied. The net ecosystem CO_2 exchange NEE was calculated every half-hour taking into account the CO_2 storage in the canopy. Small data gaps of up to 2-3 hours were filled by interpolation. Large gaps were filled by empirical equations expressing the relationship among NEE, PAR, and the air temperature.

In the present site, Saigusa et al. (2002) reported that the slope of the energy balance (H+λE) plotted against (R_n-G) was 0.76 for the daily (24-hour) values and 0.65 for the half-hourly values (H is the sensible heat flux; λE is the latent heat flux, R_n is the net radiation, and G is the heat storage). The complex topography at the site could have caused the large imbalance. In the following study, the CO_2 flux was not corrected by the lack of energy budget.

Equation (3) is an empirical formula expressing the relationship between the air temperature at 25 m height T (^oC) and the ecosystem respiration RE at the site measured by the eddy covariance method under nearly neutral atmospheric stability conditions to avoid the flux underestimation on stable nights (Saigusa et al., 2002).

$$\mathrm{RE} = A \cdot Q^{\frac{T-10}{10}} . \qquad (3)$$

$$(Q = 2.57, A = 0.17 \text{ mol m}^{-2} \text{ day}^{-1}).$$

Taking the stability dependence of NEE into consideration, the values of NEE on stable nights (friction velocity $u_* < 0.2$ m s^{-1}) were replaced by Eq. (3).

The soil CO_2 flux R_{SOIL} has been measured by plant ecologists near the tower by the chamber method since 1993 (Nishimura, 1996; Lee et al., 2002; Jia et al., 2003; Mo et al., 2003). An empirical equation of R_{SOIL} (mol m^{-2} day^{-1}) was provided as a function of the air temperature.

$$R_{SOIL} = 4.50 \times 10^{-4} T^2 + 6.91 \times 10^{-3} T + 4.87 \times 10^{-2} \quad (4)$$

In the following analyses, daily (24-hour) values of carbon budget components were estimated as follows. First, the daily net ecosystem production NEP and the daily gross primary production GPP were derived by NEE.

$$\mathrm{NEP} = -\ \mathrm{NEE} \quad , \qquad (5)$$

and

$$\mathrm{GPP} = \mathrm{NEP} + \mathrm{RE} \quad . \qquad (6)$$

The daily values of RE were calculated by Eq.(3) using the daily mean air temperature. The daily soil respiration R_{SOIL} was then calculated by Eq. (4) using the daily mean air temperature. Finally, the aboveground autotrophic respiration RA_{above} and the net primary production of aboveground biomass NPP_{above} were calculated as follows.

$$RA_{above} = \mathrm{RE} - R_{SOIL}, \qquad (7)$$

and

$$NPP_{above} = \mathrm{GPP} - RA_{above} = \mathrm{NEP} + R_{SOIL} . \quad (8)$$

4. Results

4.1 *Meteorology*

Figures 1 (a) to (d) show the year-to-year change in the annual solar radiation, the air temperature, the maximum snow depth, and the day when the snow melted away in an open field. The general weather conditions from 1994 to 2003 can be summarized as follows.

(1) The rainy season typically occurs from early June to mid-July and provides plenty of precipitation, about 300-500 mm.

(2) The snowmelt typically occurred from March to April (DOY 60-120). The site was usually covered with snow for six months.

(3) A hot summer with fine weather in 1994 caused the highest annual solar radiation (14.6 MJ m^{-2} d^{-1}) and the second highest annual air temperature (7.1 ^oC).

(4) Heavy snowfall in January and February 1996

caused the highest maximum snow depth (182 cm) and the latest snowmelt (DOY 131).

(5) An extremely warm spring in 1998 caused the earliest snowmelt (DOY 100) and the highest annual air temperature (7.6 ^{o}C). A cloudy summer in 1998 and 2003 caused low annual solar radiation (12.1-12.3 MJ m^{-2} d^{-1}).

During the observational period, the effects of El Niño were observed from spring 1997 to summer 1998 and from spring to winter 2002, while those of La Niña were observed from autumn 1998 to spring 2000 (Japan Meteorological Agency, 1998 and 2002).

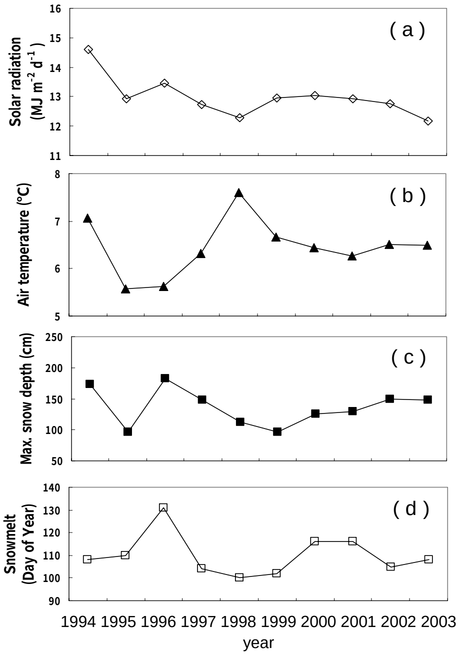

Fig. 1: (a) The annual mean solar radiation, (b) the annual air temperature, (c) the maximum snow depth, and (d) the day when the snow melted away in an open field near the tower from 1994 to 2003.

4.2 *Uncertainty in annual NEP relating to nighttime flux correction*

Nighttime correction is one of the most critical sources of uncertainty at the site because of the complex terrain around the tower. Here, the uncertainly in annual NEE caused by the nighttime correction was tested. The nighttime NEE was estimated with and without nighttime flux correction, depending on u_*. Based on the eddy covariance method, the annual NEP values for 1999, 2000, and 2001 were estimated to be 198, 309, and 290 gC m^{-2} year^{-1} with the correction (u_*<0.2 m s^{-1}) and 251, 376, and 342 gC m^{-2} year^{-1} without the correction, respectively. The nighttime flux correction is responsible for an uncertainty in the annual NEP of 52-67 gC m^{-2} year^{-1}. In the following analyses, we corrected the nighttime NEE with the condition u_*<0.2 m s^{-1}. By the correction, a remarkable number of nighttime NEE values were replaced by Eq. (3) (about 60 % of the nighttime NEE).

4.3 *Seasonal and inter-annual variation of NEP from 1994 to 2003*

Figure 2 shows the seasonal and inter-annual variation of NEP from 1994 to 2003 estimated by the aerodynamic and the eddy covariance methods with a nighttime correction. The NEP was calculated for ten years; this is the longest record at any particular site in Asia as a consequence of the flux measurements. In mid-winter, from December to March, when the forest was covered with snow, the forest released CO$_2$ about 0.2-0.6 gC m^{-2} d^{-1}. In the growing period, typically from June to September, the uptake of CO$_2$ was about 4-5 gC m^{-2} d^{-1}; these values are in a similar range to those in other broadleaf deciduous forests (3.5 gC m^{-2} d^{-1} in June 2000, Tanaka et al., 2001; 4.5-5.0 gC m^{-2} d^{-1} in May 1998, Yasuda et al., 1998) and a needle leaf deciduous (Larch) forest (4.2 gC m^{-2} d^{-1} in June 2001; Hirano et al., 2003) in central and northern Japan.

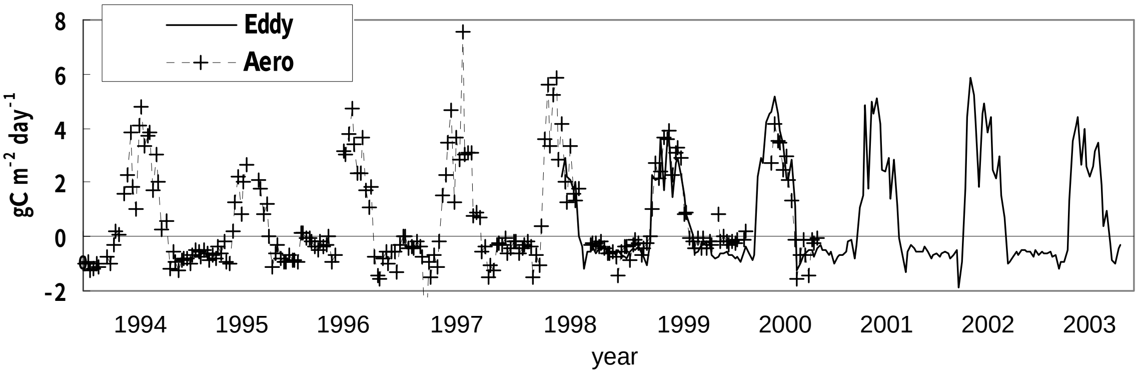

Fig. 2: Seasonal and inter-annual change in the 30-day average of NEP from 1994 to 2003 estimated by the aerodynamic (a dashed line with symbols) and the eddy covariance (a solid line) methods.

4.4 *Annual carbon budget from 1994 to 2003*

The annual carbon budget components were estimated from 1994 to 2003 using the NEE determined by the flux measurements and RE and R_{SOIL} estimated by Eqs. (3) and (4). The annual NEE was determined by the aerodynamic method from 1994 to 1998 and by the eddy covariance method from 1999 to 2003. Figure 3 shows that the annual NEP varies from 59 gC m^{-2} (1995) to 346 gC m^{-2} (the ten-year average was 237±87 gC m^{-2}, mean±SD, n=10). A large year-to-year variability of up to 287 gC m^{-2} was observed in the NEP. A high annual NEP was observed in 2002 (346 gC m^{-2}) and in 1998 (329 gC m^{-2}). The annual RE changed from 699 gC m^{-2} (1996) to 819 gC m^{-2} (1998), and R_{SOIL} varied from 620 gC m^{-2} (1995) to 731 gC m^{-2} (1998). The values of the annual RE and R_{SOIL} showed less variability than that of the NEP. The high values of RE and R_{SOIL} in 1998 were caused by the highest annual temperature in 1998 (see Fig. 1 (b)).

The annual GPP ranged from 765 gC m^{-2} (1995) to 1148 gC m^{-2} (1998). A high GPP was observed in 1998 (1148 gC m^{-2}) and in 2002 (1092 gC m^{-2}). Results shown in Fig. 3 suggest that the carbon budget components representing productivity (NEP, GPP, and NPP_{above}) had more remarkable year-to-year variability than the respiration (RE and R_{SOIL}). The results also indicate that the annual NEP had a similar year-to-year variation to that for GPP and NPP_{above}. As a consequence, the inter-annual variability in the annual NEP was supposed to be caused by the variability of photosynthetic productivity rather than respiratory CO_2 release from soil and plants.

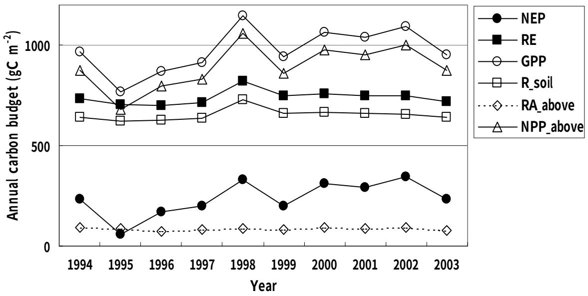

Fig. 3: Annual values of carbon budget components from 1994 to 2003.

5. Discussion

Although there are still considerable uncertainties in the estimations of the carbon budget, the year-to-year changes in NEP, RE, and GPP provide suggestive data. First of all, the production components (GPP and NEP) were considerably higher in 1998 and 2002 than in other years. As compared with 1999 (a less productive year), NEP in 2002 (a highly productive year) was remarkably higher at the beginning of the growing season (in the foliation period). The NEP in 2002 increased earlier (DOY 130-140) than in 1999 (around DOY 150). After that, a significantly high NEP in 2002 continued until the end of June (DOY 181). During the rainy season in July (DOY 182-212), the NEP in the two years decreased almost equivalently. From August to October (DOY 213-304), the values between the two years did not differ much. Here, the NEP and GPP at the site hardly suffered from drought stress during the summer with high annual precipitation (> 2,000 mm $year^{-1}$) and volumetric soil water content (0.2-0.5 at 10-40 cm deep). As a result, the CO_2 uptake was significantly higher in 2002 during the first half of the growing period, probably because of earlier leaf expansion. The foliation was earlier in 1998 and 2002 and later in 1999 and 2000. On the other hand, the end of defoliation occurred at almost the same time each year (around DOY 300).

Earlier leaf expansion could have been caused by a warm spring. Figures 4 (a) to (c) show the inter-annual variations of NEP, spring air temperature (monthly mean in April), and summer solar radiation (three-month average of June, July, and August). Unusually high spring air temperatures were observed in 1998, 2002, and 1994, before the foliation periods, and the data also show that the annual NEP had a positive correlation with the spring air temperature (NEP[gC m^{-2}] = 22.0 T[^{o}C] + 126, r= 0.54) but not with the summer solar radiation.

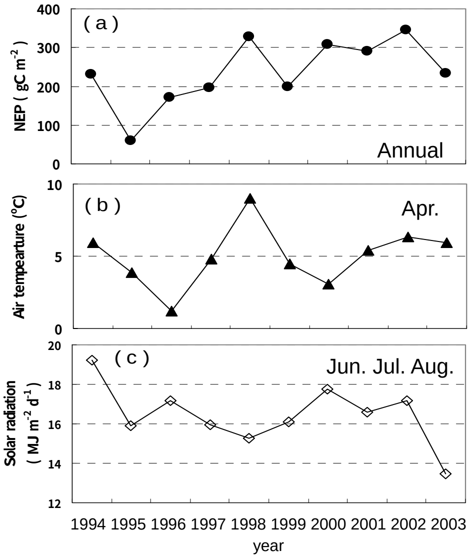

Fig. 4: Inter-annual variations of (a) the annual NEP, (b) the monthly mean air temperature in April, and (c) the three-month average of the solar radiation from June to August.

Results from the present study suggest that an unusually warm spring in 1998 and 2002 under the influence of El Niño caused earlier leaf expansion and higher annual GPP and NEP in a cool-temperate deciduous forest at the site. Similar results were reported by Black et al. (2000); they noted that a southern boreal Aspen forest also increased the CO_2 uptake in 1998 because of an unusually warm spring and a long growing period. On the other hand, recent studies based on the measurement of the atmospheric CO_2 concentration on a global scale suggest a different effect of El Niño / Southern Oscillation (ENSO) on terrestrial ecosystems. According to the inter-annual variation of the growth rate of the atmospheric CO_2, it has been pointed that many ENSO events appear to be associated with a net transfer of CO_2 from the ecosystem to the atmosphere; these reports show that El Niño produces droughts, particularly in tropical regions, which can cause a decrease in photosynthesis and an increase in the frequency of wild forest fires (Keeling et al., 1989, 1995; Langenfelds et al., 2002; Murayama et al., 2004). It is possible that the inter-annual change in GPP and NEP varies with every climatic zone; for example, the GPP in tropical forests may be decreased by drought under ENSO events, and, in cool-temperate and boreal regions, it may increase because of a long growing period. The complicated relationship between the CO_2 growth rate in the lower troposphere and ENSO events has been studied using a regional atmospheric simulation model with physical and biological interaction processes in East Asia (Mabuchi et al., 2000); however, the mechanisms have not been fully clarified. Further studies are obviously necessary to elucidate the relationship between the terrestrial carbon budget and climatic variations in detail and to gain understanding of ecosystem responses on a spatial pattern.

6. Conclusions

Seasonal and year-to-year changes in carbon budget components, such as NEP, GPP, and RE, were estimated from 1994 to 2003 by the flux measurements based on the aerodynamic and the eddy covariance methods in a cool-temperate broadleaf deciduous forest in central Japan.

From the ten-year data, the NEP of the forest was found to have a large year-to-year variability mainly due to a variability of the photosynthetic productivity rather than the respiratory CO_2 release. The NEP and GPP were especially high in the first half of the growing periods in 1998 and 2002, mainly because of early leaf emergence related to an unusually warm spring before the beginning of the growing period. The spring temperature was unusually high in 1998 under the El Niño phenomena.

The inter-annual variation of NEP showed a positive correlation with the spring air temperature but not with the summer solar radiation. The results suggested that the inter-annual variability of NEP and GPP was more affected by the spring air temperature than by the summer solar radiation.

The temperature dependence related to the length of the growing period is quite complicated but important for understanding and modeling ecosystem responses to environmental controls. The relationships among the spring air temperature, snowfall, snowmelt, leaf emergence, and seasonal changes in autotrophic and heterotrophic respiration should be investigated more extensively for a better understanding of the year-to-year change in productivity indicated by the flux measurement.

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