Tellus (2003), 55B, 305–312
Printed in UK. All rights reserved

TELLUS
ISSN 0280–6509

Year-long carbon dioxide exchange above a broadleaf deciduous forest in Sapporo, Northern Japan

By Y. NAKAI*, K. KITAMURA, S. SUZUKI and S. ABE, *Hokkaido Research Center, Forestry and Forest Products Research Institute, 7 Hitsujigaoka, Toyohira-ku, Sapporo 062-8516, Japan*

(Manuscript received 21 December 2001; in final form 19 August 2002)

ABSTRACT

This paper reports the results of a full year (2000) of measurements of CO_2 flux at a successional forest of mature birch and growing oak with Sasa-bamboo in Sapporo, Japan. Eddy covariance fluxes of CO_2 were obtained using a closed-path infrared gas analyzer. Changes in CO_2 storage under the eddy-flux measurement level were quantified using vertical profiles of the CO_2 concentration. Seasonal variations in net CO_2 exchange between the forest and the atmosphere are discussed in terms of both phenological developments of the forest canopy and micrometeorological variables. To estimate the annual exchange of CO_2, the net CO_2 exchange data both during periods of poor turbulence and during periods of missing data were replaced by simple parametric models based on measurements of soil temperatures and photosynthetically active radiation. The corrected annual carbon sequestration estimate was 260 g C m^{-2}. The estimates of annual gross carbon gain and loss at the forest were 1120 and 860 g C m^{-2}.

1. Introduction

It is necessary to understand the influence of forests on the global carbon cycle and their response to the increase in atmospheric CO_2 concentration, in order to estimate the possible global warming potential. However, variations in the carbon sequestration capacities of various forest ecosystems depending on climate, species, site productivity, topography and human activities are not well known.

In order to enhance our empirical and theoretical understanding of soil–forest–atmosphere exchanges of carbon dioxide and energy in Japan, a research network, "FFPRI (Forestry and Forest Products Research Institute) FluxNet" was initiated, in which six forest sites were set up from north to south of the Japan islands (Ohtani et al., 2001). The network introduced micrometeorological flux measurement methods, which provide a direct measure of net fluxes between the surface and the atmosphere on an ecosystem scale and with time scales from hours to years (Baldocchi et al., 2001). The network aims to characterize and analyze CO_2, energy and water vapor fluxes over various forest sites in Japan with climate, vegetative species and canopy structure, and to provide parameters and submodels for global models. Another aim is to quantify the sink strength of these forests for CO_2 and its spatial and temporal variations. This paper presents the results of measurements in made 2000 in a hardwood forest which is the northernmost site of the FFPRI FluxNet.

2. Site and instrumentation

2.1. Site description

The measurement site is located in Sapporo Hitsujigaoka Experimental Forest (SHEF). SHEF (42°59′N, 141°23′E, 180 m a.s.l.) is a natural forest with an area of 1.5 km^2 that has regenerated after a fire. The site provides a maximum fetch of 1200 m in the S-SE direction and a minimum of 500 m in the NW direction.

---

*Corresponding author.
e-mail: nakaiyui@ffpri.affrc.go.jp

The dominant wind direction is SE. Since the site is situated in a suburban area of Sapporo, it must be influenced by industrial and residential activities.

The terrain slopes 6.5° on average to the NW. It has a cool-temperate climate with an annual mean temperature of 6.5 °C and an annual precipitation of 1100 mm. Snow-cover reaches 1 m in depth and remains over 130 or more days a year from December to mid-April. The soil is loamy, originating from volcanic ashes. The area is covered with a broadleaf forest on the transitional time stage from mature birch (*Betula platyphylla*) to subclimax species consisting of Mizunara oak (*Quercus mongolica*), painted maple (*Acer mono*), caster aralia (*Kalopanax pictus*), Japanese linden (*Tilia japonica*), Japanese elm (*Ulmus davidiana var. japonica*) and 22 other species. The mean canopy height is 20 m. An understory consists of evergreen *Sasa* bamboo (*Sasa kurilensis* and *Sasa senanensis*) which densely covers the ground and has a height of 0.5–2 m. The mean nitrogen content of the leaves of the birch and the oak in late June 2000 ranged between 1.9 and 2.6% dry matter.

2.2. *Instrumentation*

A 41 m high tower was installed in SHEF. A shelter at the tower base houses the data-acquisition equipment, the gas flow controllers and infrared gas analyzers (IRGAs, Li-6262, LiCor). The instrumentation is organized into three parts: (1) an eddy covariance system at a height of 28.5 m, (2) micrometeorological profile measurements and (3) hydrological and soil physical measurements. At each of two levels (41 and 4 m) the radiation balance and photosynthetically active radiation (*PAR*) are measured. Absorbed *PAR* (*APAR*) is estimated by subtracting the reflected *PAR* from the incident *PAR* at 41 m. To quantify the storage of CO_2 under the eddy measurement level, profile measurements of CO_2 concentration were carried out by cycling through five levels (2.7, 11.0, 16.7, 20.5 and 30.0 m above the ground) of air intake tubes, using a computer-controlled solenoid-valve manifold in conjunction with an IRGA.

2.3. *Eddy-covariance data acquisition and processing*

The major sensors of the eddy-covariance system are a three-dimensional (3-D) sonic anemothermometer (SAT) and an IRGA. Sample air is absorbed from the intake near the SAT to the IRGA through 40-m long Teflon tubing (6.0 mm i.d.) at a rate of 9.5 L min^{-1}. Sample air is dehumidified in a membrane tube (MD-110-48F, Perma Pure Inc.), which can percolate only water vapor but not CO_2, before the IRGA intake. The transit time for the tubing is determined dynamically during the growing periods by maximizing the covariance between the vertical wind velocity and the CO_2 density, but is manually fixed during the non-foliation periods and is of the order of 11–13 s.

Calibration of the IRGAs against standard gases is done automatically every 24 h. The raw voltages from the IRGA, the SAT and a thermo-hygrometer go through analogue low-pass filters with a cut-off frequency of 24 Hz, and are recorded by a digital recorder at a rate of 5 Hz. Eddy-covariance fluxes are obtained via post-processing. The 3-D rotation of the coordinate axis for the wind field, linear trend removal and the correction for the effects of heat and vapor on CO_2 fluxes (WPL correction, Webb et al., 1980) are included in the processing. The effect of WPL correction on the CO_2 fluxes is small because of dehumidification of the sample air and thermal mixing through the tubing (Yasuda et al., 1998). Throughout the paper, upward CO_2 fluxes and/or loss of CO_2 from forest are assigned positive and downward fluxes negative.

To correct flux measurements for the tube attenuations, various methods have been developed (e.g. Eugster and Senn, 1995; Massman, 2000; Yasuda and Watanabe, 2001) with assumptions of the cospectrum similarity. However, the attenuations in the CO_2 fluxes measured with the closed-path IRGA were not considerable, comparing the cospectra with an open-path IRGA (E-009A, Advanet Inc.) in operation during a few days in August 2000. In addition, the similarity should be carefully examined for each site or measurement system. Thus, we make no corrections for the attenuations in high-frequency regions to the measurements of CO_2 fluxes. The lack of energy closure was about 25% of net radiation, using the data of August 2001 and assuming that the total heat storage below the measurement level is negligible.

3. Results and discussion

3.1. *Seasonal trends in canopy architecture and micrometeorological variables*

The daily albedo from 10 to 14 h at the site was determined using up- and down-looking pyranometers at 41 m height. During the initial period of foliage

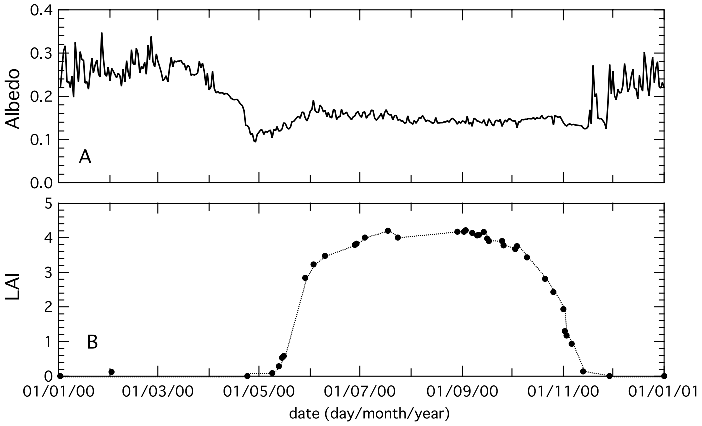

Fig. 1. Seasonal variations in (A) daily mean albedo during the mid-day periods between 10 and 14 h (JST), and (B) leaf area index (LAI) above the understory of *Sasa* bamboo.

development from the end of April to early June, the albedo increased quickly from 0.10 to 0.17, and then from early June to early September it decreased gradually as shown in Fig. 1A. This decrease could be attributed to increased leaf darkness with senescence and to trapping more radiation via multiple reflection inside the forest during the foliating period. Similar variations in the albedo above the canopy of temperate deciduous and mixed forests were reported by Watanabe et al. (2001) and Schmid et al. (2000).

Seasonal variations in leaf area index (*LAI*) were derived from the absorption of global solar radiation by the canopy, using the Beer–Lambert law, where the extinction coefficients were determined based on the measurements of leaf-litter collection in 1999 by Suzuki et al. (2001). The onset of budding was visually observed to be about 2–3 wk earlier in 2000 than in average years. As shown in Fig. 1B, the initial foliating period was completed by end of June, and then the *LAI* remained approximately constant around 4.0 until mid-September. The evolution pattern of the *LAI* at SHEF is similar to that for other deciduous forests in temperate climate over the world (Greco and Baldocchi, 1996; Yasuda et al., 1998; Granier et al., 2000; Schmid et al., 2000; etc.).

Seasonal variations both in air temperature at the height of 41 m (T_a) and in soil temperature at 0.05 m depth (T_s) are shown in Fig. 2A. Despite T_a being below 0 °C during the winter period between December and March, T_s was stable and above 2 °C. This is due to an insulation function of snow-cover, the depth of which is shown in Fig. 2B. The daily maximum of T_a frequently exceeded 25 °C during mid-summer. The matric potential at a depth of 0.4 m, as shown in Fig. 2C, was approximately steady at −4.5 kPa during the winter period. During the active snowmelt period in April, the matric potential was near zero, which means that the surface layer of the soil was nearly saturated. After saturation, the matric potential sometimes decreased to −40 or −50 kPa at minimum. These values of the matric potential mean that the trees were never water-stressed through the year at the study site.

3.2. *Seasonal variations in net ecosystem exchange of CO_2*

Net CO_2 exchange between the forest ecosystem and the atmosphere (*NEE*) was defined as the sum of the eddy covariance fluxes at 28.5 m height above the canopy, F_c, and the change of CO_2 storage in the volume from the ground to the height of the eddy covariance system, F_s. In an annual course of half-hourly *NEE* (Fig. 3), small negative values and episodic ones of large magnitude were obtained even during the leaf-off periods. This finding is consistent with the experience of other observation sites over deciduous forests (Goulden et al., 1996a; Schmid et al., 2000; Pilegaard et al., 2001). These negative fluxes and episodic ones might be attributed not only to instrument error. For this reason, they were not rejected in our estimates of *NEE*. Daily F_s ranged between −55 and 48 (mmol m^{-2} d^{-1}), the standard deviation of the daily F_s was 14.8 (mmol m^{-2} d^{-1}), and the annual sum of F_s was −5.8 (mmol m^{-2} yr^{-1}). Thus, F_s could be neglected on yearly *NEE* but not on daily *NEE*.

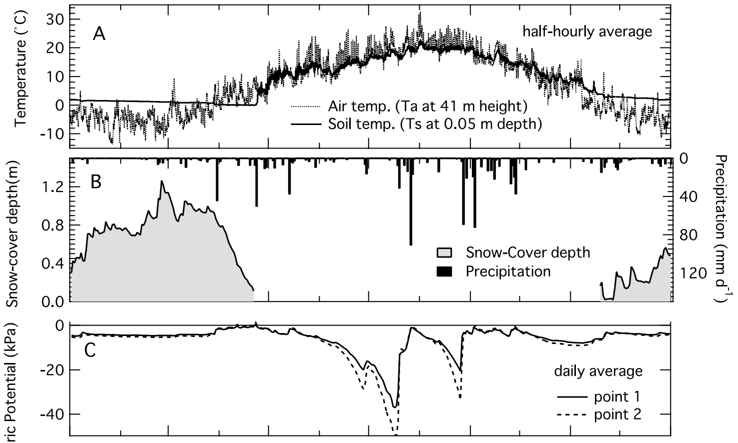

Fig. 2. Annual courses of (A) air and soil temperature, (B) snow-cover depth and precipitation and (C) matric potential pressure in the soil at a depth of 0.4 m.

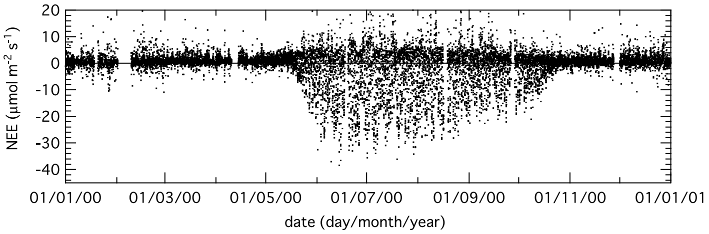

Fig. 3. Scatter plot of half-hourly *NEE* (net ecosystem exchange of CO_2) measurements in 2000.

Net uptake of CO_2 began in middle of May and increased rapidly to a maximum in late June. This change in *NEE* is consistent with the quick increase in *LAI* (Figs. 1B and 3). The sequestration continued until mid-October, when *LAI* was around 3 and the bright fall coloration of the foliage was seen overall. The minimum of half-hourly *NEE* reached nearly -40 μmol m^{-2} s^{-1}. This magnitude of net uptake can be seen in other temperate deciduous and mixed forests (Schmid et al., 2000; Pilegaard et al., 2001).The average of minimum *NEE* during mid-day in the month with the highest uptake (June) was -24 μmol m^{-2} s^{-1}. The annual course of *NEE* could clearly be related to the seasonal variation in *LAI.* This finding has been recognized in temperate deciduous forest worldwide.

During the leaf-off period of 20 d just after the end of the snowmelt, diurnal patterns in *NEE*, indicating photosynthetic activities, were seen, as well as during the leaf-off period of 20 d in autumn (not shown in figures). These diurnal patterns in *NEE* must be the result of photosynthesis by *Sasa* bamboo, which is an evergreen understory with dense biomass in eastern Asia. Note that the *LAI* shown in Fig. 1B does not include *Sasa* bamboo.

3.3. *Estimation of ecosystem respiration and gross ecosystem exchange*

NEE can be defined as the balance between the gross ecosystem exchange by primary photosynthesis (*GEE*) and the total ecosystem respiration (*RE*):

$$NEE = GEE + RE. \quad (1)$$

An empirical model of total dark respiration was established by adjusting the night-time and leaf-off *NEE* (e.g. Wofsy et al., 1993) to a relevant temperature and extrapolating this model to the daytime respiration. *GEE* can then be estimated using eq. (1). In this report the soil temperature at the depth of 0.05 m (T_s) is

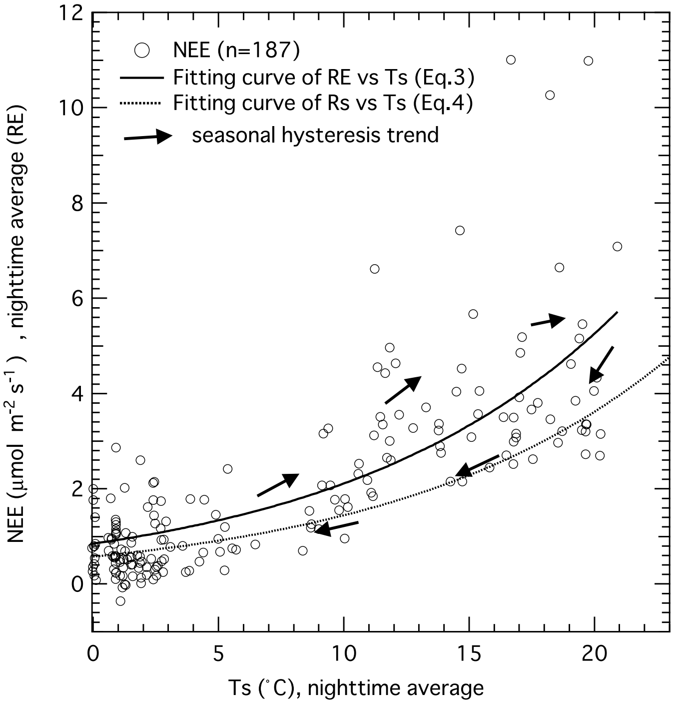

Fig. 4. Night-time-averaged *NEE* as a function of soil temperature at the depth of 0.05 m (T_s). The solid line represents eq. (3). The dotted line represents the soil respiration (R_s) as a function of T_s [eq. (4)].

chosen as a temperature parameter, and it is assumed that *RE* for the whole period could be estimated from *NEE* during night-time and leaf-off periods.

NEE is probably underestimated during the night-time periods of stably stratified conditions when CO_2 storage drains down the sloped terrain below the eddy-flux measurement level as this study site. To exclude *NEE* data under such calm night conditions, we screened the night-time average of *NEE*, using a criterion expressed by inequality (2):

$$T_{a41} - T_{a25} < 0.1 \qquad (2)$$

where T_{a41} and T_{a25} are T_a (°C) at 41.0 and 25.5 m above the ground, respectively. Both T_{a41} and T_{a25} are night-time averages. Although a large deviation in the relationship between *RE* and T_s is shown in Fig. 4, *RE* was fitted to T_s using a simple exponential function that is widely used to assess *RE* (e.g. Greco and Baldocchi, 1996; Lindroth et al., 1998; Falge et al., 2001). The fitting provided the following equation:

$$RE = 0.85 \exp(0.091 T_s) \qquad (3)$$

where *RE* is in μmol m^{-2} s^{-1} and T_s is in °C. The corresponding Q_{10} coefficient from eq. (3) is 2.49. This value lies within those reported by various authors for broadleaf deciduous forests (e.g. Valentini et al., 1996; 2000). Another feature in the relationship between *RE* and T_s is a trend of seasonal hysteresis as illustrated in Fig. 4. This hysteresis pattern can be explained by leaf senescense, as young leaves respire at a higher rate than old leaves. However, Lee et al. (1999) reported anticlockwise hysteresis reversed to that presented in Fig. 4. Several researchers have screened night-time half-hourly or hourly data on the basis of a friction velocity u^* threshold (e.g. Goulden et al., 1996a; Lindroth et al., 1998). Suzuki et al. (2001) parameterized our night-time *NEE* to T_s using half-hourly data with a u^* threshold of 0.4 m s^{-1}, and obtained a fitting curve similar to eq. (3).

Ishizuka and Tanaka (2000) measured soil respiration (R_s) using the closed chambers at SHEF, and obtained the following relationship between R_s and T_s:

$$R_s = 0.96 \exp(0.092 T_s - 0.52). \qquad (4)$$

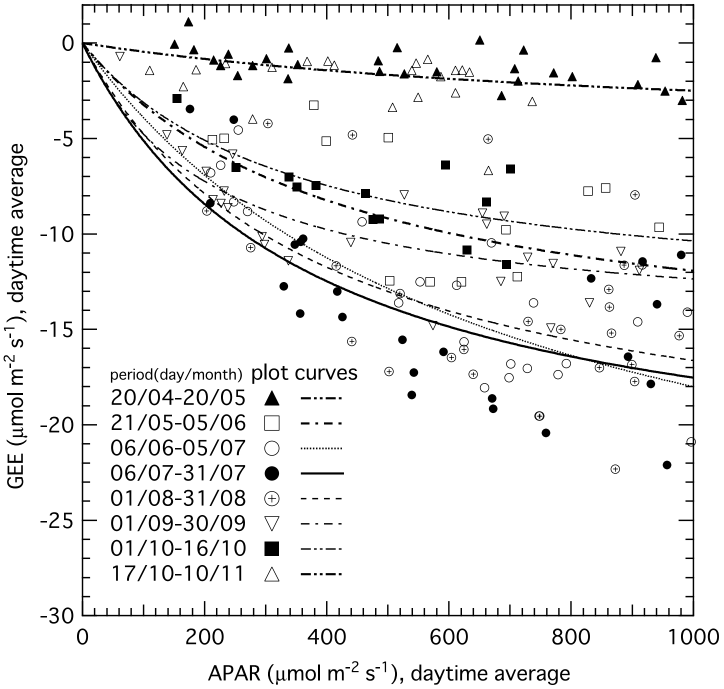

Fig. 5. Plot of the daily gross ecosystem exchange (GEE) versus absorbed photosynthetically active radiation (APAR) for each of several periods. The lines represent equation (5) fitted to the data.

Comparing eq. (3) with eq. (4), R_s is approximately 70% of *RE*, and R_s is the lower envelope for the scatter of *RE* at SHEF as shown in Fig. 4. This result seems reasonable, and the ratio $R_s = 0.7RE$, is close to the ratio $R_s = 0.65RE$ at the Euroflux sites (Berbigier et al., 2001). If no criteria are used for screening *RE* (night-time *NEE*) here, the fitted *RE* mostly overlies eq. (4) (R_s). This result is unrealistic. Thus, the criterion of inequality (2) or the u^* threshold is necessary to parameterize night-time *NEE* to temperature factors at the site. However, the data screening with these kinds of criterion has unsolved problems. For example, CO_2 storage during the calm nights is double-counted when it flushes out up to the eddy measurement level in the morning and when *NEE* is replaced by the temperature function from windy-night conditions as a correction (e.g. Aubinet et al., 2000). We cannot say how large a portion of CO_2 storage is drained out horizontally from the ecosystem at the study site. To begin with, it is unclear that the *RE* vs. *T* relationship from windy nights is applicable to all nights.

GEE was determined using eqs. (1) and (2) for daytime over the growing period. By analogy with the light-photosynthesis curve in the field of plant physiology, eq. (5) was fitted to each separate periods as shown in Fig. 5:

$$GEE = -P_{\max} \times APAR/(-P_{\max}/K_p + APAR) \qquad (5)$$

where the coefficient $P_{\max}$ is the saturated photosynthesis rate and the coefficient K_p is the initial slope of the curve. The values of $P_{\max}$ largely varied seasonally. This suggests that leaf senescence plays a role in *GEE*. For an understanding of carbon cycling in forest ecosystems, the senescence process should be universally modeled using measurable parameters in the future. It should be noted that this $P_{\max}$ is the integral photosynthesis ability of vegetative species in the site.

RE given by eq. (3) was used to correct *NEE* during the night-time and leaf-off periods of stably stratified conditions. A combination of eqs. (1), (3) and (5) was used to estimate *RE* and *GEE*, and to fill the missing data in the time series of *NEE* over the entire year. The year sums of *GEE*, *RE* and *NEE* are summarized in Table 1. *NEE* estimates are within the level reported for other deciduous broadleaf forests in the literature (100–600 g C m^{-2} yr^{-1}; e.g. Wofsy et al., 1993;

Table 1. *Annual* GEE, RE *and* NEE *in carbon (g C* m^{-2}*)*

	GEE	*RE*	*NEE*	*RE* (night)
Raw data (observed)			−285	351
Gap-filling and corrected	−1118	857	−261	429

Goulden et al., 1996b; Granier et al., 2000; Schmid et al., 2000; Aubinet et al., 2001; Pilegaard et al., 2001; Berbigier et al., 2001). When the night-time *NEE* is replaced by a temperature–*RE* relationship for windy nights, similar to eq. (3), both the estimates from the citerative and our own are usually reduced.

The measurements of *NEE* (=*RE*) during snow-cover periods fluctuated despite the constant and stable soil temperature. This fluctuation is attributed to factors other than the soil temperature. Exchange of CO_2 between snow and atmosphere during winter is important at heavy snowfall regions such as SHEF because deep snow-cover plays a role in maintaining a warm and humid environment in the soil and for holding soil respiration at a significant value. Additionally, release of CO_2 from above-snowcover biomass might play a role, because stems and branches in the leaf-off forest directly absorb global radiation and become warmer than ambient air during the mid-daytime. *RE* during winter with snow-cover amounted to 140 g C m^{-2}, which compensates approximately as much as a half of the annual sums of *NEE*.

4. Conclusions

Based on the full year measurements in 2000 of net ecosystem exchange of CO_2 between the forest and the atmosphere and of micrometeorology at the northernmost site of FFPRI FluxNet in Japan, the following conclusions are drawn. The annual sequestration of atmospheric carbon by the deciduous forest in 2000 is preliminarily determined to be 2.6 t C ha^{-1} as the result of gap-filling and correction for total ecosystem respiration. This estimate is based on both eddy-covariance and storage change measurements, with a correction scheme based on soil temperature and absorbed *PAR*. The relationship between ecosystem respiration and soil temperature has a large uncertainty, and is weakest point in this estimate.

A quantitative evaluation of the precision of long-term mass exchange estimates over tall vegetation involves unknown flow phenomena induced by topography or mesoscale inhomogeneity. It also requires the strict refinement of eddy covariance data and the development of new methodologies of experimental design to account for the entire mass balance in a soil–vegetation–atmosphere volume. Solutions to these problems are among the most exciting challenges that land–atmosphere exchange research faces today.

5. Acknowledgements

This research was funded by the Japanese Forestry Agency and the Japanese ministry of Agriculture, Fishery and Forestry. We greatly thank Y. Ohtani for his work in establishing the FFPRI FluxNet. We thank T. Watanabe, Y. Mizoguchi, Y. Yasuda, T. Sakamoto and H. Sugata for their assistance in the field and laboratory. The close cooperation with our ecological partners, H. Tanouchi, Y. Maruyama, N. Ishizuka, H. Utsugi, Y. Sakai and N. Tanaka, is valuable and is acknowledged. We thank the editor and two anonymous reviewers for their constructive comments that helped to improve the manuscript.

REFERENCES

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, Ch., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgestern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R. and Vesala, T. 2000. Estimates of the annual net carbon and water exchange of European forests: the EUROFLUX methodology. *Adv. Ecol. Res.* **30**, 113–175.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, Ch., Davis, K., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw U, K. T., Pilegaard, K., Schmid, H. P., Valentini, R., Verma, S., Vesala, T., Wilson, K. and Wofsy, S. 2001. FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. *Bull. Am. Meteorol. Soc*. **82**, 2415–2434.

Berbigier, P., Bonnefond, J. M. and Mellmann, P. 2001. CO_2 and water vapor fluxes for 2 years above a Euroflux forest site. *Agric. For. Meteorol*. **108**, 183–197.

Eugster, W. and Senn, W. 1995. A cospectral correction model for measurement of turbulent NO_2 flux. *Boundary-Layer Meteorol*. **74**, 321–340.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Lai, C. T., Law, B. E., Meyers, T., Moncrieff, J., Moors, E., Munger, J. W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K. and Wofsy, S. 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agric. For. Meteorol*. **107**, 43–69.

Goulden, M. L., Munger, J. W., Pan, S.-M., Daube, B. C. and Wofsy, S. C. 1996a. Measurements of carbon sequestration by long-term eddy-covariance: methods and a critical evaluation of accuracy. *Global Change Biol*. **2**, 169–182.

Goulden, M. L., Munger, J. W., Fan, S.-M., Daube, B. C. and Wofsy, S. C. 1996b. Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability. *Science*, **271**, 1576–1578.

Granier, A., Ceschia, E., Damesin, C., Dufrêne, E., Epron, D., Gross, P., Lebaube, S., Le Dantec, V., Le Goff, N., Lemoine, D., Lucot, E., Ottorini, J. M., Pontailler, J. Y. and Saugier, B. 2000. The carbon balance of a young Beech forest. *Func. Ecol*. **14**, 312–325.

Greco, S. and Baldocchi, D. D. 1996. Seasonal variations of CO_2 and water vapor exchange rates over a temperate deciduous forest. *Global Change Biol*. **2**, 183–198.

Ishizuka, S. and Tanaka, N. 2000. CO_2 and CH_4 emission by forest soils in Hokkaido, Japan. *Trans. Mtg. Hokkaido Br. Jap. For. Soc*. **48**, 157–160 (in Japanese).

Lee, X., Fuentes, J. D., Staebler, R. M. and Neumann, H. H. 1999. Long-term observation of the atmospheric exchange of CO_2 with a temperate decidious forest in southern Ontario, Canada. *J. Geophys. Res.* **104**, 15975–15984.

Lindroth, A., Grelle, A. and Moren, A. S. 1998. Long-term measurements of boreal forest carbon balance reveal large temperature sensitivity. *Global Change Biol*. **4**, 443–450.

Massman, W. J. 2000. A simple method for estimating frequency response corrections for eddy-covariance systems. *Agric. For. Meteorol*. **104**, 185–198.

Ohtani, Y., Mizoguchi, Y., Watanabe, T., Yasuda, Y. and Okano, M. 2001. Seasonal change of CO_2 flux above an evergreen needle leaf forest in temperate region, Fujiyoshida, Japan. *Proc. international workshop for advanced flux network and flux evaluation.* (eds. Y. Fujinuma, M. Takada, K. Tashiro, T. Nagahama, M. Abe, T. Hagiwara and J. Zeng) Center for Global Environmental Research, Tukuba, 129–132.

Pilegaard, K., Hummelshøj, P., Jensen, N. O. and Chen, Z. 2001. Two years of continuous CO_2 eddy-flux measurements over a Danish beech forest. *Agric. For. Meteorol*. **107**, 29–41.

Schmid, H. P., Susan, C., Grimmond, B. Cropley, F., Offerle, B. and Su, H.-B. 2000. Measurements of CO_2 and energy fluxes over a mixed hardwood forest in the mid-western United States. *Agric. For. Meteorol*. **103**, 357–374.

Suzuki, S., Kitamura, K., Nakai, Y., Abe, S., Shirai, T. and Terajima, T. 2001. Measurements of CO_2 and energy fluxes above a secondary-successional deciduous forest in a cool-temperate and snowy zone, Northern Japan. Proceedings of *International workshop for advanced flux network and flux evaluation*. (eds. Y. Fujinuma, M. Takada, K. Tashiro, T. Naganuma, M. Abe, T. Hagiwara and J. Zeng) Center for Global Environmental Research, Tukuba, 139–143.

Valentini, R., de Angelis, P., Matteucci, G., Monaco, R., Dore, S. and Scarascia Mugnozza, G. E. 1996. Seasonal net carbon dioxide exchange of a beech forest with the atmosphere. *Global Change Biol*. **2**, 199–207.

Valentini, R., Matteucci, G., Dolman, A. J., Schulze, E.-D., Rebmann, C., Moors, E. J., Granier, A., Gross, P., Jensen, N. O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalski, A. S., Vesala, T., Rannik, Ü., Berbigier, P., Loustau, D., Guomundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi S. and Jarvis, P. G. 2000. Respiration as the main determinant of carbon balance of European forests, *Nature* **404**, 861–864.

Watanabe, T., Yasuda, Y., Yamanoi, K., Ohtani, Y., Okano, M. and Mizoguchi, Y. 2001. Seasonal variations in energy and CO_2 fluxes over a temperate deciduous forest at Kawagoe, Japan. Proceedings of *International workshop for advanced flux network and flux evaluation*. (eds. Y. Fujinuma, M. Takada, K. Tashiro, T. Naganuma, M. Abe, T. Hagiwara and J. Zeng) Center for Global Environmental Research, Tukuba, 139–143.

Webb, E. K., Peannan, G. J. and Leuning, R. 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. *Q. J. R. Meteorol. Soc*. **106**, 85–100.

Wofsy, S. C., Goulden, M. L., Munger, J. W., Fan, S.-M., Bakwin, P. S., Daube, B. C., Bassow, S. L. and Bazzaz, F. A. 1993. Net exchange of CO_2 in a mid-latitude forest. *Science* **260**, 1314–1317.

Yasuda, Y., Watanabe, T., Ohtani, Y., Okano, M. and Nakayama, K. 1998. Seasonal Variation of CO_2 flux over a broadleaf deciduous forest. *J. Jpn. Soc. Hydrol. Water Resour.* **11**, 575–585 (in Japanese with English summary).

Yasuda, Y. and Watanabe, T. 2001. Comparative measurements of CO_2 flux over a forest using closed-path and open-path CO_2 analyzers. *Boundary-Layer Meteorol*. **100**, 191–208.