B-4.2 Modeling of the Carbon Cycle in Forest Ecosystems through Field Measurements

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Abstract

Larch forests broadly distributed eastern Eurasian Continent is expected to fix elevated atmospheric CO_2. From this view, the measurements of fluxes of CO_2 have been carried out at Tomakomai Flux Research Site (a larch forest) in Hokkaido of Japan. Simultaneously, daily and seasonal changes in photosynthetic capacity of Japanese larch trees and soil respiration were measured at the same site. Also, measurement results in a cool-temperate forest at Takayma Site in Honshu of Japan were collected. These data were analyzed synthetically and carbon budgets in two sites were investigated.

(1) Fluxes of CO_2, water vapor, and sensible heat have been measured by the eddy covariance method at Tomakomai Site since July 2000. Two closed-path type flux measurement systems have been installed at different heights of a meteorological tower with 40 m high. During the period from July 2000 to June 2001, CO_2 flux and evapotranspiration over the forest showed clear seasonal changes according to the change in the leaf area of larch trees.

(2) Seasonal change in photosynthetic capacity of short- and long-shoot needles of Japanese larch trees were measured with an open system of infrared gas analyzer from April 1999 in Tomakomai Site in order to evaluate the CO_2 flux. Light compensation point of both short- and long-shoot needles increased with increasing age of needles. Seasonal change in chlorophyll content of needles was coincided with the net photosynthetic rate. The relationships among intercellular CO_2 concentration, the vapor pressure deficit, and net photosynthetic rate were investigated.

(3) Open-top-chamber techniques to measure the CO_2 efflux from soil were examined in a simulator of temperature, humidity and blowing conditions. And, daily and seasonal changes of soil respiration in two Research Sites were measured using the open-flow infra-red gas analyzer method.

(4) Net primary production(NPP) was studied in a cool-temperate deciduous forest at Takayama Site. The mean litter production of foliage and branches were 3.30 and 1.09 ton ha^{-1} yr^{-1}. NPP was calculated as the sum of aboveground growth, coarse roots growth and litter production. NPP in the stand for the mean value of the past 10 years (1989-1998) were 6.65 ton ha^{-1} yr^{-1} and 5.99 by the SA-method and the CS-method, respectively. The annual soil CO_2 efflux of 1994, 1995 and 1996 were 602. 7, 570.9 and 457.7 (g C m^{-2} y^{-1}), respectively.

Key Words Carbon Cycle, Forest Ecosystems, CO_2 Flux, Photosynthesis, Soil Respiration, Net Primary Production (NPP), Open-flow method

1. Introduction

Uncertainty of estimation of carbon budgets in terrestrial ecosystems was pointed out in IPCC95 reports (IPCC,1996). Understanding terrestrial carbon metabolism is critical because terrestrial ecosystems, especially in forest ecosystems, play a major role in the global carbon cycles (Canadell et al.

2000). The eastern part of the Eurasian Continent is considered an important carbon sink because of this region is covered with larch species, which are the main species of the Taiga (Gower,et al.,1990, Koike et al., 2000). The southern edge of larch distribution locates in central Japan. Larch species broadly distributed eastern Eurasian Continent is expected to fix elevated atmospheric carbon, because of their high carbon uptake capacity (e.g. Koike et al., 2000). From these reasons, Tomakomai Flux Research Site (Tomakomai Site) was established at Tomakomai National Forest, Hokkaido, northern Japan (42°44' N, 141°31' E and 115~140m above the sea level.) in 1999-2000 mainly by the National Institute for Environmental Studies for a long-term monitoring of carbon budget of a larch forest. The soil at the study site was immature volcanic ash soil. Studies were being carried out by both meteorological and biological aspects, for example, long-term flux measurements of CO_2 and water vapor, respiration of plants, photosynthetic activity, and remote sensing data analysis.

On the other hand, the CO_2 flux from soil surface to atmosphere, soil respiration, is a major source of CO_2 in terrestrial ecosystems and a key component of the carbon balance. The soil CO_2 flux estimated from the combination of biological and physiological processes is highly variable in space and time. In order to relate soil respiration to environmental factors, it is necessary to make measurements at the same temporal scale of the driving variable. Open-top-chamber techniques to measure the CO_2 efflux from soil were developed, and daily and seasonal changes in soil respiration of a cool-temperate and a larch forest were measured.

2. Research Objectives

2.1 Measurements of fluxes of CO_2, water vapor, and sensible heat at Tomakomai Site

1) To make clear the relationship between CO_2 uptake of the forest and meteorological conditions such as temperature, radiation, and water vapor deficit.
2) To analyze on the contribution of each biological responses such as photosynthesis and respiration to the observed CO_2 flux over the forest.
3) To understand more about technological problems of the eddy covariance method to estimate CO_2 budget of a forest ecosystem.

2.2 Seasonal change in photosynthetic capacity of Japanese larch trees in Tomakomai Site

1) To elucidate light use capacity of these morphological different type needles, the light-photosynthetic curves were examined to evaluate quantitative efficiency of photosynthesis versus photon flux density using the standard hyperbolic formula.
2) To determine the influence of different leaf position on photosynthetic capacity, relationship between intercellular CO_2 concentration and photosynthesis of short-shoot needles under both sun and shaded conditions during summer were examined.

2.3 Relationships between soil respiration and the environmental and biological factors

1) To develop open-top chamber methods (OTC-methods) eliminating the limitation of measuring in rainfall or snowfall and having a fast and sensitive response to environmental variation.
2) To decide statistically how many measuring points is needed for estimating the averaged soil respiration rate.
3) To elucidate the relationships between soil respiration rates and the environmental and biological factors.

2.4 Carbon budgets in forest ecosystems

Carbon budgets in forest ecosystems were determined by the balance of net primary production (NPP) of plant community and decomposition of soil carbon (soil respiration). To clarify the mechanisms of variation of CO_2 flux in forest ecosystems, it is needed to study long-term direct measurements of bio-process (primary productivity and soil respiration) together with tower measurement. In this study, the NPP and soil respiration of the cool-temperate deciduous broad-leaved forest at Takayama Site were investigated. The results obtained in this site will be compared with results in a larch forest at Tomakomai Site.

3 Research Method

3.1 Measurements of fluxes of CO_2, water vapor, and sensible heat at Tomakomai Site

Fluxes of CO_2, water vapor, and sensible heat are measured at different heights on the tower (40 m and 22 m) by the eddy covariance method using three dimensional ultrasonic anemometer-thermometers (Kaijo, DA-600TV), and closed-path type CO_2/H_2O analyzers (LI-COR, LI-6262). Prior to a long-term measurement, error of the closed-path system due to the attenuation of high frequency components has been investigated by comparing with open-path system.

3.2. Seasonal change in photosynthetic capacity of Japanese larch trees

1) Study site and plant material: A tower was constructed in the Tomakomai Site to monitor the functional aspect of trees (height was 25m). Canopy of three trees were approached by the tower. For measurement of CO_2 exchange rates, short- and long-shoot needles were selected from these trees.

2) Measurements: Gas-exchange rates of needles were measured once a month for both short- and long-shoot needles. Net photosynthetic rates were determined with a portable gas analyzer (ADC-H4A, ADC, U.K. and LI-6400, LiCor, Lincoln, NE, U.S.A.), under steady-state conditions at ambient temperature. Supplementary lights were provided by a halogen lamp (Walz, Germany). Under non-limiting climatic conditions (light saturation, optimal needle temperature, and high air humidity) and ambient CO_2 concentration, the photosynthetic photon flux density (PPFD) was changed from high to low to obtain relationships between PPFD and the rate of photosynthesis. Finally, the chamber was wrapped with aluminum foil for determination of the dark respiration rate. After taking measurements, the needle projection area was measured with an image scanner (GT-7000, EPSON, Japan). The needles were oven dried at 60℃ for 48 h for dry mass determination.

3) Quantitative analysis of photosynthetic rates: Light-dependent photosynthesis was analyzed using the hyperbolic formula: $Pn = \underline{b}I / (1+\underline{a}I) - R$ where Pn is the net assimilation rate, R is the rate of dark respiration, I is the PPFD, a is the reciprocal number of PPFD at the half the photosynthetic rate under light saturation, and $\underline{b}$ is the initial slope of the tangent near the point at 0 ($\mu E \cdot m^{-2}s^{-1}$) on the curve of PPFD versus the rate of photosynthesis, which stands for photosynthetic capacity at low PPFD. The light compensation point (Ic) was defined by the following equation : $Ic = R / (\underline{b} - \underline{a}R)$. Stomatal limitation (Ls) was analyzed by curves of A-Ci. The value of Ls was calculated by the following equation : $Ls = 1 - Ai / Aa$,where Ai is net photosynthetic rate of observed CO_2 concentration in leaf and Aa is net photosynthetic rate at ambient CO_2.

3. 3 Relationships between soil respiration and the environmental and biological factors

1) Two types of OTC-methods were examined to measure the CO_2 efflux from soil. One was based on measuring CO_2 concentration gradients in the chamber. The second was based on the technique of

Fang and Moncrieff (1986). The effect of environmental condition on the determined CO_2 efflux rate was examined in a simulator in which temperature, humidity and blowing were controlled.

2) 30mx30m quadrate in Tomakomai Site was devided into 36 quadrates (5mx5m), where two or four points for measuring the soil respiration rate were each set up. 24 hours measuring was carried out twice at each small quadrate in August, 2000.

3) In Tomakomai Site, soil respiration rates were measured using the OF-method (Nakadai et al. 1993) and the OTC method (Fang and Moncrieff 1998). Three chambers for OF-methods and six chambers for OTC-methods were set around the 25m eco-tower. Temperature (thermistor), soil water content (TDR) and ambient CO_2 concentration were monitored during the soil respiration measurements. The soil profiles was investigated from surface to 1.2 m depth.

3. 4 Carbon budgets in forest ecosystems

1) Study site: The study site is situated near Takayama forest research center, Gifu University on the middle of Mt Norikura in central Japan. The original vegetation around the research center was cool-temperate deciduous broad-leaved forests, dominated by Fagus crenata (Japanese beech). The forest floor is covered by dense Sasa senanensis community. Permanent plot of 1 ha was set on a west-facing slope (ca. 1395 – 1425 m a.s.l.), and was divided into one hundred of 10 m × 10 m subplots. The site is under a seasonal cool-temperate climate; an annual mean temperature of 9.4 ℃ and annual rainfall of 2382 mm. The snow usually covered more than 1 m in winter from November to April.

2) Tree census and litter production: All tree species in the permanent plot taller than 1.3 m high were numbered and identified in autumn, 1998. Tree position diagram was made for each subplot. A measuring position of the diameter at breast height (dbh, cm) for all tree stems was painted and dbh was accurately recorded using steal measure in each subplot in March and May 1999 before growing season. Ten litter traps (each 1 m^2 area) made of nylon net were set up on the forest floor. Fine litter in the traps were corrected every month and sorted into leaves and the other materials (mainly dead branches and twigs). They were oven dried at 80 ℃ and weighed.

3) Soil respiration: The CO_2 effluxes from soil or snow surface were 24-hour continuously measured with the open-flow IRGA method every month or more frequent from December 1994 to December 1995. The measurement system was followed by Bekku et al. (1995), and was improved for measuring the CO_2 flux from snow surface (Mariko et al. 2000a). The ambient air entered the chambers at the flow rate of 1.2 to 1.6 L min^{-1} during summer, and 0.8 L min^{-1} during winter. The air flow to the IRGA was maintained at 0.5 L min^{-1} which was lower than the chamber-through flow rate. The air and soil surface temperatures were measured at the same time.

4. Result and discussion

4.1 Measurements of fluxes of CO_2, water vapor, and sensible heat

Clear seasonal changes in CO_2 and water vapor fluxes have been observed during from July 2000 to June 2001. Figure 1 shows the relation between CO_2 flux (30-minute average) and photon flux density (PPFD) measured from August 2000 to May 2001. The daytime maximum CO_2 uptake of the forest (negative values of CO_2 flux in Fig.1) was about 25 μ mol/m^2/s in August. In August 2000, CO_2 uptake increased with PPFD when PPFD was less than 1000 μ mol/m^2/s (weak light condition), however, CO_2 uptake decreased with PPFD under strong light condition (PPFD >1000 μ mol/m^2/s). The reason of decreased CO_2 uptake with could be related to such conditions as increased respiration of both

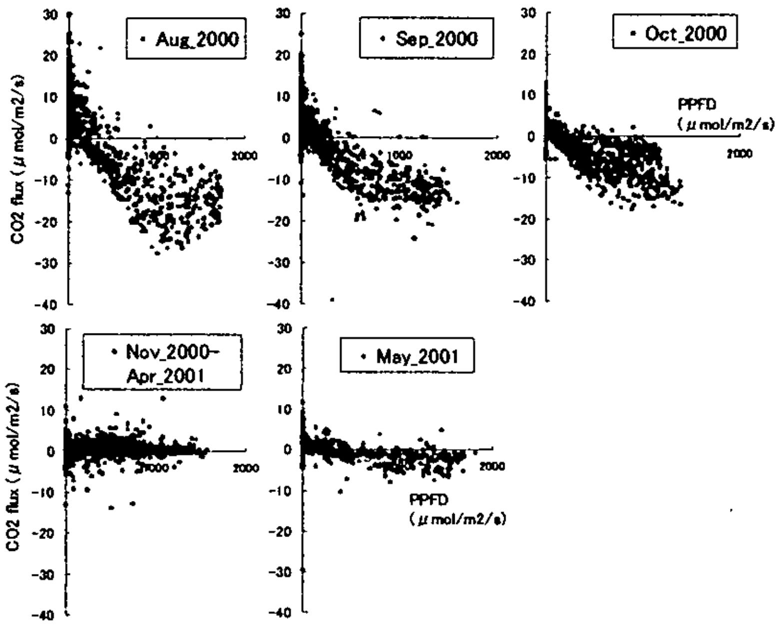

Fig.1. Relation between CO_2 flux and photon flux density (PPFD) from August 2000 to May 2001.

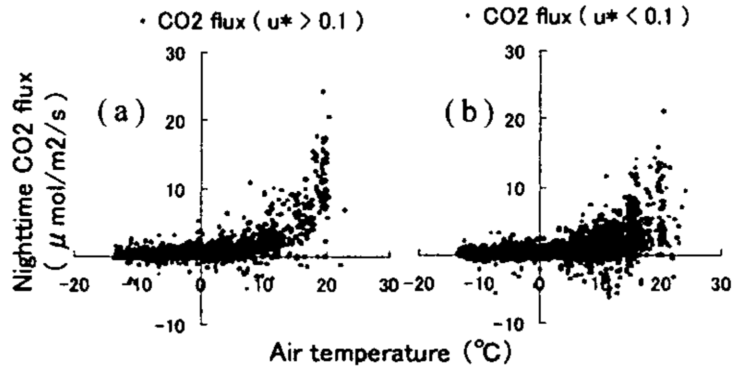

Fig.2. Relation between nighttime CO_2 flux and temperature
(a) $u_* > 0.1$ m/s, (b) $u_* < 0.1$ m/s (u*; friction velocity)

soil and plants with temperature, decreased stomatal conductance caused by high vapor deficit, and decreased photosynthetic activity undertoo high temperature orlight condition. Figures 2 (a) and (b) show the relationship between thenighttime CO_2 flux (30-minute average) and nighttime temperature from August 2000 to June 2001 under the condition of (a) friction velocity $u_* > 0.1$ m/s, and (b) $u_* < 0.1$ m/s, respectively.The nighttime CO_2 (CO_2 release rate from the forest) increased exponentially with temperature.The maximum CO_2 release rate was as about 15-20 μ mol/m^2/s observed in August 2000.

Clear seasonal changes in CO_2 and water vapor fluxes have been observed by the eddy covariance method at different heights on the tower. The relation between nighttime CO_2 flux and temperature will be compared with studies on the respiration of both soil and plants, in order to test the validity of the nighttime flux measurement and to make clear the contribution of soil and plant respiration to the ecosystem respiration. The daytime CO_2 flux should be compared with studies on photosynthetic activity of individual leaves in order to analyze on the dependence of CO_2 uptake of the forest on the light and temperature conditions. In future studies, the energy budget of the forest and vertical profile of the fluxes should be analyzed for the purpose of better understanding of the accuracy of the flux measurements and how to solve the technological problems of the eddy covariance method to estimate the carbon budget of a forest ecosystem.

4.2 Seasonal change in photosynthetic capacity of Japanese larch trees

Light photosynthetic curves of short-shoot needles in sunny and shaded crown, fitted by Tamiya's equation of hyperbolic formula were shown in Fig. 3. There were no marked differences observed in needles between sun and shaded crowns. However, the curves were apparently well fitted under low PPFD conditions. Seasonal changes in light compensation points were shown in Fig. 4. In short-shoot needles, their values was rapidly increased from May to June, then it maintained high values until September. In contrast, in long-shoot needles, the value is rapidly increased in August. Finally, the values decreased at the end of October.

Larch is a typical light demanding species (Gower et al.,1990), however short-shoot needles can use low light more efficiently than long-shoot needles. In fact, our results of light photosynthetic curves and seasonal changes of Ic suggest that short-shoot needles may have adapted to low light environments. In general, long-shoots are positioned upper parts of the branch and received more lights compared to inner positioned short-shoots, which may bring this functional adaptation. The photosynthetic capacity of the Japanese larch was compared with that of F_1 hybrid. Stomatal limitations were calculated from Fig. 4 for Japanese larch. Notice that stomatal limitation of shaded crown in Japanese larch was considerably higher as compared to that of F_1 hybrid. Photosynthesis is strongly regulated by stomatal behavior (Farquhar et al.,1982), especially in larch species (Benecke et al.,1981, Matyssek et al.,1987). This big difference in the the stomatal limitation may be attributed to the effects of vapor pressure deficit and stomata opening of shaded crown, because stomatal regulation is always affected by water condition of plants. In view of the

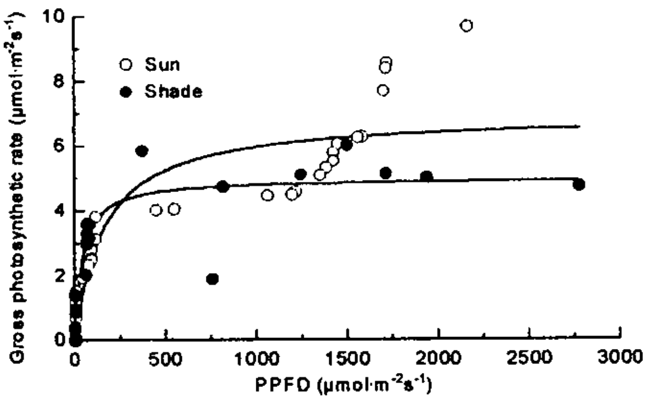

Fig. 3. Gross photosynthetic rate of sun and shade leaves in summer fitted by hyperbolic formula.

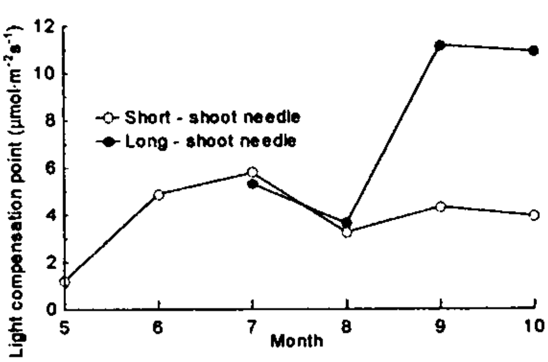

Fig. 4. Seasonal changes of light compensation points (Ic) of Japanese larch

A-Ci relationship of short-shoot needles under both sunny and shaded conditions, the results of present study suggest that the RuBP regeneration rate and carboxylation efficiency may be higher in sunny crown than that of shaded crown (Farquhar et al.,1982, Sharkey,1985). Indeed, functional development of larch was made by climatic conditions, e.g. temperature and light flux, rate of RuBP regulation is controlled by the amount of Pi (ortho-phosphate) in chloroplast. RuBP regeneration rate of shade needles was lower than that of sun needles, which should be considered through the metabolism of Pi because the plantation area of larch is characterized by immature volcanic ash suffering from the phosphorous deficiency (Farquhar et al.,1982, Sharkey,1985).

4. 3 Relationships between soil respiration and the environmental and biological factors

1) By the OTC-chamber method based on measuring CO_2 concentration gradients, the level of 0.1ppm, the respiration rate could be determined under wind condition, at height 0.6m above ground. In the case of the other OTC-chamber method based on Fang and Moncrieff (1998), wind blowing (> 1.5 m/s) affect the measurement of CO_2 efflux which was under estimated.

2) To obtain the average rate of soil respiration on forest floor, 28 to 34 measuring points for less than 10% error, or 7 to 9 points for less than 20% error on significant level 95% were needed in artificial Larix forest .

3) Soil profile showed that the O and A horizons were very thin and a depth of about 15 cm. Soil type was classified into Volcanogenous Regosols. Although the soil was poor and not thick, almost soil organic carbon and microbial biomass carbon consisted in these surface horizons. Soil CO_2 flux showed significant diurnal and seasonal changes and the trend was similar to those of the soil surface temperature. The spatial variation of the measuring points ranged from 20 to 30 % at CV value. Soil CO_2 flux related to the depth of the A horizon. The higher soil CO_2 flux was obtained at the measuring point in which the depth of the A horizon was thin. This suggested that the depth of soil horizon would indicate the soil microbial activities in this field.

4. 4 Carbon budgets in forest ecosystems

Annual leaf-litter and branch-litter fall varied with year to year in the stand. The mean litter production (1993-1999) of foliage and branches were 3.30 and 1.09 ton ha^{-1} yr^{-1}. Annual litter production of foliage and branches in 1999 was 3.28 and 0.39 ton ha^{-1}. Net primary production of the trees by the three methods was calculated as the sum of aboveground growth, coarse roots growth and litter production. Net primary productions (NPP) in the stand were 6.65 ton ha^{-1} yr^{-1} and 5.99 by the SA-method and the CS-method respectively, which were the mean value for the past 10 years (1989-1998). Annual NPP in 1999 to 2000 by the TC-method was 7.09 ton ha^{-1} yr^{-1}. The aboveground biomass (123.8 ton ha^{-1}) of the stand was less than a half of the natural Japanese beech (Fagus crenata) forests (250 - 400 ton ha^{-1}), which are climax of cool-temperate zone. Typical pioneer tree species in secondary forests such as Betula spp., Magnolia obovata and co-dominant species in climax beech forest such as Quercus crispula are mixed with the study area. The density of tree stems was rather high (1255 ha^{-1} over 5 cm dbh, 882 ha^{-1} over 10 cm). Thus, the study forest was still early pioneer tree stage on secondary succession in cool-temperate zone.

Daily soil CO_2 efflux increased sharply from late spring (6.64 ± 0.52 g CO_2 m^{-2} d^{-1} in May 11) and peaked in summer (15.46 ± 1.53 g CO_2 m^{-2} d^{-1} in August 31), and then decreased in autumn (2.64 ± 0.19 g CO_2 m^{-2} d^{-1} in November 21). It was found that daily soil CO_2 efflux significantly correlated with soil surface temperature and air temperature ($r=0.912$ and $r=0.851$ respectively, $p<0.001$, $n=30$). Diurnal trends in CO_2 efflux, however, showed a slight change in emission rate especially during the tree canopy closure. In winter, soil surface temperature kept over 0°C because of the thermal insulation effect of snow-pack. The daily CO_2 efflux from snow surface was ranged from 0.66±0.29 to 2.49±0.77 g CO_2 m^{-2} d^{-1}. Annual masses of CO_2 efflux (from soil and snow surfaces) were estimated from the relationship between CO_2 efflux (y, g C m^{-2} d^{-1}) and soil surface temperature (x, °C): $y=0.4893e^{0.0949x}$ (R^2=0.7439, P<0.001, n=30). Accordingly, the annual CO_2 efflux of 1994, 1995 and 1996 were 602.7, 570.9 and 457.7 (g C m^{-2} y^{-1}) respectively, and suggesting that the annual variation of CO_2 efflux may range between 5 to 15% for the studied forest ecosystem. The winter CO_2 efflux was estimated to be 98.20±3.93 g C m^{-2} over an entire winter, and the winter carbon loss may account for 16% of the annual loss.

5. Summary

Understanding terrestrial carbon metabolism is critical because terrestrial ecosystems, especially in forest ecosystems, play a major role in the global carbon cycles. The eastern part of the Eurasian Continent is considered an important carbon sink because of this region is covered with larch species, which is expected to fix elevated atmospheric carbon. From this view, the measurements of fluxes of CO_2, water vapor, and sensible heat have been carried out at Tomakomai Flux Research Site (a larch forest) since July 2000. Simultaneously, daily and seasonal changes in photosynthetic capacity of Japanese larch trees and soil respiration were measured at the same site. Also, measurement results in a cool-temperate forest at Takayma in central Japan were collected. These data were analyzed synthetically and NEP (net ecosystem production) and carbon budgets were investidgated.

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