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Eddy covariance fluxes over a boreal Scots pine forest

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We report the results on eddy covariance measurements of net ecosystem exchange (NEE) and accompanying latent and sensible heat fluxes for 44 months in boreal Scots pine forest (southern Finland). We analysed the temperature dependence of ecosystem respiration and PPFD (photosynthetic photon flux density) dependence of daytime CO_2 exchange and calculated the annual carbon budget filling the gaps in data series with the temperature and light dependences. The estimated annual balances of the NEE's were –234 g C m^{-2}, –262 g C m^{-2} and –191 g C m^{-2} in 1997, 1998 and 1999, respectively. We calculated also NEE's for every possible 365-day periods included in the data series and the maximum and minimum of such NEE's were –165 g C m^{-2} and –304 g C m^{-2}. The growing season started around 28 April, 16 April and 25 March in 1997, 1998 and 1999, respectively. The maximum light saturated CO_2 uptake rate reached the value of 12 μmol m^{-2} s^{-1} gradually by the end of June. In autumn, the uptake did not decline gradually but ceased rapidly round the beginning of November. The non-growing season activity is also important, because soil carbon decomposition occurs all year around, even in cold climates under snow cover. The wintertime average CO_2 respiration rate was 0.44 μmol m^{-2} s^{-1}.

Introduction

Our understanding of the global carbon budget is incomplete. It is not known whether the observed sequestration of half of the anthropogenic emissions of CO_2 is sequestered in the oceans, in soils or in plant biomass (*see* e.g. Baldocchi 1996). However, recent studies have confirmed the important role of terrestrial vegetation in climate change and, especially, the role of circumpolar boreal forests in the global carbon cycle (e.g. Ciais *et al*. 1995). The boreal forest is a mixture of coniferous and deciduous tree species which covers currently about 1400 Mha, or 10%, of the earth's terrestrial surface (Bonan and Shugart 1989, Dixon *et al*. 1994).

The three principal experimental techniques for estimating the carbon balance of forest biomes are micrometeorological measurements of surface fluxes, biomass inventories, and the inversion of atmospheric gas concentrations. The advantages and drawbacks of these approaches were recently reviewed by Malhi *et al*. (1999). The primary method adopted for CO_2 flux measurements is presently eddy covariance (EC), measuring flux densities directly between biosphere and atmosphere typically by means of towers. However, on a daily scale, the net balance is the relatively small residual of opposite day and night fluxes, and a small error in determination of one of these processes could lead to a miscalculation of the balance (Moncrieff *et al*. 1996). Likewise, in annual scale, the accurate determinations of summertime carbon sink and wintertime source are desired. This may be a complicated task since the response of the ecosystem to the environmental factors changes over the year (e.g. Greco and Baldocchi 1996, Goulden *et al*. 1997). The annual net balance can even deviate in one or another direction as a result of varying climatic conditions (Lindroth *et al*. 1998). The biggest uncertainties in the EC technique presently relate to nighttime fluxes and, in high latitudes, to wintertime carbon exchange. Notwithstanding, measurements of CO_2 fluxes above plant canopies are useful tools for parameterizing and for testing of the models to assess NPP (net primary production) and GPP (gross primary production) (e.g. Ruimy *et al*. 1996).

In the present paper, we report the results of EC measurements of the net ecosystem exchange (NEE) and accompanying latent and sensible heat fluxes for 44 months in a boreal Scots pine (*Pinus sylvestris* L.) forest in southern Finland. We introduce the site and experimental set-up briefly and report the long-term time series as well as representative seasonal data. We analyse the temperature dependence of ecosystem respiration and PPFD (photosynthetic photon flux density) dependence of daytime CO_2 exchange and calculate the annual carbon budget. In addition, we consider the significance of inaccuracies related to the nighttime problem, determination of seasonal changes in activity and different interpolation (gap-filling of data) procedures. All of these issues are also highly relevant to the research carried out within the global flux tower network (Aubinet *et al*. 2000, Kaiser 1998).

Methods

The data were collected at the SMEAR II field measurement station (Station for Measuring Forest Ecosystem–Atmosphere Relations), which is located in Hyytiälä, southern Finland (61°51´N, 24°17´E, 181 m a.s.l.) (*see* Vesala *et al*. 1998).

Site

The 34-year-old (1996) Scots pine (*Pinus sylvestris* L.) dominated stand is homogeneous for about 200 m in all directions from the measurement site, extending to the north for about 1.2 km (60° sector). The terrain is subject to modest height variation. The height of the dominant trees in the stand is 14 m, its zero plane displacement is about 9 m and roughness length is 1.2 m. The mean diameter at breast height was 13 cm and the total (all-sided) needle area index at its maximum was 9. The Scot pine stem biomass was 45 t ha^{-1}, the total biomas (needles, branches, stem and roots) was 72 t ha^{-1} and the tree density was 2100–2500 per ha (Ilvesniemi and Liu 2000).

The dominant stand contained only 1% of species other than Scots pine: downy birch (*Betula pubescens* Ehrh.), grey alder (*Alnus incana* (L.) Moench) and aspen (*Populus tremula* L.). The ground vegetation consists of heather (*Calluna vulgaris* L.), lingonberry (*Vaccinium vitis-idaea* L.) and blueberry (*V. myrtillus* L.). The dominating moss species was *Dicranum undulatum*. The annual mean temperature is 3 °C and precipitation is 700 mm. The parent material of the soil is coarse, silty, glacial till and the soil is a Haplic Podzol.

Measurements of CO_2 exchange of the ecosystem

The eddy covariance method is based on the average of the product of instantaneous vertical velocity (*w*) and a scalar quantity (*s*). (Kaimal and Finnigan 1994, Aubinet *et al*. 2000). The vertical flux is given by

$$F = \overline{w's'}, \tag{1}$$

where the primes denote instantaneous fluctuations from mean values and the overbar represents a mean over a given period. If the scalar is the atmospheric concentration of a gas or the air temperature, the quantity obtained is proportional to the vertical flux of the gas or to the flux of the sensible heat, respectively. When the scalar is replaced by fluctuations of horizontal wind speed and multiplied by the air density the equation produces momentum flux (τ). By taking a square root of ratio of momentum flux and air density (ρ_0) an important quantity called friction velocity is attained. Thus, the equation for friction velocity is

$$u_* = \sqrt{\tau/\rho_0} = \left[\left(\overline{u'w'}\right)^2 + \left(\overline{v'w'}\right)^2\right]^{1/4}, \tag{2}$$

where u and v denote the horizontal wind speeds perpendicular to each other. The friction velocity is a measure of turbulent velocity fluctuations in the air. Generally, the sum of emissions and/or uptake by underlying vegetation layer and ground is not equal to the flux at the measurement level because of storage or release in the air layer. The rate of accumulation or release is called storage flux and it can be estimated by means of gas gradient measurements. The equation used for the storage flux is

$$F_{st} = \int_0^h \frac{dc}{dt} dz, \tag{3}$$

where h is the measuring height and c is the concentration of the measured quantity. During calm periods atmospheric stability affects the storage flux. Obukhov length (L) (Seinfeld and Pandis 1994) is often used as a measure of atmospheric stability. The storage fluxes are biggest under stable stratification conditions or under transition from stable to unstable when a quantity is released into the atmosphere above the measurement level. At the Hyytiälä site, EC fluxes were measured at two heights from a measurement tower that is 72 m high. Both measurement set-ups included an ultrasonic anemometer (Solent 1012R2, Gill Instruments Ltd., Lymington, UK) and a closed-path infrared gas analyser (LI-COR 6262, Licor Inc., Lincoln, NE). The distance of the anemometer from the mast was 3.5 m, and a 7 m long heated teflon (PTFE) tube (inner diameter of 4 mm) was used to sample air from near the anemometer (tube inlet fixed below the sensing head of the anemometer, about 15 cm from the centre) to the gas analyser. The flow rate was 6.3 dm^3 min^{-1} in order to produce turbulent flow. In addition to a membrane filter (1 µm PTFE) at the gas analyzer inlet, there was a sintered brass filter at the inlet of the gas sample line to remove particles larger than 50 µm. Pure, dry nitrogen was used as the reference gas for the gas analyser. The fluctuating components were extracted from the turbulent records by linear detrending (*see* e.g. Rannik and Vesala 1999). The delay time due to sample gas flow in the tube was obtained by determining the maximal vertical covariance. Finally, the flux was corrected for the imperfect frequency response of the system (damping of fluctuations in the sampling line, frequency response of the gas analyser) according to Moore (1986) by using the model co-spectra of atmospheric surface layer turbulence (Kaimal *et al.* 1994). A more detailed description of the operation of the set-up is given by Rannik (1998a) (*see also* Rannik 1998b).

Continuous measurements of energy and gas fluxes were started in April 1996 at 23 m, 10 m above the forest canopy. In February 1998, measurements were also started at 46 m. Since then the measurements were done at either of the heights, except for breaks for the maintenance or calibration of the instrumentation or failures in the operation of the set-ups.

Measurements of gas concentration gradient and other environmental quantities

The temperature, wind speed, and gas concentration gradients are continuously measured from the flux tower at six levels: 4.2, 8.4, 16.8, 33.6, 50.4 and 67.2 m. Wind speed is measured with Vector A101M/L cup anemometers (Vector instruments, UK) and temperature with PT-100 sensors (platinum resistance thermometer). The temperature sensors are shielded from solar radiation and ventilated. Wind directions are registered with Vector W200P wind vanes (Vector instruments, UK) at three heights (4.2, 16.8 and 50.4 m). The cup anemometers and the temperature sensors are attached to horizontal booms about 4.5 m and 2 m from the mast, respectively, pointing to the north–north-west. From each measurement level the air is sucked through teflon tubes of equal lengths (100 m, inner diameter 14 mm) to a measurement cottage near the tower where it is analysed for concentrations of CO_2, water vapour and trace gases. The CO_2 and H_2O concentrations are measured with URAS 4 (Hartmann & Braun, Frankfurt am Main, Germany) infrared analysers in sequence using a valve system. Soil temperature is measured at seven locations with silicon temperature sensors (Philips KTY81-110).

Results

We first present the measured fluxes of CO_2, H_2O, and sensible heat for the period of April 1996 to December 1999. Next we analyze the validity of the data as regards the measurement height, the wind direction, the atmospheric stability, and the friction velocity. This analysis provides criteria for the representativeness of the data and using these criteria we present the seasonal patterns of daily CO_2 and storage fluxes, Bowen ratios and ecosystem exchange under radiation saturation. The gap-filling of the CO_2 flux data series is carried out in three different ways and finally daily and yearly balances of the exchange are presented for the Hyytiälä Scots pine site.

The measured CO_2 and water vapour exchange data at either measurement heights covered 83% of all the half-hourly periods during the 1354 days of continuous measurements. Data coverage of sensible heat measurements was 86%, being somewhat larger than that of the gases. The CO_2 and water vapour exchange and sensible heat flux exhibited a clear seasonal pattern (Fig. 1). Absolute values of all the fluxes had their seasonal minima in winter when there was snow cover and the vegetation was in a state of dormancy. In spring, the sensible heat flux started to increase due to the increasing intensity of solar radiation. The snow melted as the air temperature increased and the water vapour flux increased gradually its from winter values. Negative CO_2 fluxes implying CO_2 uptake by vegetation occurred later than the increase in sensible heat and water vapour fluxes. The growing season was considered to begin when the absolute value of the daytime CO_2 fluxes started to increase strongly and become clearly PPFD controlled as opposed to the temperature regulated winter fluxes. The growing season started on 28 April 1997, 16 April 1998 and 25 March 1999. In 1996, fluxes were negative from the beginning of the data series and according to the criterion used the growing season began before the start of the measurements. The end of the growing season was determined with the opposite criterion to the determination of the beginning, the end days being 11 November 1996, 1 November 1997, 30 November 1998, and 14 November 1999. Thereafter, the growing season is referred to as summer (or summertime).

Furthermore, summertime was divided into nighttime and daytime to separate the periods of pure CO_2 release from the periods containing light controlled uptake of CO_2 by the vegetation. Mean sun elevation angles of the half-hourly periods were used to separate nighttime from daytime. By comparing calculated sun elevation angles and measured photosynthetically active radiation values the limit of night and day was found to be at a sun elevation angle of –3°. Then the PPFD reached 10 μmol m^{-2} s^{-1} and the CO_2 flux turned towards negative values due to the light controlled photosynthesis by the plants. The sun elevation angle was negative since the atmospheric scattering of the visible light makes the sky bright even when the sun is below the horizon. With this criterion the nocturnal period was at least three hours long every night.

Methodologically, EC measurements are based on the existence of turbulence (vertical mixing). However, NEE should be evaluated as the sum of the turbulent and storage fluxes (Eqs. 1 and 3, respectively), henceforth called the total flux, where the significance of the storage flux diminishes when the intensity of mixing increases. The sum of the summertime nocturnal fluxes for a limited temperature range should not be dependent on the friction velocity, which de-

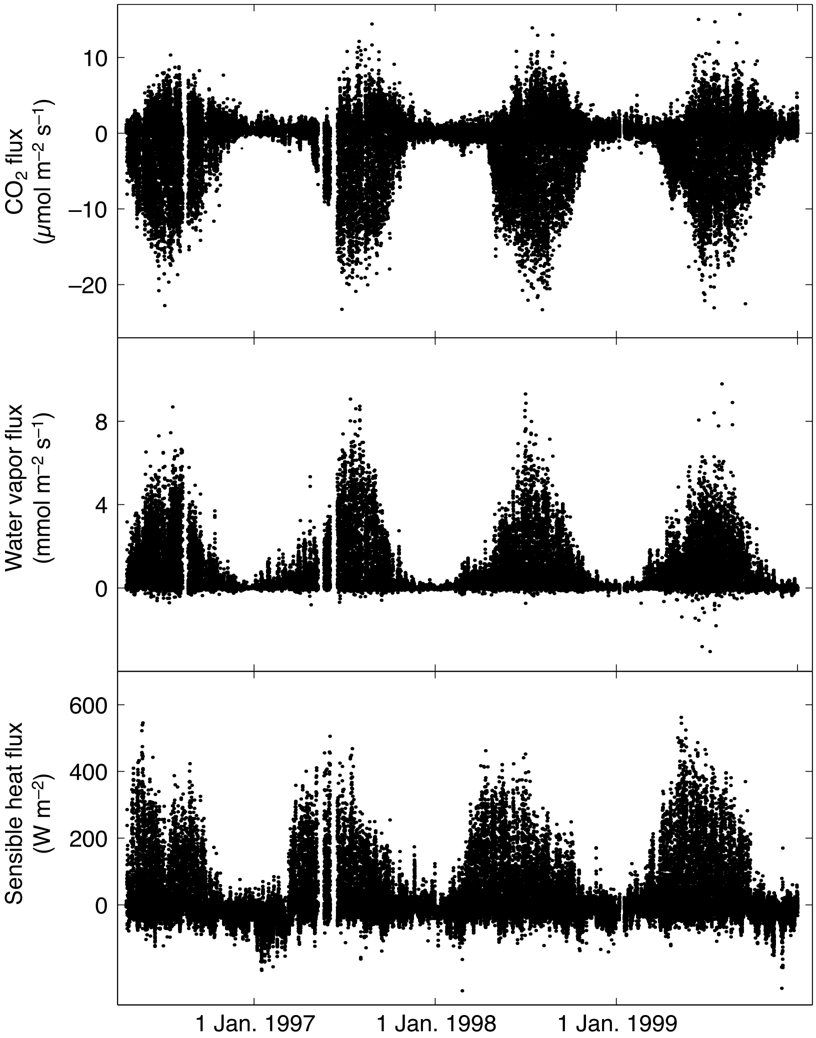

Fig. 1. Half hourly EC values of gas and energy fluxes measured above a Scots pine dominated site in southern Finland from April 1996 to December 1999. Compelete data series of CO$_2$ flux, water vapour flux, and sensible heat flux are presented without any validation criteria.

scribes the amount of mechanical turbulence (Eq. 2). Even though the storage term was included the total flux decreased at the low friction velocity (Fig. 2). Several studies (*see* e.g. Goulden *et al.* 1996, Jarvis *et al.* 1997) have discovered this discrepancy and the common procedure to deal with the problem is the rejection of the total flux data using a threshold value for $u*$. Within the air temperature range of 2 °C $< T_a <$ 8 °C the sum of nighttime CO$_2$ and storage fluxes was relatively constant when friction velocity exceeds the threshold value of 0.25 m s^{-1} (Fig. 2). Values of threshold $u*$ were somewhat larger if storage flux was not included in the total flux.

According to foot-print analysis based on the stochastic simulation of air parcel trajectories (Rannik *et al.* 2000), 80% of the flux measured at the lower level originates from the area within 240 meters of the measurement tower when -75 m $< L <$ 0 m. Because the site is not perfectly homogeneous, meteorological factors other than mixing affect the representativeness of the data. In wintertime, the total CO$_2$ flux has a clear dependence on wind direction at the upper level during both stable and unstable conditions. During stable periods wind direction dependence is distinguishable at the lower measuring level as well. When wind is in west–southwest direction the CO$_2$ flux is considerably larger as compared with the fluxes during periods with other wind directions. This is due to the

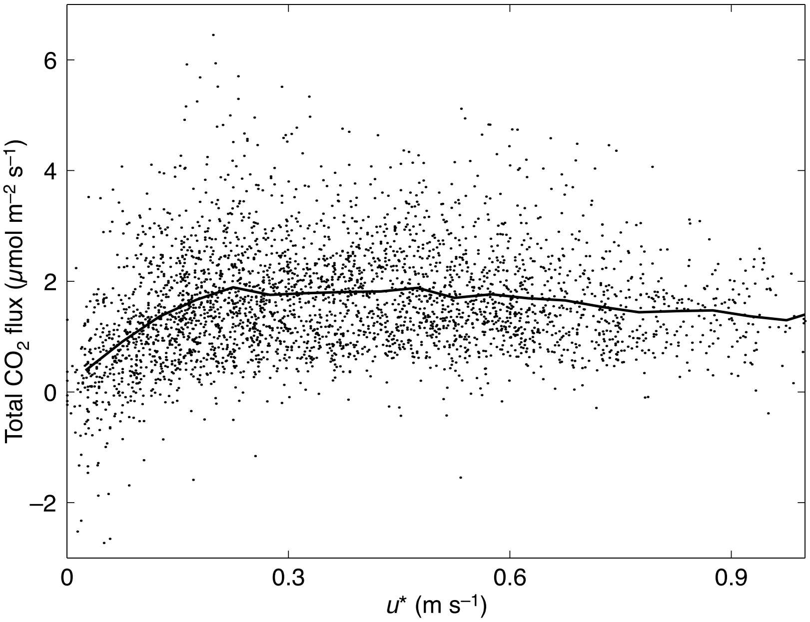

Fig. 2. Nocturnal summertime total fluxes (at 23 meters) of the periods with air temperature 2 °C < T_a < 8 °C as a function of friction velocity. Total flux is a sum of flux measured by eddy-covariance and the storage term calculated from the gas concentration gradient. The line indicates a running average of the total flux.

station buildings located 800 m west–south-west from the site. Sun elevation, wind direction, friction velocity and atmospheric stability dependent criteria were used to select the representative data for analysis of the ecosystem CO_2 exchange hereafter in this work (Table 1).

Seasonal characteristics of the measured fluxes were studied separately for three complete calendar years (1997, 1998 and 1999). The daily pattern of the total CO_2 flux in April changed considerably from year to year (Fig. 3A). This variation may be partly explained by differences in temperature because the state of the ecosystem is strongly controlled by air and soil temperature. Averages of air temperatures were 0.2 °C, 2.1 °C and 4.5 °C and standard deviations were 3.8 °C, 7.2 °C and 4.3 °C during April 1997, 1998 and 1999 respectively. Soil temperatures did not change significantly from their midwinter averages during the considered periods, the average values of April being 0.5 °C, 0.6 °C and 0.4 °C. The dates of abrupt increase in soil temperature indicating completion of the snow melting were 18 May 1997, 2 May 1998 and 16 May 1999. The soil does not freeze at the depth of 5 cm in the site in wintertime. Differences in magnitudes and variations of CO_2 fluxes in July and October (Fig. 3B) were not as large as they were in springtime.

The Bowen ratio describes the energy parti-

Table 1. Criteria for selecting reliable data for NEE estimates. The values given in parentheses in the friction velocity column is the limit for friction velocity when storage measurement is not available.

Measurement height	Season	Sun elev. (°)	u^* (m s^{-1})	Wind dir. (°)	O length (m)
23	summer	< –3	> 0.25 (0.35)	any	any
23	summer	> –3	> 0.25 (0.35)*	any	< 0 and > -10^5
23	winter	any	> 0.25 (0.35)	< 215 or > 265*	< 0 and > -10^5
46	summer	< –3	> 0.25 (0.35)	any	any
46	summer	> –3	> 0.25 (0.35)*	any	< 0 and > -10^5
46	winter	any	> 0.25 (0.35)	< 215 or > 265	any

* If the condition is not fulfilled the Obukhov length criterion was used.

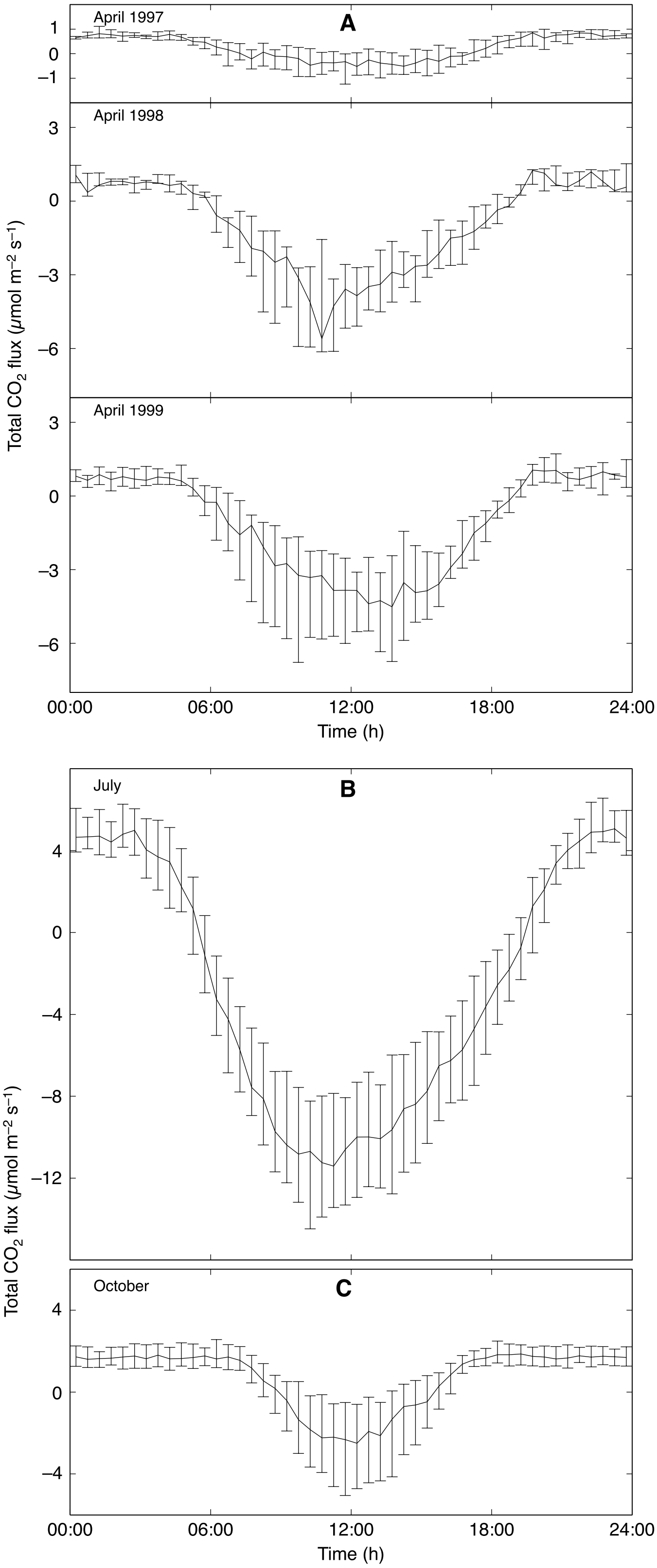

Fig. 3. Daily total CO_2 fluxes during (**A**) April of each year separately, combined data for (**B**) July and (**C**) October of all the three years. The line indicates monthly median and the bars are the first and third quartiles of the qualified data.

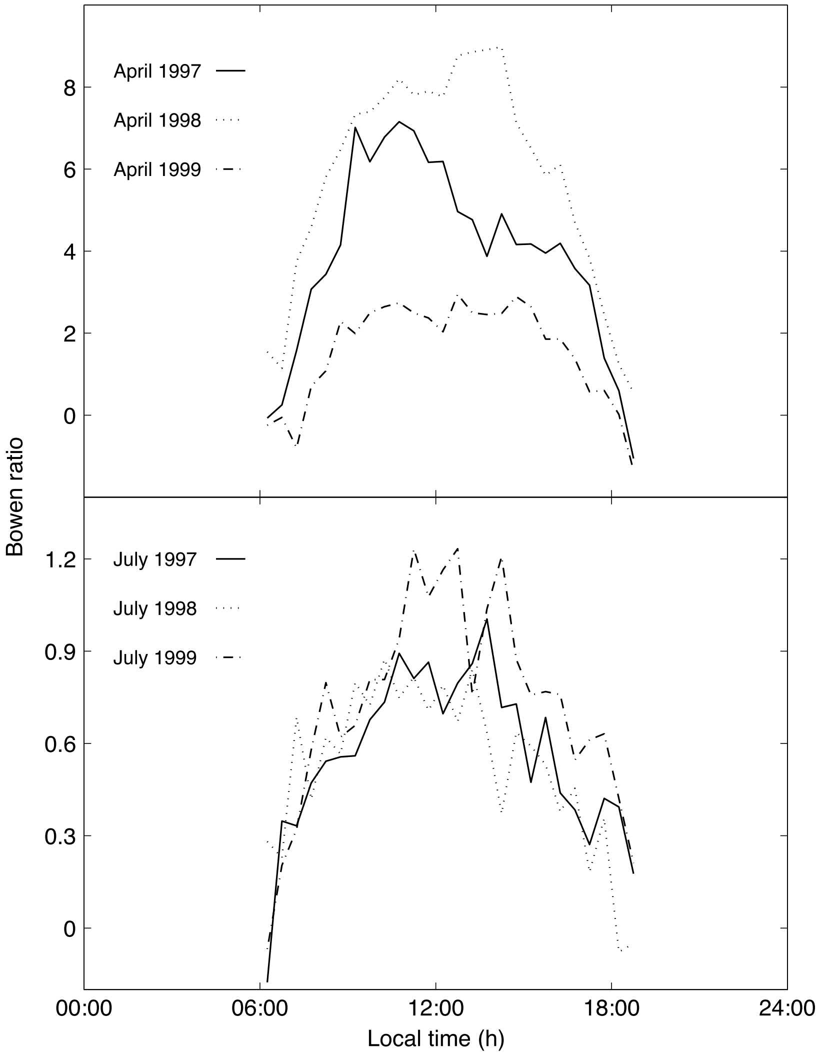

Fig. 4. Monthly medians of Bowen ratios in April and July daytime periods.

tioning between sensible heat and latent heat. Latent heat flux is the water vapour flux converted into energy units through multiplication by the latent heat of vaporization. In springtime mid-day, the Bowen ratios varied a lot from year to year (Fig. 4). In July, daily patterns of the Bowen ratio were nearly similar during the three years.

Daily averages of the CO_2 fluxes during periods when PPFD > 850 µmol m^2 s^{-1} and T_{air} > 8 °C can be considered as maximal uptake rates during each day. The criterion for radiation is selected so that ecosystem exchange is practically in saturation in regard to radiation which means that an increase in the intensity of the radiation does not increase the rate of the CO_2 uptake significantly. The maximal rate of CO_2 uptake had its minimum at the beginning of every summer reaching gradually a stable level by mid-summer (Fig. 5). Besides the changes in the physiological state of the forest, the growth of needle mass during the first few months of the growing season affects the maximal uptake rate. There was no clear decline in maximal uptake rates in autumn which is contradictory to the results obtained from measurements in a black spruce forest by Coulden *et al.* (1997).

The percentages of qualified data varied according to the season and the time of day (Table 2). During winters 1997–1999 the measurements at the lower level were considered unreliable because of the unusually large per-

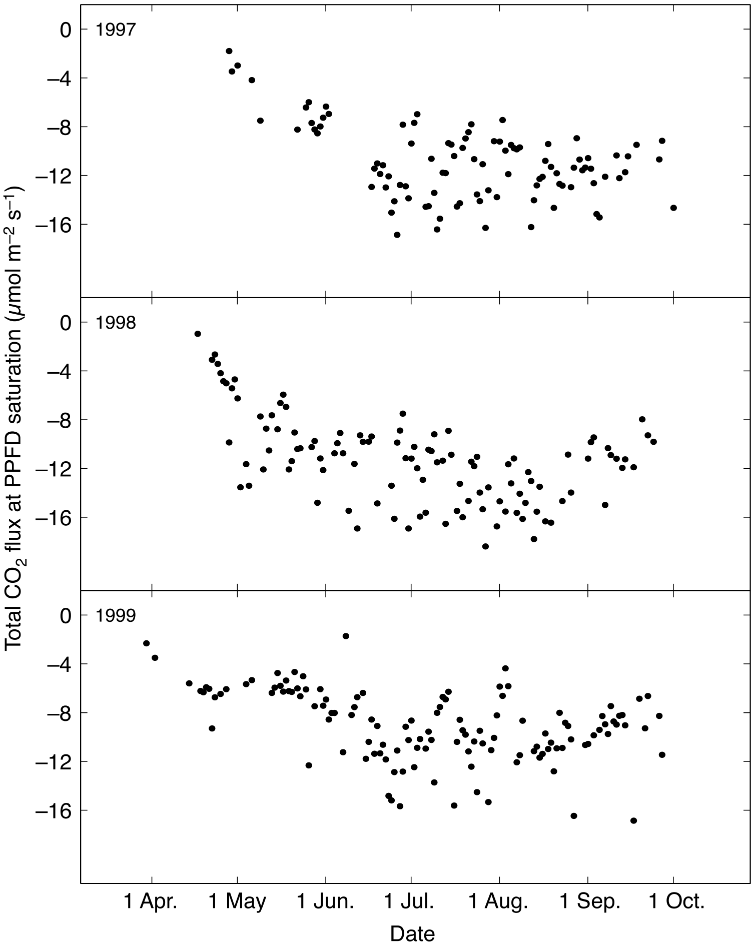

Fig. 5. Daily averages of CO_2 fluxes of the periods with PPFD > 850 μmol m^{-2} s^{-1} and T_a > 8 °C during the growing seasons of each year.

centage of negative fluxes. Consequently, only measurements at the upper level were taken into account in the calculations of the carbon balance and in the determination of the temperature dependence of the wintertime respiration. Because the trees are in a state of dormancy and soil respiration is controlled by the relatively constant soil temperature, respiration has no strong air temperature dependence in wintertime (Fig. 6). The range of wintertime soil temperature was –1.1 °C to 5.2 °C the average temperature being 0.9 °C. The average wintertime flux was 0.44 μmol m^{-2} s^{-1}. Variation in CO_2 fluxes increased with increasing temperatures and at the highest temperatures the overall level of fluxes decreased slightly instead of growing uniformly. During the summers the nocturnal ecosystem respiration had a clear dependence on the air and soil temperatures.

The air temperature at 8 meters and the soil temperature in a depth of 5 cm were used for the temperature regression between combined wintertime and summer nighttime ecosystem respiration. The coefficient of determination r^2 was better for a regression with both air and soil temperatures than for regressions with either of

Table 2. Amount of measured half hourly periods during each year with complete data series (longest continuous break in measurements 2 week) and percentages of qualified data.

Period	1997	1998	1999
Existing (1/2 h) data	13 381	15 620	15 542
Qualified data			
Summer day (%)	60	83	80
Summer night (%)	43	46	47
Winter (%)	34	31	32

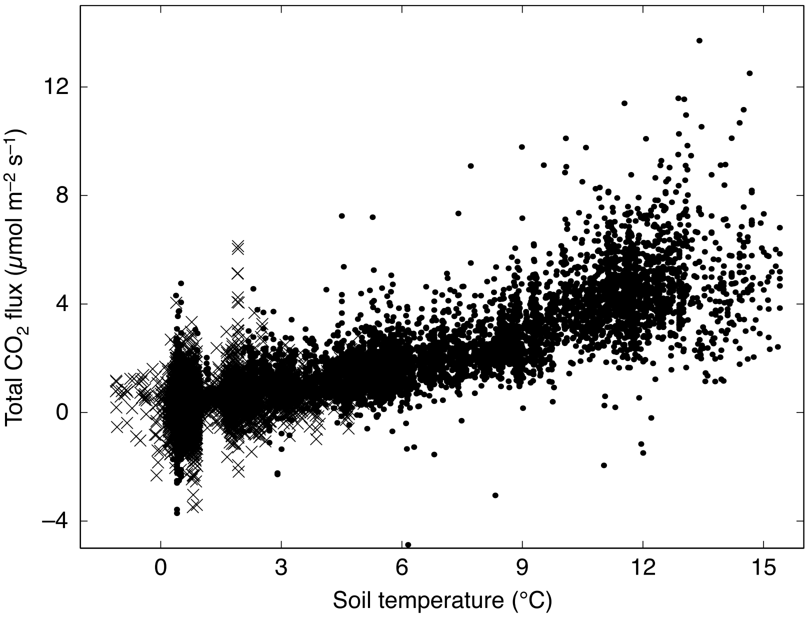

Fig. 6. Winter (cross) and Summer night (circle) ecosystem respiration as a function of the average soil temperature in 5 cm. A storage term is included if available.

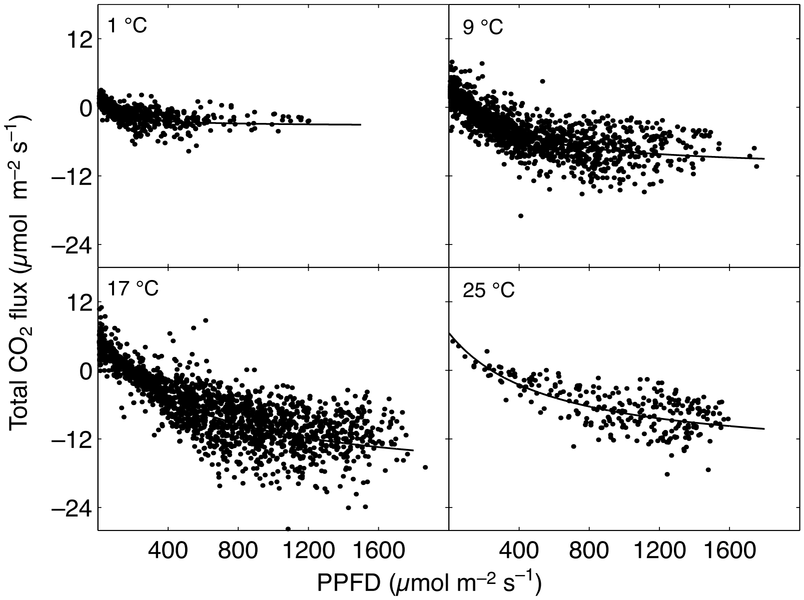

Fig. 7. Four examples of total daily CO_2 fluxes classified according to air temperature in classes of 2 °C as a function of PPFD.

the temperatures separately. The equation used for the temperature dependence was:

$$R_e = 0.25T_{soil} + 0.27e^{0.14T_{air}} \quad (4)$$

producing a coefficient of determination $r^2 = 0.72$, whereas coefficients of determination for exponential functions of soil temperature and air temperature were $r^2 = 0.69$ and $r^2 = 0.61$, respectively. Other forms of the temperature regression function were tested but none of them produced a considerably better fitting. We also considered the importance of the soil water content but it appeared to be small. In the short term, the instantaneous light is the environmental factor having the dominant effect on photosynthesis. A common way to model the CO_2 exchange of the ecosystem in daytime is to determine the light

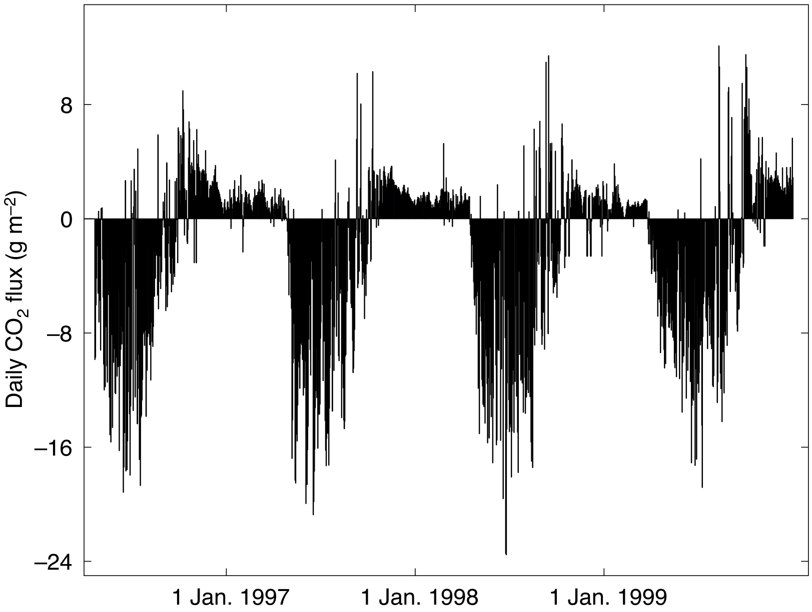

Fig. 8. Daily sums of CO_2 exchange. Periods with no reliable data due to instrumentation failures, maintenance and calibration breaks or inappropriate meteorological state have been estimated by the light and temperature relationships of ecosystem respiration and daytime canopy uptake.

dependence of the measured fluxes. Usually, a Michaelis–Menten type equation is used (Valentini *et al.* 1996, Goulden *et al.* 1997, Hollinger *et al.* 1999):

$$F_c + F_{st} = \frac{A_{max} I}{K + I} - R_d, \quad (5)$$

where F_c and F_{st} are canopy flux measured with EC and storage flux respectively, I denotes the incident PPFD, R_d is the daytime ecosystem respiration rate, A_{max} is canopy photosynthetic capacity, and K is half-saturation constant. The values of the parameters in Eq. 5 change over the summer due to seasonal changes in the state of the ecosystem, temperature and soil water content. Here the effect of temperature was taken into account by determining the PPFD dependences for several temperature classes (Fig. 7). The parameter values for each temperature class were used in the gap-filling (Table 3). In the gap-filling procedure temperature classes with $r^2 < 0.5$ or $K > 1\,000$ µmol m^{-2} s^{-1} where excluded. After filling the gaps with available temperature and PPFD regressions 4% of the half-hourly periods were still lacking an estimate for CO_2 exchange. These periods were filled with the average exchange rate over the respective year.

Daily balances of CO_2 reached zero level during a maximum of two days after the beginning of the growing season every year (Fig. 8). Thus, the beginning of the growing season was reasonably selected in regard to the daily balances as well. There were a few days with negative daily balances also in wintertime. During summertime, on the other hand, there were days of positive daily balance when the weather was cloudy but warm. A similar behaviour of ecosystem exchange has been reported by Grelle (1997) about the ecosystem exchange of mixed Norway spruce–Scots pine site.

According to the three different gap-filling methods used in this work, the site was a net sink of carbon during each year (Table 4). The yearly average temperatures were 4.4 °C, 3.5 °C and 4.4 °C and growing season lengths estimated based on the measured flux data were 189, 206 and 235 days in 1997, 1998 and 1999 respectively, thus, variations in either of these quantities alone do not explain the variation in the yearly NEE values. The sink strength was of average level of all the coniferous sites within the EUROFLUX network (Valentini *et al.* 2000) where yearly NEE varied from 90 g C m^{-2} to –670 g C m^{-2}. Besides calculating NEE for the three complete calendar years, the balances of all the 365 day periods were calculated to find out the variation between all the possible years

Table 3. Coefficients of rectangular hyperbola function: $F_{CO_2} = \frac{A_{max} I}{K + I} - R_d$. describing the PPFD dependence of the ecosystem CO_2 exchange classified according to the air temperature T_a. I is PPFD above the canopy, r^2 is the coefficient of determination between the data and the fitting.

Temp. (°C)	Mean temp. (°C)	K (µmol m^{-2} s^{-1})	A_{max} (µmol m^{-2} s^{-1})	R_d (µmol m^{-2} s^{-1})	r^2
–6 < T < –4	–4.7	389.1	1.29	0.67	0.15
–4 < T < –2	–2.9	5.6	2.35	2.71	0.11
–2 < T < 0	–0.8	110.4	3.43	1.17	0.49
0 < T < 2	1.0	79.3	5.21	1.92	0.73
2 < T < 4	3.1	99.8	6.74	2.04	0.81
4 < T < 6	5.0	191.4	10.20	2.68	0.83
6 < T < 8	7.0	187.6	11.44	3.53	0.81
8 < T < 10	9.0	286.5	14.84	3.80	0.85
10 < T < 12	11.0	276.1	17.45	5.23	0.87
12 < T < 14	13.0	288.2	20.49	6.00	0.87
14 < T < 16	15.0	409.0	23.16	5.90	0.85
16 < T < 18	16.9	556.2	26.45	6.20	0.82
18 < T < 20	18.9	682.7	24.85	4.84	0.78
20 < T < 22	21.0	536.5	24.82	7.00	0.78
22 < T < 24	22.9	630.6	25.90	7.10	0.73
24 < T < 26	24.9	578.5	22.18	6.55	0.70
26 < T < 28	26.9	2810.7	36.63	4.24	0.80
28 < T < 30	28.8	–	–	4.64	0.86

within the series. Starting from 17 May 1996, the total amount of these 365 day NEE values was 988. The minimum and maximum running annual NEE values were –165 g C m^{-2} and –304 g C m^{-2}, respectively. The maximum was 14% larger and the minimum was 16% smaller than the maximum and the minimum NEE's of the three calendar years.

Table 4. Yearly NEE's estimated on the basis of the EC measurements using different gap filling procedures. (1) Gaps during winter and summer night and day periods were filled with the averages of the corresponding period in each year individually. (2) Gaps were filled with common temperature and PPFD regressions over all the growing seasons. (3) Gaps were filled with separate PPFD regressions for the beginnings and ends of the growing seasons.

Method	NEE 1997 (g m^{-2})	NEE 1998 (g m^{-2})	NEE 1999 (g m^{-2})
1	–403	–323	–256
2	–234	–262	–191
3	–217	–267	–200

Thus, according to the 44 month data series used for the current study the site seemed to be a net sink of carbon at its present state of development contrary to the behaviour of the Northern American black spruce site reported by Goulden *et al.* (1998) or the Norway spruce–Scots pine site in central Sweden reported by Lindroth *et al.* (1998) which both can turn from net sink to net source of carbon from year to year depending on the climatic conditions. Cumulative gap filled NEE over the 1354 day period reached a value –905 g C m^{-2} (Fig. 9), the ecosystem respiration based on the soil and air temperature regression (Eq. 4) during the same period was 3258 g C m^{-2} and the gross ecosystem exchange (GEE) which can be estimated as NEE minus respiration was –4163 g C m^{-2}.

Conclusions

Measurements of mass and energy exchange between the atmosphere and biosphere can be carried out by several methods in various spatial

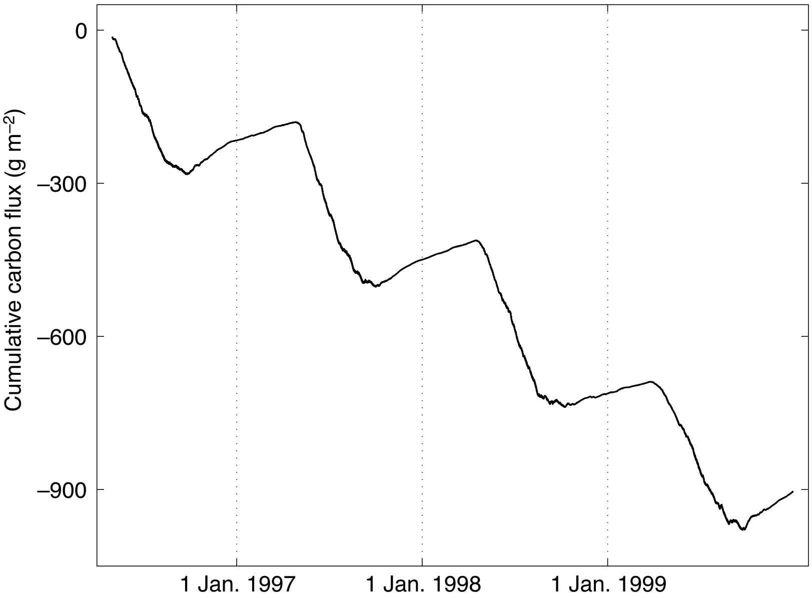

Fig. 9. Gap-filled cumulative net carbon exchange between the atmosphere and ecosystem starting at zero on 17 April 1996.

and temporal scales. Nevertheless, the estimate of the total exchange between the atmosphere and ecosystem is a difficult task because of the heterogeneity of the system at every scale and non-linear relationships between the driving variables and fluxes (Jarvis 1995). The eddy covariance technique is considered as an effective measurement method for the CO_2, water vapour and energy surface fluxes (*see* Baldocchi *et al.* 1996). The technique involves certain requirements for the site (such as a flat terrain and an adequate fetch) that only seldom can be perfectly fulfilled by a natural forest. However, the natural variability of the topography and canopy composition is the reality we live with. The deficiencies of the eddy covariance method and the site characteristics must be taken into account in data evaluation and interpretation.

In this paper, we reported the results of EC measurements of net ecosystem exchange (NEE) for 44 months in a boreal Scots pine forest (southern Finland). The annual cumulative NEE, calculated for three gap-filled calendar years, varied from –190 g C m^{-2} to –260 g C m^{-2}.

There was a significant variation in daily total CO_2 fluxes in April between the years. In contrast to sites with freezing soil temperature in the wintertime, the soil temperature did not have such a strong impact on the beginning of the CO_2 uptake by the vegetation in spring time as has been reported by e.g. Hollinger *et al.* (1999).

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