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Inter-Annual Variability of Carbon Budget Components in a Cool-temperate Deciduous Forest in Japan (Takayama, AsiaFlux)

By

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Key words: Annual carbon budget, biometric method, inter-annual variability, long-term flux measurement, micrometeorological method, net ecosystem production.

Summary

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Net ecosystem production NEP, gross primary production, and total ecosystem respiration are estimated by a micrometeorological method for ten years at a cool-temperate deciduous forest in central Japan, one of the AsiaFlux forest sites. The CO₂ flux has been estimated by an aerodynamic method since 1993 using the vertical gradient of CO₂ concentration and the diffusion coefficient, and by the eddy covariance method since 1998. A ten-year average of annual NEP from 1994 to 2003 is estimated to be $240 \pm 90 \text{ gC m}^{-2} \text{ year}^{-1}$ (mean $\pm$ SD). The year-to-year change in the annual NEP is primarily affected by the air temperature before and at beginning of the growing period (the mean temperature from April to June, T_{AMJ}), and by the solar radiation in summer (the mean solar radiation from June to July, S_{JJ}), and is functionally expressed as $\text{NEP} = 51.4 T_{AMJ} + 1.8 S_{JJ} - 612.0$ ($r = 0.76$, $p < 0.05$). Inter-annual variations of T_{AMJ} and NEP show a clear periodicity of about 4-5 years, and is coincident with the occurrences of El Niño events during the last decade.

The annual NEP is compared with that obtained from the biometric method, in order to highlight the source and magnitude of uncertainties in both methods. The NEP estimated by the micrometeorological method is $200 \text{ gC m}^{-2} \text{ year}^{-1}$ higher than that by the biometric method ($40 \text{ gC m}^{-2} \text{ year}^{-1}$). A large uncertainty in the biometric method is related to the estimation of carbon flow in the soil. The uncertainty in the micrometeorological method is about the same as the difference in the NEP values obtained by the two methods. Further studies are clearly necessary to improve the estimation of carbon budget components and to reduce the uncertainties in both methods.

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Introduction

A global network of micrometeorological tower sites has been established at various ecosystems since 1990s (<http://www-eosdis.ornl.gov/FLUXNET/>). Several stations in the world including Takayama site (central Japan, broadleaf deciduous forest) have achieved ten years of observation. In order to understand the response of the terrestrial carbon cycle to climatic change, long-term observations of the net ecosystem production NEP are important, and the measurements need to be interpreted within the context of: (1) What are the important factors contributing to the variability of seasonal and annual NEP in each ecosystem? (2) How can the long-term NEP estimated by the micrometeorological method be confirmed?

Based on micrometeorological measurements, inter-annual variability of NEP for several ecosystems has been investigated, and the role of important factors such as the growing period length and the summer drought stress have been identified. (BLACK & al. 2000, CARRARA & al. 2003, SUYKER & al. 2003). While the micrometeorological method remains suitable for investigating NEP variability on diurnal, seasonal and inter-annual time scales, large errors result in the summing of the actual NEP values over a long period of time, such as over a year. It is therefore useful to perform an inter-comparison of NEP between micrometeorological and biometric methods.

We have observed seasonal and inter-annual variability of NEP at Takayama site for the last ten years by the micrometeorological method. Objectives of this study are (1) to present the long-term trend of the carbon budget components estimated by the micrometeorological method, (2) to elucidate the important factors influencing the variability of NEP, and (3) to specify the source of uncertainty in the estimation of annual NEP by comparing micrometeorological and biometric methods.

Site and Methods

The study site (36° 08' N, 137° 25' E, elevation 1,420 m) is located in a cool-temperate zone in central Japan, with annual mean temperature of about 6.4 °C and annual precipitation of about 2300 mm. Vegetation is an approximately 50-year-old secondary deciduous forest, dominated primarily by oak (*Quercus crispula*) and birch (*Betula ermanii*; *Betula platyphylla* var. *japonica*) (JIA & al. 2002, MURAOKA & al. 2003, OHTSUKA 2003). The understory is dominated by a dense evergreen dwarf bamboo (*Sasa senanensis*). The site comes under a significant influence of the Asian monsoon. The Asian summer monsoon, often characterized by heavy rains and high humidity, provides abundant water to most ecosystems during the growing season. 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. Further descriptions of the site have been given by YAMAMOTO & al. 1999 and MURAYAMA & al. 2003.

Carbon budget components estimated by the micrometeorological method

The CO₂ flux above the canopy has been measured since September 1993 by an aerodynamic method using the vertical gradient of CO₂ concentration and the diffusion coefficient over the canopy (YAMAMOTO & al. 1999). The vertical gradient of CO₂ concentration is estimated by the mean CO₂ concentration above the canopy (27 m and 18 m in height). The diffusion coefficient is

estimated by the mixing length and the vertical gradient of the mean wind speed measured at 26 m and 10 m in height. The CO₂ flux has been continuously measured by the eddy covariance method since July 1998 at 25 m on the tower using a three-dimensional sonic anemometer and a closed-path infrared gas analyzer (SAIGUSA & al. 2002). The net ecosystem CO₂ exchange NEE is calculated every half-hour, taking into account the CO₂ storage in the canopy. The CO₂ flux by the aerodynamic method has been intensively compared with that by the eddy covariance method for 1999 to validate the parameters, such as the mixing length, used in the aerodynamic method. Detailed description of the inter-comparison has been given by SAIGUSA & al. 2003.

Daily (24-hour) values of NEP and the gross primary production GPP are derived by the daily NEE and the total ecosystem respiration RE.

$$GPP = NEP + RE = -NEE + RE \quad (1)$$

RE is estimated by the nighttime NEE under windy conditions to avoid the methodological problems associated with the flux measurement on calm nights, and is expressed by an exponential function of the air temperature T at 25 m height (SAIGUSA & al. 2002).

$$RE = A Q^{(T-10)/10} \quad (Q = 2.57, A = 2.04 \text{ gC m}^{-2} \text{ d}^{-1}, r = 0.69) \quad (2)$$

Carbon budget components estimated by the biometric method

The annual net primary production NPP has been estimated by the biometric method since 1998 for trees (NPP_T) and since 1993 for understory species (NPP_U) on a permanent plot of 1 ha (100 x 100 m) which is set on a west-facing slope that encompasses the flux tower. The NPP_T is estimated by the annual biomass increment of trees B_T, the increment in dead plant mass (coarse woody debris) D_T, and annual litter production L_T as expressed in the following equation (OHTSUKA 2003). The NPP_U is estimated by the annual growth in new organs G_U and the annual loss of carbon in storage organs L_U (NISHIMURA & al. 2004).

$$NPP = NPP_T + NPP_U = (B_T + D_T + L_T) + (G_U - L_U) \quad (3)$$

B_T and D_T have been estimated every year by the direct measurement of the diameter at breast height DBH for all trees taller than 1.3 m in the permanent plot. The biomass of above-ground and root is calculated by the DBH-weight allometric relations established in 1998 by 24 sample trees (12 species) (OHTSUKA 2003). The production of coarse root is taken into account, but that of fine root is not estimated explicitly. Values of L_T are estimated by 14 litter traps (each 1 m² in area) set on the forest floor.

The biometric NEP is estimated by NPP and the heterotrophic respiration HR.

$$NEP = NPP - HR \quad (4)$$

HR is derived by the annual value of total soil respiration measured by chambers (MO & al. 2003, JIA & al. 2003), and the contribution of root respiration to the total soil respiration estimated for the site (27-71 %; LEE & al. 2003). The decomposition rate of coarse woody debris is not included in HR.

Results and Discussion

Year-to-year change in NEP

Fig. 1 shows the seasonal change in the ten-year average (from 1994 to 2003) of the daily NEP and the standard deviation SD estimated by the micrometeorological method. The daily NEP is negative (-0.5 - -1.5 gC m⁻² d⁻¹) during the leafless period. The highest NEP (4.5-5.5 gC m⁻² d⁻¹) occurs from late June to July

(DOY 170-210). In the same period, the rainy season (referred to as ‘Baiu’) reduces NEP intermittently to about half of the maximum. The SD is highest during the first half of the growing period, and is partly caused by the rainy season. Another cause is related to the year-to-year change in the beginning of the growing period. SAIGUSA & al. 2003 have reported that the beginning of the foliation period is highly changeable at the site, varying from DOY 120 (1998) for an early case to DOY 149 (1996 and 2000) for late cases. The SD slightly decreases in the late summer (DOY 190-250), probably caused by stable weather condition and leaf area after the rainy season. The maximum plant area index at the site is 3.5 - 4.0 without large year-to-year variability. The influence of drought stress is not seen clearly because of the sufficient precipitation during the early growing period.

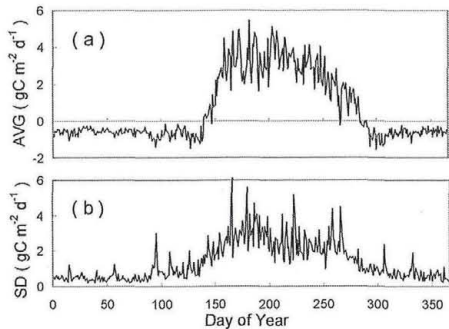


Fig. 1. Seasonal change in (a) the ten-year average of the daily NEP from 1994 to 2003 and (b) the standard deviation estimated by the micrometeorological method.

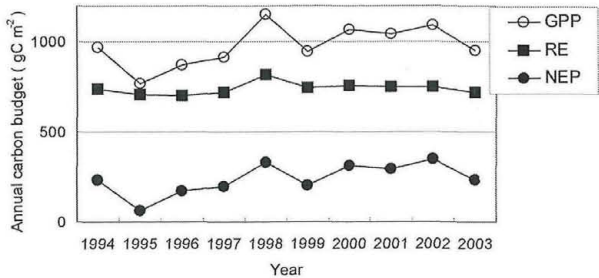


Fig. 2. Year-to-year change in the annual GPP, RE and NEP from 1994 to 2003 estimated by the micrometeorological method.

Fig. 2 shows the annual values of GPP, RE and NEP. The annual NEP has a similar year-to-year variation to that of GPP, and the variability of NEP and GPP was more marked than that of RE. In order to highlight the important processes responsible for the variability of NEP, correlations between the inter-annual varia-

tions of NEP and the monthly values of GPP and RE are examined. The annual NEP is positively correlated with the monthly GPP in June, July and August ($r > 0.5$, $p < 0.05$), i.e., during the most important part of the growing season. The highest correlation is found in June ($r = 0.77$), the period of leaf expansion and maturity. The results show that the variation in the annual NEP is highly influenced by the productivity, especially during the early growing period.

The correlations of the annual NEP with the monthly air temperature (at 25 m height) and the solar radiation are also examined. The annual NEP increases with the spring air temperature ($NEP = 54.9 T_{AMJ} - 300.5$; T_{AMJ} the mean air temperature from April to June, $r = 0.65$, $p < 0.05$). A positive correlation is also found between the annual NEP and the mean solar radiation from June to July S_{JJ} , and the inter-annual variability in NEP is well expressed by the variations in T_{AMJ} and S_{JJ} as follows.

$$NEP = 51.39 T_{AMJ} + 1.83 S_{JJ} - 612.00 \quad (r = 0.76, p < 0.05) \tag{5}$$

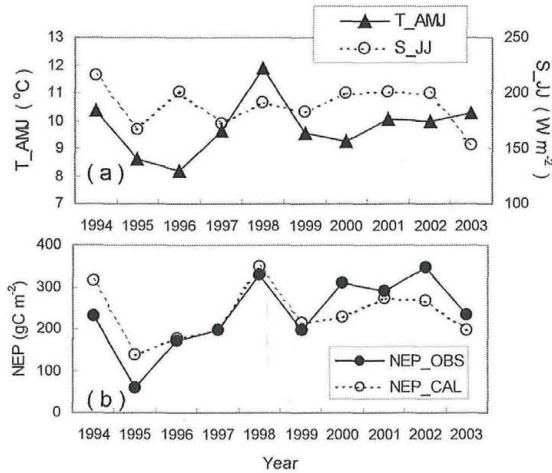


Fig. 3. Inter-annual variations of meteorological conditions and NEP from 1994 to 2003. (a) The mean air temperature from April to June T_{AMJ} , and the mean solar radiation from June to July S_{JJ} , (b) the observed NEP by the micrometeorological method and the calculated NEP by Eq.(5).

Fig. 3 shows the inter-annual variations of T_{AMJ} , S_{JJ} , the observed NEP, and the calculated NEP by Eq.(5). T_{AMJ} represents the temperature before and during the foliation period, and S_{JJ} reflects the solar radiation in the rainy season (i.e., the most productive part of the growing season). T_{AMJ} is characterised by a periodicity of about 4-5 years, corresponding well with the cyclic El Niño events (1993-1994, 1997-1998, and 2002). When T_{AMJ} is high (1994, 1998, 2001-2003), the NEP increases because of the earlier leaf out and the high productivity during the early stage of the growing period. On the other hand, the year-to-year variability in S_{JJ} is

unsystematic, affecting NEP only partly. For example, sharp decreases in NEP from 1994 to 1995 and from 2002 to 2003 were probably enhanced by the associated decrease in the summer solar radiation in 1995 and 2003. Future studies will be conducted to analyse more quantitatively the relation between NEP and meteorological variables, by clarifying individual responses in ecosystem such as foliage, stem, root, and soil microbes to changes in meteorology.

Comparison of NEP between micrometeorological and biometric methods

Based on the micrometeorological method, the ten-year averages of NEP, GPP and RE are estimated to be 240 ± 90 , 980 ± 110 and 740 ± 30 $\text{gC m}^{-2} \text{ year}^{-1}$ (mean $\pm$ SD) for 1994-2003, respectively. It is important to verify this large carbon accumulation at the site (>2 $\text{tC ha}^{-1} \text{ year}^{-1}$ for ten years) by comparing with biometric method.

Using the biometric method, NPP is estimated to be 440 $\text{gC m}^{-2} \text{ year}^{-1}$, with trees and understory contributing 320 $\text{gC m}^{-2} \text{ year}^{-1}$ (NPP_T) and 120 $\text{gC m}^{-2} \text{ year}^{-1}$ (NPP_U), respectively (OHTSUKA 2003, NISHIMURA & al. 2004). The coarse woody debris increases ($D_T = 180$ $\text{gC m}^{-2} \text{ year}^{-1}$) while the live tree biomass decreases ($B_T = -30$ $\text{gC m}^{-2} \text{ year}^{-1}$) for the study period. The method assumes that the dense understory community is relatively stable and that the biomass increment is negligible. NPP_U would then be equivalent to the understory litter production. The total soil respiration estimated by chamber method is 730 ± 40 $\text{gC m}^{-2} \text{ year}^{-1}$ (1999-2002) (MO & al. 2003), and HR is 400 $\text{gC m}^{-2} \text{ year}^{-1}$ (55% of the total soil respiration; LEE & al. 2003). Finally, biometric NEP ($= \text{NPP} - \text{HR}$) is estimated to be 40 $\text{gC m}^{-2} \text{ year}^{-1}$.

The result shows that the NEP estimated by the micrometeorological method is 200 $\text{gC m}^{-2} \text{ year}^{-1}$ higher than that estimated by the biometric method. The cause of the difference is not clear, however, there are several sources of error in both methods. Micrometeorological method has a large uncertainty caused by the energy imbalance which could affect the annual NEP by about 24 % (SAIGUSA & al. 2002). Another source of error results from the nighttime flux, contributing an uncertainty of $50\text{-}70$ $\text{gC m}^{-2} \text{ year}^{-1}$ to the annual NEP estimate for the site (SAIGUSA & al. 2003). For example, the annual RE estimated by the micrometeorological method is 750 $\text{gC m}^{-2} \text{ year}^{-1}$ for the period of 1999-2002, which is only 3% higher than the soil respiration obtained by the chamber method for the same period (730 $\text{gC m}^{-2} \text{ year}^{-1}$). Since the total ecosystem respiration is composed of soil respiration and the above-ground plant respiration, the micrometeorological based RE could be underestimated. If a correction for the energy imbalance were to be applied (multiplying daytime and nighttime fluxes by 1.24 to compensate for the lack of energy balance), the annual RE would be increased to 930 $\text{gC m}^{-2} \text{ year}^{-1}$ which would be 27 % higher than the soil respiration. This value is consistent with previous studies in the temperate forest (the contribution of soil respiration was 60-90 % of the total ecosystem respiration; MO & al. 2003). As a consequence, the level of uncertainty in the micrometeorological method is about the same as the difference in the NEP estimated by the two methods.

The biometric method also has a large uncertainty. The decomposition of

coarse woody debris and the fine root production are not taken into account in the method and could contribute to an underestimation of SOC (soil organic carbon) sequestration. As a balance between the litter production (trees $170 +$ understory $120 \text{ gC m}^{-2} \text{ year}^{-1}$) and decomposition ($\text{HR} = 400 \text{ gC m}^{-2} \text{ year}^{-1}$), SOC shows a significant decrease of $110 \text{ gC m}^{-2} \text{ year}^{-1}$. SATOMURA 2003 suggested that the biometric NEP could be increased by almost $200 \text{ gC m}^{-2} \text{ year}^{-1}$ at the site if the fine root production were to be carefully measured and taken into account.

There are only a few studies on the inter-comparison of the long-term NEP between biometric and micrometeorological methods (BARFORD & al. 2001, LAW & al. 2001, CURTIS & al. 2002, GRIFFIS & al. 2004), and the degree of agreement depends greatly on individual site conditions. For example, CURTIS & al. 2002 summarized measurements at five deciduous forests in North America and showed that the micrometeorological NEP was $100\text{--}330 \text{ gC m}^{-2} \text{ year}^{-1}$ higher than the biometric NEP at three sites, similar at a 4th site, and $120 \text{ gC m}^{-2} \text{ year}^{-1}$ lower at a 5th site. The cause of the differences was not explained.

Results presented in this study show that a long-term micrometeorological flux measurement is useful for a quantitative analysis of the relationship between annual NEP and meteorological variables. If the relationship between NEP and meteorological conditions is better understood for various ecosystems in different climatic zones, then the reliability of our predictions of ecosystem response to climatic change will increase significantly. However, we need to overcome many problems in obtaining accurate absolute values of NEP at different ecosystems, including at our site. We need to carry out additional studies to reduce the uncertainties in NEP estimates associated with both micrometeorological and biometric methods.

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