# Net ecosystem $CO_2$ exchange of mixed forest in Belgium over 5 years

Arnaud Carrara [a], Andrew S. Kowalski [a], Johan Neirynck [b],
Ivan A. Janssens [a], Jorge Curiel Yuste [a], Reinhart Ceulemans [a,*]

[a] *Research Group of Plant and Vegetation Ecology, Department of Biology,
University of Antwerpen (UIA), Universiteitsplein 1, B-2610 Wilrijk, Belgium*
[b] *Institute for Forestry and Game Management (IBW), Ministry of the Flemish Community,
Gaverstraat 4, B-9500 Geraardsbergen, Belgium*

## Abstract

In this paper, we present and discuss the annual net ecosystem exchange (NEE) results from 5 years (1997–2001) of continuous eddy covariance measurements of $CO_2$ flux above a mixed temperate forest. The forest was a 70-year-old coniferous (Scots pine)—deciduous mixture, with slow growth rate and a leaf area index (LAI) of about 3, and was part of the European CARBOEUROFLUX research network. Effects of the data pre-treatment and the gap filling method on annual NEE estimates were analyzed. The $u_*$-correction increased the annual NEE by $+61 \, \mathrm{g \, C \, m^{-2}}$ per year on average. The maximum difference in annual NEE estimates from different gap filling methods amounted up to $130 \, \mathrm{g \, C \, m^{-2}}$ per year in a year with a large gap in the $CO_2$ flux series. The estimated average annual NEE over the 5 years was $+ 110 \, \mathrm{g \, C \, m^{-2}}$ per year (ranging from $-9$ to $255 \, \mathrm{g \, C \, m^{-2}}$ per year) when using the most defensible gap filling strategy. We also analyzed the inter-annual variability of carbon balance, which was found to be mainly dependent on the length of the growing season and on the annual temperature. The observation that this forest acted as a $CO_2$ source contrasts with previous results from most other temperate forests.
© 2003 Elsevier B.V. All rights reserved.

*Keywords:* Carbon balance; Eddy covariance; Data gap filling; Net ecosystem exchange; Inter-annual variability; CARBOEUROFLUX

## 1. Introduction

A better understanding of the global carbon balance, and particularly of the role of terrestrial ecosystems represents an important current challenge to the scientific community, e.g. the "missing sink" issue (Schimel, 1995; Ciais et al., 1995; Keeling et al., 1996; Houghton et al., 1998; Sarmiento and Gruber, 2002).

Given the importance of temperate forests in the global carbon balance (Reich and Bolstad, 2001), measuring and modeling the net ecosystem exchange (NEE) of these forests has become a major research activity.

Within this context (Baldocchi et al., 1996) networks of tower-stations have been established performing long-term, continuous measurements of $CO_2$ exchange between forest ecosystems and the atmosphere (Baldocchi et al., 2001), including EU-ROFLUX (1996–1999) and CARBOEUROFLUX (2000–2003) which supported the present study. Recent investigations have shown that mature and

* Corresponding author. Tel.: +32-3-820-2256;
fax: +32-3-820-2271.
*E-mail address:* reinhart.ceulemans@ua.ac.be (R. Ceulemans).

undisturbed forests were generally sizable carbon sinks, although large variations in their $CO_2$ sequestration rates were observed (Valentini et al., 2000; Falge et al., 2002). However, information about the inter-annual variability of NEE and the effects of management is still rather poor, but essential to characterize the role of forests in the global carbon budget. Furthermore, only very few long-term eddy covariance sites have been established in mixed coniferous/deciduous or patchy forest types, although these are typical of many regions in Europe. Despite the challenging circumstances, measurements over such sites can be helpful to study the specific behavior of the existing complex forests and take them into account in SVAT global models.

The purpose of this paper is to present 5 years (1997–2001) of eddy correlation measurements of $CO_2$ flux above a managed mixed coniferous/deciduous forest in Belgium, and the resulting annual NEE. In order to achieve defensible annual sums of NEE, data quality tests and gap filling procedures are required to provide consistent and complete datasets. The different data selection and gap filling methods used are presented and their effects on the NEE estimates are discussed. We also analyze the inter-annual variability of NEE in relation to climatic variables. Since the forest was rather intensively managed during the measurement period, we also discuss the effects of forest management practices on the annual carbon budget.

## 2. Site description

The forest under investigation is 'De Inslag', a mixed patchy coniferous/deciduous forest located in Brasschaat (51°18′33″N, 4°31′14″E), in the Belgian Campine region (de Pury and Ceulemans, 1997), about 20 km north-east of Antwerp. The site is part of the European CARBOEUROFLUX network (http://www.bgc-jena.mpg.de/public/carboeur/) and is a level-II observation plot of the European network program (ICP-II forests) for intensive monitoring of forest ecosystems (EC-UN/ECE, 1996), managed by the Institute for Forestry and Game Management (Flanders, Belgium). The landscape is a coastal plain, almost flat (slope <0.3%) at a mean elevation of 16 m. The climate is temperate maritime with a mean annual temperature of 9.8 °C and 750 mm of annual precipitation. The site is located in an area with high nitrogen deposition (30–40 kg ha$^{-1}$ per year; Neirynck et al., 2002).

This relatively small (150 ha) forest consists of many patches of different coniferous and deciduous species, with a variety of understorey species as well (Fig. 1). Scots pine (*Pinus sylvestris* L., 80% of the coniferous species) and pedunculate oak (*Quercus robur* L., 80% of the deciduous species) dominate the canopy composition. The undergrowth is dominated by black cherry (*Prunus serotina* Ehrh.), rhododendron (*Rhododendron ponticum* L.) and grass (*Molinia caerulea* L. Moench), and an extensive moss cover (dominated by *Hypnum cupressiforme* Hedw.) characterizes some patches on the ground. A more complete description of the forest, with vegetation composition of the various patches has been previously published (de Pury and Ceulemans, 1997; Janssens et al., 2000). Due to changing management policies over the last decades, the composition and structure of the forest vary among patches, but the forest remains relatively even-aged. The 40 m scaffold measurement tower is located within an even-aged Scots pine stand planted in 1929. In this experimental stand, the current density is 375 trees ha$^{-1}$, mean tree height is about 21 m, mean diameter at breast height (DBH) is 30 cm and stem basal area is 27 m$^2$ ha$^{-1}$. About half of the forest consists of similar pine stands, and most of the remainder part consists of pedunculate oak stands of similar age (planted in 1936) with tree density about 320 ha$^{-1}$, mean tree height about 17 m, mean DBH about 24 cm and stem basal area about 16 m$^2$ ha$^{-1}$. Leaf area index (LAI) varies considerably among patches and, in areas characterized by deciduous species, also seasonally. The area-weighted LAI, including both over- and understorey LAI for the entire forest, is about 3 m$^2$ m$^{-2}$ (between 1.7 m$^2$ m$^{-2}$ in winter and 3.6 m$^2$ m$^{-2}$ in summer, recalculated from Gond et al., 1999).

Most stands have canopy heights similar to the experimental pine stand. The fetch is about 500 m in the west sector, the prevailing wind direction (Fig. 1). Better conditions regarding fetch (>800 m) are met in eastern sectors. The roughness length is about 1 m and the zero plane displacement is about 19 m. The forest is bordered to the north and west by the residential town of Brasschaat, and to the south and east by rural, partially forested terrain.
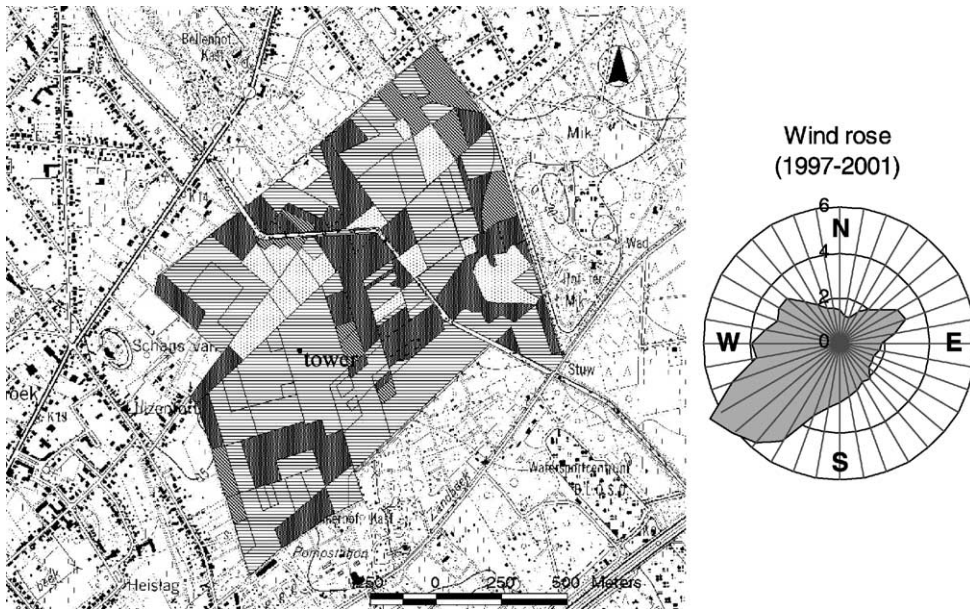
Fig. 1. Map with composition of the forest surrounding the tower and wind rose. Wind frequencies are expressed in percent and computed by 10° wind sectors for the period 1997–2001: (▦) deciduous; (☰) coniferous; (▨) mixed; (▩) grassland; (●) measuring tower.

The soil is loamy sand, moderately wet, with a distinct humus and iron B-horizon (Baeyens et al., 1993) and is classified as Umbric Regosol (FAO classification, Roskams et al., 1997). Below the sandy layer, at a depth of 1.5–2 m, lies a clay layer. Due to this clay layer, the site has poor drainage, and groundwater depth usually is between 1.2 and 1.5 m (Baeyens et al., 1993). A more detailed description of the physical and chemical properties of the soil is available (Janssens et al., 1999; Neirynck et al., 2002).

## 3. Material/instrumentation

### 3.1. Eddy correlation measurements

The vertical flux of $CO_2$ between the forest and the atmosphere was measured using the eddy correlation technique, originally proposed by Swinbank (1951) and applied to measure the net flux of carbon dioxide at ecosystem scale (NEE) since the 1980s (Desjardins, 1985; Verma et al., 1986; Baldocchi et al., 1988). Fluxes of $CO_2$ ($F_c$), water vapor ($\lambda E$) and sensible heat ($H$) have been measured continuously since

mid-1996, from a scaffold tower at a height of 41 m. The $CO_2$ vertical flux was calculated as the covariance between fluctuations in the vertical wind speed ($w$) and $CO_2$ concentration ($c$). The fast-response sensors used were a three-dimensional sonic anemometer (Model SOLENT 1012R2, Gill Instruments, Lymington, UK) for wind speed and temperature, and an infrared gas analyzer (IRGA) (Model LI-6262, LI-COR Inc., Lincoln, NE, USA) for $CO_2$ and water vapor concentrations. The IRGA was used in absolute mode with pure nitrogen flowing through the reference cell as zero air. Air is drawn through a 1 µm PTFE-Teflon filter (Gelman Acro 50, PN 4258, Ann Arbor, MI, USA) at $6.21 \text{min}^{-1}$ by a membrane pump (Model N811 KNDC, KNF Neuberger, Freiburg, Germany) installed downstream of the analyzer. It then enters a 3 m long PTFE-Teflon tube of 4.33 mm (inner diameter), heated to prevent condensation. A subsequent filter (Ballston 300-01961, USA) cleans the air prior to sampling by the IRGA. The distance between the air inlet and the central point of the sonic measurements is about 40 cm. Calibration of the IRGA with a reference gas was performed monthly. The data were logged at 20.8 Hz and the fluxes computed in real

time using the EDISOL software (Moncrieff et al., 1997).

### 3.2. Complementary measurements

Above canopy meteorological measurements were made at the top of the tower (40 m) and stored as half-hourly means on a data logger (Campbell CR10, CSI, Logan, UT, USA). They include global radiation (pyranometer, Kipp and Zonen CM6B, Delft, The Netherlands), net radiation (REBS 07, Seattle, WA, USA), photosynthetically active radiation (PAR quantum sensor, JYP-1000, SDEC, Tours, France), precipitation (tipping-bucket rain gauge, Didcot DRG-51, Didcot Instrument Co. Ltd., Abington, UK), relative humidity and temperature (psychrometer, Didcot DTS-5A, UK).

In order to estimate $CO_2$ storage in the air layer below the eddy correlation measurements height, measurements also include a profile of $CO_2$ concentrations at four levels (10, 24, 32 and 40 m above the ground). From each inlet, air is drawn through 53.5 m of tubing to an instrument shelter, heated to 35 °C, and filtered through a 0.5 mm PTFE-Teflon filter. Each level is sampled for a total duration of 6 min each half-hour by a gas analyzer (IRGA, LI-800, LI-COR Inc., Lincoln, NE, USA).

Other pertinent environmental variables include the soil measurements. Two heat flux plates (Campbell HFT03, CSI, Logan, UT, USA) measured the soil heat flux ($G$). Soil temperature was measured with probes (Didcot DPS-404, UK) installed at 2 and 9 cm depth. Since January 2001, $CO_2$ soil efflux has been measured with a closed dynamic system (IRGA, CIRAS-1, PP SYSTEMS, Hitchin, Herts, UK), in nine patches (different associations of canopy/understorey vegetation) representative for the forest composition.

More details about the instruments and methods used for the measurements performed at the site can be found in Overloop and Meiresonne (1999) and in Kowalski et al. (2000) for the complementary meteorological measurements, and in Curiel Yuste et al. (2003) for the soil efflux measurements.

### 4. Methods

The NEE (biotic $CO_2$ exchange, $F_{NEE}$) can be deduced from the conservation equation of a scalar

($CO_2$), in applying the Reynolds decomposition (Stull, 1988). Assuming stationarity and horizontal homogeneity of turbulence, and under the hypothesis of negligible horizontal flux divergence and molecular diffusion, $F_{NEE}$ can be written as (Aubinet et al., 2000)

$$F_{NEE} = F_c + F_{\Delta S} + \text{advection terms} \qquad (1)$$

where $F_c = \overline{w'c'}$ is the eddy correlation flux and $F_{\Delta S}$ is the $CO_2$ storage in the air layer below the eddy measurements height. Since a reasonably accurate estimate of the advection terms was impossible with available measurements, they were neglected in this study and $F_{NEE}$ was simply deduced from the eddy flux and the storage term. Following the micrometeorological sign convention, these terms are defined such that positive values represent release from the ecosystem (upward flux), and negative values represent an uptake by the ecosystem (downward flux).

### 4.1. Calculation of eddy correlation fluxes

The measurement system and the data treatment both follow the guidelines of the standard EUROFLUX methodology (Aubinet et al., 2000). The half-hourly mean flux values (covariance $\overline{w'c'}$) were computed in real-time (by the EDISOL software, Moncrieff et al., 1997) with a running-mean removal technique based on a digital recursive filter with a time constant of 200 s (McMillen, 1988). The three-angle co-ordinate rotations of the wind vector were applied in order to remove the effects of instrument tilt or terrain irregularity on the airflow. The time delay of the IRGA signal was set by determining the time lag optimizing the correlation between vertical wind speed ($w$) and $CO_2$ concentration ($c$), within the range of 1–4 s (the theoretical time lag calculated from flow rate and tube characteristics: 1.6 s).

Corrections for high frequency response losses in the eddy flux system were examined in detail by Aubinet et al. (2000) for the standard EUROFLUX closed chamber system, using description of the transfer functions of eddy covariance systems from the literature (Moore, 1986; Leuning and King, 1992; Leuning and Judd, 1996; Moncrieff et al., 1997). It was shown that the only important effects needing correction were the damping of scalar concentration fluctuations in the IRGA sampling tube, and the separation

between the IRGA sampling tube inlet and the sonic anemometer. In our case, these effects were negligible due to the short tube length and small sensor separation (Kristensen et al., 1997). There was also no need to apply the "Webb" corrections for air density fluctuations (Webb et al., 1980) because of the closed-path configuration of the LI-6262 gas analyzer. Consequently, no correction was made to the real time computed flux.

The applicability of the eddy correlation method is limited by a number of restrictive assumptions (Baldocchi et al., 1988; Dabberdt et al., 1993; Foken and Wichura, 1996). These include horizontal homogeneity of the upwind surface, homogeneity of the turbulence and mean flow, and stationarity. The general reliability of the flux measurements with this eddy system set-up was first verified by examination of spectra and co-spectra (comparison with the model of Kaimal et al., 1972) for several measurements performed under different meteorological conditions. The spectral characteristics of the fluxes were not examined in the routine treatment. However, a quality control (QC) program (Vickers and Mahrt, 1997) was run systematically on the raw data in order to reject poor quality data. All data failing the QC were then removed from the set of half-hourly flux data output by the EDISOL software. Furthermore in the routine treatment, a quality test was applied to integral turbulence characteristic of the vertical wind ($\sigma_w/u_*$) as recommended and described by Foken and Wichura (1996). In order to discard the most critically non-stationary $CO_2$ flux measurements, which could significantly influence the NEE sums, a simple test was also routinely performed limiting the variances of vertical velocity and $CO_2$ concentration ($\sigma_w^2$ and $\sigma_c^2$) below a threshold. This simple test has shown (comparative study on a 2-month-period) its ability to remove most of the fluxes not fulfilling the instationarity test proposed by Foken and Wichura (1996), and was preferred for its applicability to routine treatment.

### 4.2. Storage term computation

The storage of $CO_2$ in the layer below the eddy measurements ($F_{\Delta S}$) was estimated by the simple approach using only the change in $CO_2$ concentration measured at 41 m by the LI-6262 (Hollinger et al.,

1994; Greco and Baldocchi, 1996):

$$F_{\Delta S} = \frac{\Delta c(z)}{\Delta t}\Delta z \qquad (2)$$

where $\Delta c(z)$ is the change in $CO_2$ at the height $z$, $\Delta t$ the time period, and $\Delta z$ the height of the layer. This method was chosen for the systematic treatment of all flux data in order to avoid additional data rejection due to failure of the $CO_2$ profile measurement system during the 1997–2001 period. Comparison with the storage term $F_{\Delta S}$ determined from the full profile measurements (method as described by Aubinet et al., 2001) validated this simple approach. The two methods showed good overall agreement (Fig. 2) and the associated discrepancies in annual sums of NEE were negligible ($<10\,\mathrm{g\,C\,m^{-2}}$ per year). The morning and early evening showed the largest discrepancies, due to the inaccuracy of the simple approach to estimate
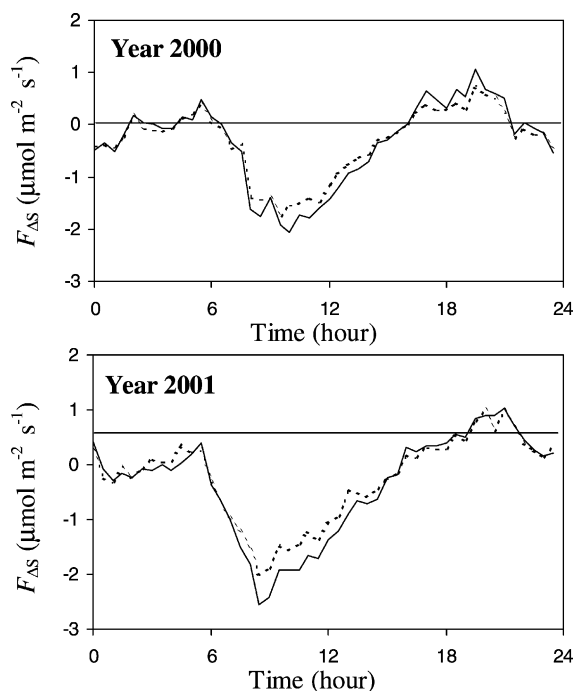


Fig. 2. Mean diurnal course of the storage term ($F_{\Delta S}$) during the years 2000 and 2001, estimated with two different methods: the simple approach using the LI-6262 $CO_2$ measurements (solid line) and the calculation from $CO_2$ profile measurements (dotted line). For each year, averages are calculated for the periods of qualified $CO_2$ eddy flux data and when both systems were properly functioning (LI-6262 and profile).

important $F_{\Delta S}$ associated with transitory conditions. In order to remove these events for systematic treatment, a test excluded data for which:

$$|[CO_2]_{t+\Delta t} - [CO_2]_t| + |[CO_2]_t - [CO_2]_{t-\Delta t}| > 10\,ppm_v$$

This test therefore limited the storage term $F_{\Delta S}$ to a maximum absolute value of $5.1\,\mu mol\,m^{-2}\,s^{-1}$.

## 4.3. Corrections due to low-mixing conditions ($u_*$-correction)

### 4.3.1. Nighttime

It is now accepted by the eddy flux community that, during stable nighttime conditions, surface exchanges are underestimated by eddy covariance measurements, owing to a lack of turbulent transport (Goulden et al., 1996; Moncrieff et al., 1996; Aubinet et al., 2000; Falge et al., 2001). This underestimation of nighttime $CO_2$ fluxes constitutes a selective systematic error, and as such can lead to serious problems when long-term budgets are estimated by integration of short-term flux measurements (Moncrieff et al., 1996). Despite the awareness of the problems in accurately determining nighttime fluxes, no general consensus has been reached for correcting the flux (Falge et al., 2001). The method most widely used to correct for flux underestimation during stable nights was applied in this study. It consists of replacing the flux measured during stable nighttime periods (defined by $u_*$ below a threshold) by a value simulated with a temperature response function derived during well-mixed nighttime conditions (defined by $u_*$ above this threshold). The function that was used is the Lloyd and Taylor respiration equation (Lloyd and Taylor, 1994, Eq. (11)):

$$F_{NEE,night} = F_{RE,night}$$
$$= F_{RE,283}e^{A[(1/(283.16-T_0))-(1/(T_K-T_0))]} \quad (3)$$

where $T_K$ is air temperature (in K), $A$ is set to 309 K, whereas $T_0$ and $F_{RE,283}$ the respiration rate at reference temperature ($283.16\,K = 10\,°C$), are the fitted parameters. In our case, we used air temperature as the principal driver since it gave better results (higher $R^2$ values) than soil temperature.

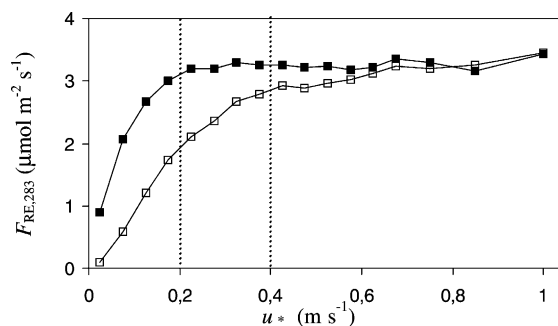Temperature response functions were evaluated for all the 1997–2001 nighttime data sorted for $u_*$



Fig. 3. Parameter describing the nighttime ecosystem respiration at the reference temperature of 283 K ($F_{RE,283}$) estimated using the equation of Lloyd and Taylor (1994) (fitted using the least square method) from all the nighttime data (1997–2001) of storage corrected (■) and not storage-corrected (□) eddy $CO_2$ fluxes, sorted by $u_*$ classes (0.05 m s$^{-1}$ classes).

(0.05 m s$^{-1}$ $u_*$ classes). In our case, the derived values for the parameter ($F_{RE,283}$) describing the ecosystem respiration rate at 10 °C showed a typical saturation above a $u_*$ threshold value (Fig. 3). Indeed, the $CO_2$ biotic efflux corresponding to nighttime ecosystem respiration is considered as independent of turbulence ($u_*$) for biophysical and physiological considerations. It appears that for low mixing conditions ($u_* < 0.2\,m\,s^{-1}$), storage did not account for the total loss of flux (Fig. 3), and some of the $CO_2$ that is released by the ecosystem seemed to leave the forest by as yet undetermined pathways. Therefore, the value of $0.2\,m\,s^{-1}$ was used as threshold for the $u_*$-correction. The potential risk of 'double counting', if there is a morning flush out of $CO_2$, is avoided by applying the $u_*$-correction on the storage-corrected fluxes.

### 4.3.2. Daytime

There is some likelihood that underestimation of the eddy fluxes under low-mixing conditions also occurs during daytime (Goulden et al., 1996; Blanken et al., 1998). In addition to the advection terms which are not accounted for in the eddy measurements, Sakai et al. (2001) argue that a possible explanation for underestimating daytime flux is the inadequate sampling of the turbulent long-period fluctuations under low-wind conditions in daytime. By illustrating the importance of low-frequency contributions to eddy fluxes measured over rough surfaces, their study showed that, for a sample summer at a temperate deciduous forest, large eddies with periods from 4 to 30 min contributed

about 17% to eddy $CO_2$ flux. In the present study, the 200 s running mean used for eddy flux calculations effectively filtered the contribution of the low frequency eddies.

To estimate the effects of low mixing on daytime $CO_2$ flux, similarly to nighttime, light response functions describing the daytime $CO_2$ flux were evaluated for daytime data sorted into $u_*$ classes. The function that was used is a modified form (see Falge et al., 2001, Eq. (A.8)) of the Michaelis–Menten equation (Michaelis and Menten, 1913):

$$F_{NEE} = \frac{a' R_g}{1 - (R_g/1000) + (a' R_g/F_{GPP,opt})} - F_{RE,day}$$

(4)

where $R_g$ is global radiation (W m$^{-2}$) and the fitted parameters are $F_{RE,day}$, the ecosystem respiration during daytime ($\mu$mol $CO_2$ m$^{-2}$ s$^{-1}$), $a'$ the ecosystem quantum yield ($\mu$mol $CO_2$ J$^{-1}$), and $F_{GPP,opt}$ the optimum GPP ($\mu$mol $CO_2$ m$^{-2}$ s$^{-1}$) at a $R_g$ value of 1000 W m$^{-2}$.

The parameters describing the daytime $CO_2$ flux were derived for bimonthly seasonal periods (Fig. 4). All parameters exhibited a positive correlation with $u_*$. Since these estimates are derived from temperature pooled datasets, potential explanations are the correlation between low $u_*$ and cold early-mornings following stable nights (leading to lower $F_{RE,day}$ estimates for lower $u_*$), and the correlation between low $u_*$ and warm conditions during low-wind sunny days (inhibition of photosynthesis leading to lower $a'$ and $F_{GPP,opt}$ estimates for lower $u_*$). An additional explanation is the contribution of the storage term which may be underestimated for lower $u_*$ (storage only below eddy system height and then invisible from it) and overestimated for higher $u_*$ (flush out of $CO_2$), leading to lower estimates of both uptake ($F_{GPP,opt}$ and $a'$) and respiration ($F_{RE,day}$) for lower $u_*$. Nevertheless, for $u_*$ below 0.2 m s$^{-1}$, the values of the regression parameters are too low to be consistently explained by these biases, and the $u_*$-correction was applied similarly as for the nighttime. Daytime fluxes measured during low-mixing conditions ($u_* < 0.2$ m s$^{-1}$) were replaced by simulated values. Daytime $u_*$-correction did not much affect the annual NEE estimates (average effect was only + 5 g C m$^{-2}$ per year). This is because it concerned a smaller
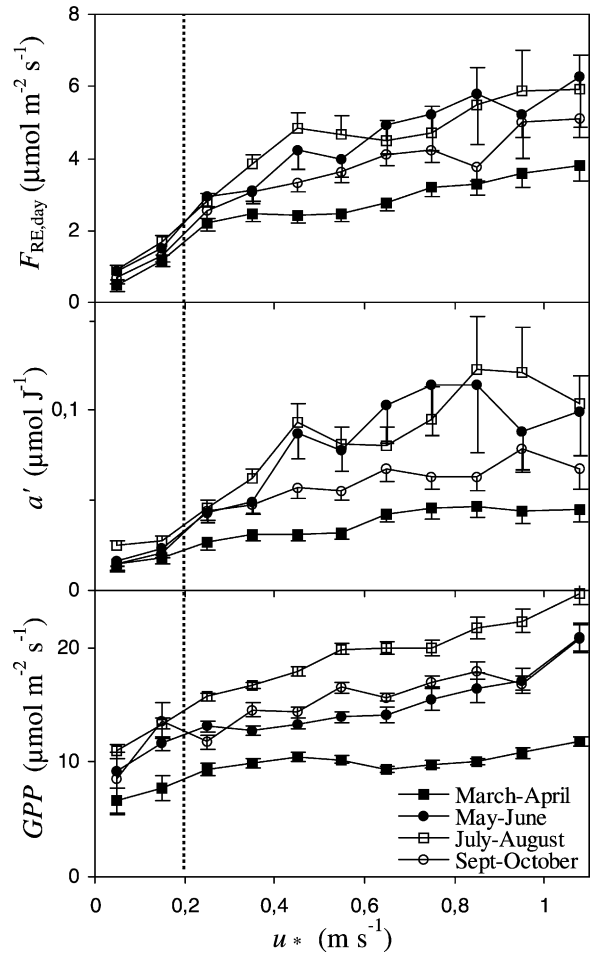


Fig. 4. Daytime ecosystem respiration ($F_{RE,day}$), equivalent quantum yield ($a'$) and optimum gross primary production (GPP) estimated using the Michaelis–Menten light response equation (fitted using the least square method) from the daytime storage corrected eddy $CO_2$ fluxes (1997–2001), sorted by $u_*$ (0.1 m s$^{-1}$ classes) and by bimonthly seasons. Error bars represent the 95% confidence intervals. For reasons of clarity, error bars are presented only one-sided in the $F_{RE,day}$ and $a'$ graphs.

amount of data than for nighttime and because the underestimation is a systematic error (always underestimation) but not a selective error (occurring for both positive and negative fluxes). Nonetheless, the $u_*$-correction improved the fit of the light response equations, and significantly increased the daytime ecosystem respiration estimates (13% average increase in $F_{RE,day}$ estimates from Michaelis–Menten model).

## 4.4. Data gap filling

### 4.4.1. Meteorological data gap filling

Since $F_{NEE}$ filling methods rely on meteorological variables, particularly temperature and radiation, it is essential to have reliable and continuous series of these variables to achieve defensible NEE estimates. Linear interpolation was used to fill small gaps ($<2$ h). Longer gaps in meteorological variables were filled using redundant measurements when available. Gaps in air temperature measurements ($T_a$) were filled with the temperature from the sonic anemometer when available, or from a nearby meteorological station (about 20 km, same elevation). Down-welling global solar radiation ($R_g$) was used as the radiation variable in $F_{NEE}$ filling routines, since it was the most robust radiation measurement and showed a very strong relationship ($R^2 = 0.99$) with photosynthetically active radiation (PAR) (Ceulemans et al., 2003). Gaps in $R_g$ were filled using PAR measurements or net radiation when PAR was not available. Remaining $R_g$ missing data (1% of daytime) were filled by the mean diurnal variation method based on a few adjacent days, selected visually and manually, exhibiting a similar diurnal temperature pattern. Gaps in precipitation were filled with data from a nearby meteorological station. Gaps in soil temperature $T_s$ (1.8% of all values) were inferred by simple model predicting $\Delta T_s / \Delta t$ from ($T_a - T_s$).

### 4.4.2. CO₂ flux gap filling

During the period analyzed (1997–2001), the average CO₂ flux ($F_{NEE}$) data coverage was 71% due to maintenance and system failures. The different quality tests, including $u_*$-correction, discarded 36% of the measured $F_{NEE}$ data, leading to an average yearly data coverage of only 46% (Table 1). This is rather low, compared to the average coverage of 65% for the 28 yearly dataset included in the study on gap filling by Falge et al. (2001). Therefore, the estimation of annual or monthly sums of NEE might be highly dependent on the used gap filling procedure. In order to test the sensitivity of NEE to the gap filling procedure, different commonly used gap filling strategies were applied to the 5-year dataset, including non-linear regressions, look-up tables and neural networks. However, look-up tables were subsequently rejected, due to poor performance during periods of poor data coverage.

Table 1
Percentage of $F_{NEE}$ (net ecosystem exchange) measured and qualified (not rejected by quality check tests, including $u_*$-selection) data for the 5 years of measurements

| Period | Existing data (%) | Qualified data (%) | | |
|---|---|---|---|---|
| | | Total | Daytime | Nighttime |
| 1997 | 62.0 | 35.2 | 38.2 | 32.1 |
| 1998 | 71.1 | 47.1 | 51.9 | 42.3 |
| 1999 | 75.6 | 50.6 | 58.6 | 41.4 |
| 2000 | 80.5 | 52.7 | 55.2 | 48.9 |
| 2001 | 67.6 | 43.6 | 51.3 | 35.1 |
| 1997–2001 | 71.4 | 45.8 | 51.7 | 40.0 |

#### 4.4.2.1. Semi-empirical methods: non-linear regressions

Semi-empirical gap filling preserves the response of $F_{NEE}$ to the expected controlling factors (temperature and radiation), as found in the data. Responses are described by non-linear regressions. These methods were applied following procedures and recommendations from Falge et al. (2001). Missing values of $F_{NEE}$ are filled with regression relationships established between $F_{NEE}$ and controlling factors (temperature and radiation) for bimonthly periods (January–February, March–April, . . . ). Daytime and nighttime data were addressed separately. For nighttime data, the Lloyd and Taylor respiration equation (Eq. (3)) was used with air temperature as driver to model $F_{NEE}$. For daytime $F_{NEE}$, the Michaelis–Menten light response equation (Eq. (4)) was used. The effect of temperature on the light response equations was not taken into account, as the regressions were performed on data not temperature sorted. This approach was chosen since splitting the dataset into temperature classes made some of the seasonal regressions unstable because of the rather high percentage of gaps.

Bimonthly periods were selected to perform the regressions because it appeared to optimize the trade-off between having sufficient data for statistically valid regressions, and describing seasonal variations of forest carbon exchange. Nevertheless, this choice posed some problems because of some long-term system failures, yielding regressions that were highly biased or were even impossible. In order to be able to fill the long-term gaps with data measured during the same bimonthly period from other years, regression
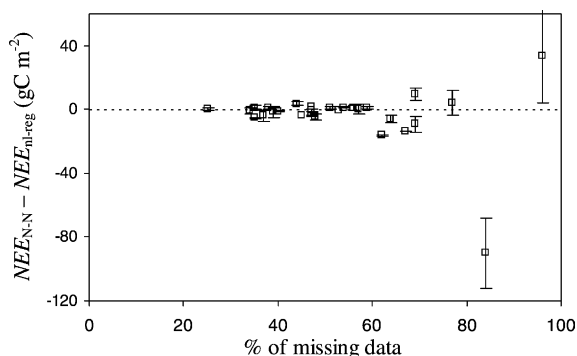
Fig. 5. Bimonthly NEE sum differences between $NEE_{N-N}$ (gaps filled using the half-hourly neural networks method) and $NEE_{nl-reg}$ (gaps filled using the non-linear regressions method) versus percentage of missing data. The standard deviation is calculated from the different versions of half-hourly neural networks.

relationships were also established for each bimonthly period pooled over 5 years.

### 4.4.2.2. Neural networks

We have used neural networks as a tool for filling gaps in the $F_{NEE}$ series at two different time scales: half-hourly values and daily series.

*Neural networks for gap filling at half-hourly scale.* The $F_{NEE}$ series first was screened by quality tests (including $u_*$-selection) and sorted by bimonthly periods. Gaps in the $F_{NEE}$ half-hourly dataset were then filled using a single-hidden-layer feed-forward neural network (Saxén and Saxén, 1995) by predicting $F_{NEE}$ from four variables: global radiation, air temperature, soil temperature and relative humidity. Attempts to introduce precipitation or other additional variables were unfruitful. Each bimonthly period was treated separately. The neural networks method at half-hourly scale posed some problems for periods with more than 80% missing data. For these periods, the established networks were dependent on training options, and resulting NEE therefore was dependent on network versions (Fig. 5). For periods with fewer gaps, the neural network technique applied successfully (different versions were very close) and the NEE results were very similar to non-linear regressions (Fig. 5), as the most important drivers of neural networks (temperature and radiation) are the driving variables of the non-linear regressions.

*Neural networks for gap filling at daily scale.* The $F_{NEE}$ series was screened by quality tests and sorted by year. Days with more than a threshold number (12 or 18) of missing half-hourly $F_{NEE}$ data were considered as "missing", others as "good". The "missing" days values were filled using single-hidden-layer feed-forward neural networks (Saxén and Saxén, 1995) by predicting daily NEE from daily averages of global radiation, air temperature, soil temperature, relative humidity, day length and precipitation. Neural networks were trained with the daily $F_{NEE}$ sums of the "good" days, from both measured and modeled (using the non-linear regression method) half-hourly $F_{NEE}$ values. The modeling method is assumed to have a negligible effect on the $F_{NEE}$ daily sums of the "good" days, as the amount of filled data remains low. The average missing data per "good" day represented respectively 11.6 and 16.7%, for respectively 12 and 18 as the maximum number of half-hourly gaps allowed per day. The resulting neural-network fitted the measured daily NEE well (Fig. 6), with $R^2$ values ranging from 0.91 to 0.97 for the 5 years, and with a satisfactory coverage of the entire annual range of the driving variables. Unlike the methods based on a bimonthly sorting, this method treats each year as a whole and therefore enables to fill the long-term gaps without special operation.

## 5. Results and discussion

### 5.1. Energy balance closure

The energy budget includes energy terms obtained by eddy covariance (sensible heat flux $H$ and latent heat flux $\lambda E$) and by other methods (net radiation $R_n$, soil heat flux $G$, heat storage $S_t$). A comparison of these terms can be used to check the quality of the eddy covariance measurements (Aubinet et al., 2000). Fig. 7 shows the half-hourly values of the eddy covariance energy fluxes versus the other terms of the energy budget equation. Despite the strong correlation ($R^2 = 0.91$), the sum of the eddy covariance flux was lower (slope of the regression = 0.76) than the available energy. The closure deficit of the energy balance was similar in the other years (slope between 0.7 and 0.8). Such a closure deficit of about 20% is rather common with eddy covariance measurements above tall forest
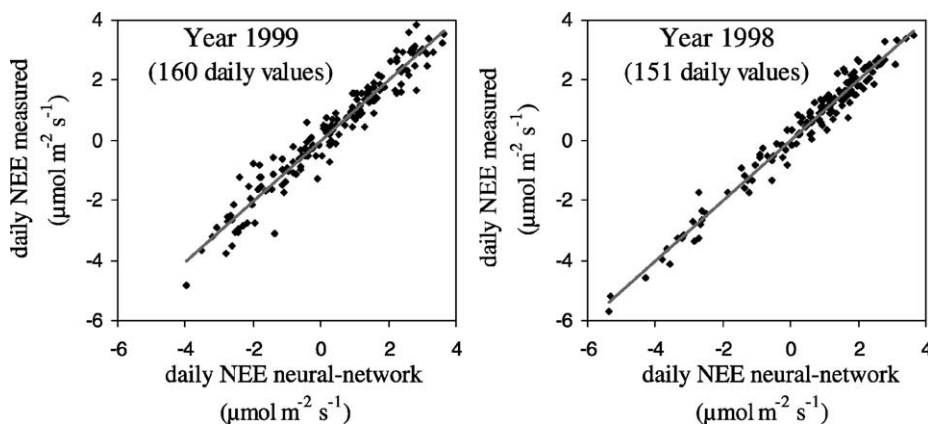
Fig. 6. Results of daily net ecosystem exchange (NEE) neural network training (maximum number of half-hourly gaps per day = 18) for the years 1998 ($y = 1.0001x$, $R^2 = 0.97$) and 1999 ($y = 1.006x - 0.01$, $R^2 = 0.94$).

canopies (Goulden et al., 1996; Lee, 1998; Aubinet et al., 2000). The closure deficit of the energy balance was found to be independent of the wind direction (data not shown).

### 5.2. $CO_2$ fluxes

The evolution of the biotic $CO_2$ flux ($F_{NEE}$) and the main meteorological variables, measured between
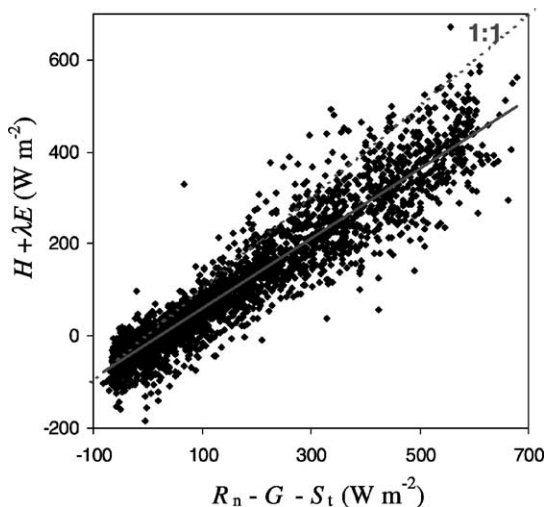


Fig. 7. Energy balance closure at half-hourly scale in 2001. Eddy covariance energy fluxes ($H + \lambda E$) vs. available energy ($R_n - G - S_t$). $H$ sensible heat flux; $\lambda E$ latent heat flux; $R_n$ net radiation; $G$ soil heat flux; $S_t$ heat storage in canopy air. The linear regression (solid line) equation is $(H + \lambda E) = 0.76(R_n - G - S_t) - 16.8$ ($R^2 = 0.91$).

1997 and 2001, are displayed in Fig. 8. Climatic conditions are characterized by a rather high variability at synoptic scales in all seasons. Precipitation was distributed rather regularly in the course of the year, and drought stress episodes were quite limited (and had no significant effects on tree performance or physiology, as shown by Meiresonne et al., 2003). Annual total precipitation was above the long-term average (750 mm) for every year except 1997 (658 mm). The average daily air temperature was typically around 5 °C during winter and around 15 °C during the growing season. The incoming global radiation reached 30 MJ m$^{-2}$ per day in summer and was lower than 5 MJ m$^{-2}$ per day during winter. Maximum measured nighttime flux (respiration) was between 5 μmol m$^{-2}$ s$^{-1}$ in winter and 8 μmol m$^{-2}$ s$^{-1}$ in summer. Maximum measured negative (uptake) flux was about −20 μmol m$^{-2}$ s$^{-1}$ in summer. Net uptake fluxes during daytime were measured even in winter (Fig. 8c), which is mainly due to photosynthesis by the pines. Net uptake on a daily basis, however, only occurred from the beginning of April until the end of September (Fig. 8d), leading to a maximum length of the growing season of about 6 months. From monthly mean diurnal courses (not shown), we observed that the average nighttime flux (dark respiration) varied from about 2 μmol m$^{-2}$ s$^{-1}$ during the coldest months (December–January) to about 5 μmol m$^{-2}$ s$^{-1}$ during the warmest months (July–August). The average uptake flux during mid-day in the months with highest uptake (July and August) was −10 μmol m$^{-2}$ s$^{-1}$.
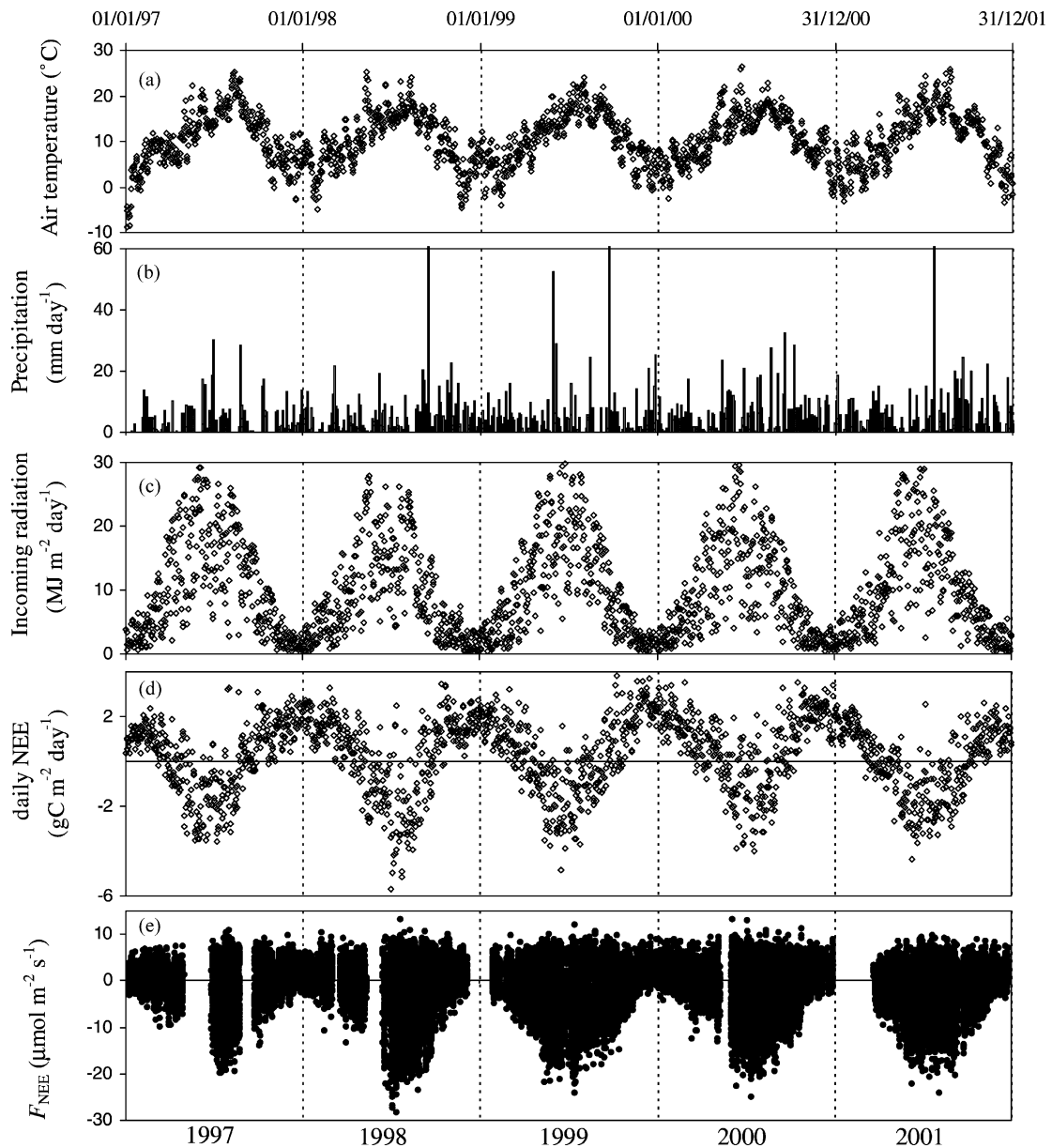
Fig. 8. Evolution from 1 January 1997 to 31 December 2001 of: (a) air temperature daily average; (b) daily precipitation; (c) daily incoming radiation; (d) daily NEE, periods with no data were filled using the non-linear regression method; (e) half-hourly measurements (after quality check) of biotic $CO_2$ exchange: $F_{NEE}$ = eddy correlation flux + storage term.

## 5.3. Effect of pre-treatment and gap filling procedures on annual NEE estimates

The effects of pre-treatment ($u_*$-correction and storage term) and gap filling methods on annual NEE estimates are summarized in Table 2. During the 5 years studied, three large gaps in the $CO_2$ flux series led to unsatisfactory results from the non-linear regression method for three bimonthly periods (May–June 1997; May–June 1998 and January–February 2001).

Table 2
Annual NEE estimates (in $g\,C\,m^{-2}$ per year) obtained with different pre-treatment and gap filling methods for the years 1997–2001

| Gap filling method and pre-treatment | 1997[a] | 1998[a] | 1999 | 2000 | 2001[a] | Average (5 years) | S.D. (5 years) |
|---|---|---|---|---|---|---|---|
| Non-linear regression $u_*$-corrected[b] (no storage term) | 7[c] | 116[c] | 134 | 229 | −19[c] | 93 | 90 |
| Non-linear regression not $u_*$-corrected | −1 | 72 | 58 | 176 | −53[c] | 50 | 77 |
| Non-linear regression $u_*$-corrected | 67[c]/99[d] | 112[c]/48[d] | 130 | 255 | −9[c]/−60[d] | 111[c]/94[d] | 86[c]/103[d] |
| Neural network half-hourly scale $u_*$-corrected | 85 | 61 | 134 | 238 | −30[c]/−82[d] | 97[c]/87[d] | 88[c]/104[d] |
| Neural network daily (gaps >18) $u_*$-corrected | 31 | 52 | 133 | 224 | −68 | 74 | 98 |
| Neural network daily (gaps >12) $u_*$-corrected | 21 | −18 | 137 | 248 | −69 | 64 | 114 |

[a] Years containing a long-term gap.

[b] Nighttime $u_*$ threshold is $0.4\,m\,s^{-1}$ (instead of $0.2\,m\,s^{-1}$ for storage-corrected series).

[c] Missing bimonthly period gap filled with non-linear regressions from 5-year-pooled data.

[d] Missing bimonthly period gap filled with neural network at daily scale (gaps >18).

These were filled with an alternative technique, the non-linear regressions from 5-year-pooled datasets or the neural network gap filling at daily scale.

The $u_*$-correction strongly affected annual NEE estimates, resulting in a more positive annual sum of NEE, $+61\,g\,C\,m^{-2}$ per year on average, with a maximum of $+79\,g\,C\,m^{-2}$ per year in 2000, the year with the highest ecosystem respiration estimates. This effect is similar to results observed in previous studies (Lindroth et al., 1998; Schmid et al., 2000; Falge et al., 2001; Aubinet et al., 2002). In a study on the effects of different gap filling procedures, Falge et al. (2001) also showed that the largest effect on annual NEE estimates was due to the $u_*$-correction ($+65\,g\,C\,m^{-2}$ per year on average, up to $+147\,g\,C\,m^{-2}$ per year, for storage-corrected data). The effect of $u_*$-correction was found to vary seasonally (stronger in summer than in winter), due to higher respiratory fluxes and higher frequency of stable conditions events in summer.

The effect of the storage term correction on annual NEE was found to be weak when no long-term gap occurred, and providing that the nighttime $u_*$-correction was applied with a suited threshold of $0.4\,m\,s^{-1}$ (Fig. 3).

Uncertainty associated with gap filling can have two sources, the uncertainty introduced by using different filling methods and the error introduced by the filling process itself. Errors introduced by the filling process are mostly random errors, and partly compensated during time integration. Falge et al. (2001) showed that these random errors did not differ much between the methods tested in their study, and were directly proportional to the percentage of gaps filled

during a period. Their results showed that for the non-linear regression method, the maximum observed errors on annual NEE (for four different biomes) were $\pm0.40\,g\,C\,m^{-2}$ per percentage filled in the year for daytime and $\pm0.36\,g\,C\,m^{-2}\,\%^{-1}$ for nighttime. In our case, the maximum error introduced thus ranged between $\pm36$ and $\pm49\,g\,C\,m^{-2}$ per year ($\pm41\,g\,C\,m^{-2}$ per year on average).

The NEE results from different gap filling methods varied mainly when the yearly dataset contained large gaps. Annual NEE estimates were not very sensitive to the gap filling method during 1999 and 2000, but more sensitive during 1997, 1998 and 2001. In this study, the absolute uncertainty in annual NEE associated with the gap filling strategy, for the same data pre-treatment (storage term and $u_*$-correction), was $64\,g\,C\,m^{-2}$ per year on average, ranging between 7 and $130\,g\,C\,m^{-2}$ per year. In years where gaps occurred predominantly early in the growing season (1997, 1998 and 2001; see Fig. 8), the neural network gap filling methods operating at daily scale produced lower annual NEE estimates than the other methods. This is probably due to the absence from the neural network of a biotic parameter that could describe the seasonal variation of the forest potential for $CO_2$ exchanges (directly like LAI or indirectly like latent heat flux). The neural networks were trained with annual datasets, but the NEE and the neural network drivers (e.g. radiation) present asynchronous annual variations. In those years (1997, 1998 and 2001), the early growing season gaps may have been filled with underestimated daily NEE values because of the imbalance between early and full/late growing

season data. Therefore, the most defensible gap filling methods appeared to be, in this study, the non-linear regression and the neural networks at half-hourly scale, both operating on bimonthly periods.

For further analysis and discussion on NEE, we will use the annual estimates obtained with the non-linear regression method.

## 5.4. Annual NEE estimates

The NEE estimates from the non-linear regression method exhibited an average of 111 ($\pm$41) g C m$^{-2}$ per year, an inter-annual maximum variability of 264 g C m$^{-2}$ per year and a standard deviation of 86 g C m$^{-2}$ per year over the 5 years (1997–2001). The finding that this forest ecosystem was a $CO_2$ source (positive NEE) contrasts with the previous results from most of the other CARBOEUROFLUX forest sites (Valentini et al., 2000; Berbigier et al., 2001; Pilegaard et al., 2001; Dolman et al., 2001; Aubinet et al., 2002). Only the Swedish site in Norunda (Lindroth et al., 1998) has reported a positive NEE on long-term. The NEE results from other studies, including most of the CARBOEUROFLUX sites with similar climatic conditions are displayed in Table 3. The amplitude of the inter-NEE annual variability at our site is similar to other studies, although two sites reported higher maximum variability: Hesse (France), which experienced significant changes due to a violent storm in December 1999, and Norunda (Sweden), which reports on a longer period of measurement (Table 3).
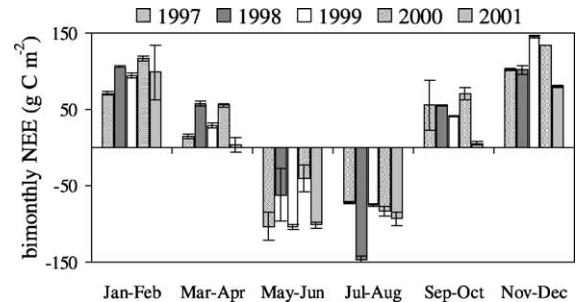


Fig. 9. Bimonthly sums of NEE for the years 1997–2001. Results obtained with non-linear regression gap filling method, presented with standard deviations of the bimonthly sums obtained with different gap filling methods.

### 5.4.1. Inter-annual variability in NEE

The cumulated NEE was computed for each bimonthly season (Fig. 9). The maximum inter-annual variations in bimonthly NEE varied from 23 g C m$^{-2}$ per month (January–February) to 37 g C m$^{-2}$ per month (July–August). This is similar to results from a nearby Belgian coniferous/deciduous forest site (Aubinet et al., 2002), which showed a maximum inter-annual variation between 15 g C m$^{-2}$ per month in winter and 40 g C m$^{-2}$ per month in summer, over the same period of measurements (1997–2001).

At the annual scale, NEE was not significantly correlated with radiation ($R^2 = 0.10$) and weakly correlated with air temperature ($R^2 = 0.26$). Both observed effects were in the expected direction: NEE became more positive (towards a source) with increasing

Table 3
Overview of annual NEE and maximum NEE inter-annual variability observed at different CARBOEUROFLUX sites

| Site and references | Forest type | Latitude | NEE average (g C m$^{-2}$ per year) | NEE inter-annual variability (g C m$^{-2}$ per year) | Period of measurement |
|---|---|---|---|---|---|
| Brasschaat (present study) | Mixed | 51°18′N | 111 | 264 | 1997–2001 |
| Hyytiala (Suni et al., 2003) | Coniferous | 61°51′N | −194 | 77 | 1997–2001 |
| Norunda (Grelle, A., unpublished) | Coniferous | 60°05′N | 220 | 450 | 1995–2001 |
| Soro (Pilegaard, K., unpublished) | Deciduous | 55°29′N | −177 | 165 | 1996–2001 |
| Loobos (Moors, E., unpublished) | Coniferous | 52°10′N | −319 | 175 | 1996–2001 |
| Vielsam (Aubinet et al., 2002) | Coniferous | 50°18′N | −720 | 190 | 1997–2001 |
|  | Deciduous |  | −460 | 190 | 1997–2001 |
| Hesse (Granier, A., unpublished) | Deciduous | 48°40′N | −322 | 514 | 1996–2001 |
| Le Bray (Berbigier, P., unpublished) | Coniferous | 44°05′N | −483 | 88 | 1997–2001 |
| Harvard[a] (Goulden et al., 1996) | Deciduous | 42°32′N | −220 | 140 | 1991–1995 |

[a] From AMERIFLUX.

temperature and more negative with increasing radiation. The highest correlation ($R^2 = 0.80$) was observed between annual NEE and the length of the growing season (LGS). The sensitivity of NEE to LGS was $-3.5 \, \mathrm{g \, C \, m^{-2}}$ per year per additional day of growing season (Fig. 10). It is rather similar to, although higher than the dependence observed by Falge et al. (2002) between annual NEE normalized for LAI and LGS results from several sites. Assuming a constant LAI of $3 \, \mathrm{m^2 \, m^{-2}}$, we found $-1.15 \, \mathrm{g \, C \, m^{-2}}$ leaf area per year per day in our case versus about $-0.85 \, \mathrm{g \, C \, m^{-2}}$ leaf area per year per day for the temperate evergreen forest sites from Falge et al. (2002). The LGS regression residuals (Fig. 10), computed as the difference between the measured NEE and the regression NEE estimates, were strongly correlated with temperature ($R^2 = 0.88$), but not significantly correlated with radiation ($R^2 = 0.04$).

A simple linear model (from a multiple regression analysis) of NEE based only on LGS and annual mean temperature was therefore able to simulate the measured annual NEE very well ($R^2 = 0.98$). Despite the strong correlation observed, this dependence is of limited use for predictive modeling, since LGS was estimated with the NEE value (period during which the 10-day averaged NEE was negative). The correlation was significantly lower when the LGS estimate was based on temperature. This may be due to the importance of the variations in temperature at synoptic scales compared to the yearly seasonal variation (difference between winter and summer average temperatures). However estimated, the length of the growing season certainly influences annual NEE. For the year 2001, the annual NEE was lower due to the exceptionally low NEE during the bimonthly periods of the beginning (March–April) and the end (September–October) of the growing season (Fig. 9). This stronger $CO_2$ uptake was supported by phenological observations (very late senescence observed for the deciduous species, leaf abscission only started in the beginning of December) and by inter-annual comparison of monthly relationships between daytime $F_{NEE}$ and radiation ($R_g$) during autumn, which also suggest an exceptionally late end of the growing season in 2001.

Despite the old age of most of the trees, this forest ecosystem was not in equilibrium state because of the rather intensive management over the last decade. During the period of measurements, many of the for-
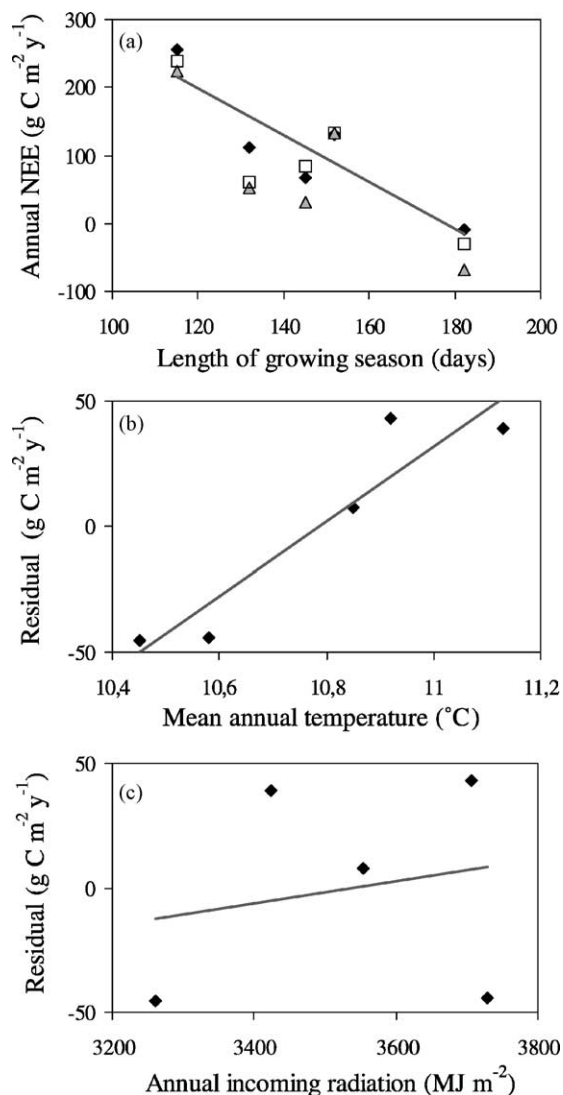


Fig. 10. (a) 1997–2001 annual NEE sums vs. length of growing season (LGS). Different gap filling methods used to calculate annual NEE: (◆) non-linear regressions; (□) neural-network at half-hourly scale; (△) neural network at daily scale. The linear regression is performed on the NEE sums calculated with the non-linear regressions gap filling method. The linear regression equation is NEE = 613 − 3.46LGS ($R^2 = 0.80$); (b and c) regression residual vs. mean annual temperature ($R^2 = 0.88$) and annual incoming radiation ($R^2 = 0.04$). Residuals are computed as the difference between the measured NEE and the LGS regression NEE estimates.

est patches were subject to changes due to thinning or to partial removal of the understorey vegetation. The average LAI of the forest may therefore have decreased during the 5 years of measurement, modifying both ecosystem respiration and uptake capacity of the forest. In November 1999, the 2 ha pine stand surrounding the tower was subjected to a thinning (harvest of 30% of the trees), leading to a decrease of net primary production (NPP) of about 25% (estimated from repeated biomass inventories, Xiao et al., 2003). The large number of different patches in the forest and their relatively small size not only made these changes in LAI quite frequent, but also made their effect on the measured $CO_2$ flux impossible to estimate without a reliable high-resolution footprint analysis. The inter-annual variability in NEE resulted from combined effects of these changes and of the changes in climatic conditions. It is impossible to deconvolute these effects without ancillary information, such as regular forest-scale LAI estimates. The relative contributions of changes in climate and management practices to the inter-annual variability in NEE can therefore not be quantified from the $CO_2$ flux measurements only.

### 5.4.2. Possible explanations for positive NEE

The average annual NEE over the measurement period (1997–2001) was about $+110$ g C m$^{-2}$ per year. The net annual C increment in wood biomass of the pines was estimated to about 180 g C m$^{-2}$ per year for the period (1995–2001) (Xiao et al., 2003). Using standing biomass to extrapolate NPP from the pine stands to the oaks, resulted in a mean annual C increment for the entire forest of about 150 g C m$^{-2}$ per year for (1995–2001). Different hypotheses, such as the effects of climatic anomalies and forest management practices, can be put forward to explain this large discrepancy between the annual biomass C increment and NEE.

#### 5.4.2.1. Climatic anomalies

During the 5 years of measurements, the annual temperatures were all above the normal average (5-years average was 10.8 °C and normal is 9.8 °C). Normal climatic conditions are the 30-year means from a nearby (30 km) meteorological station. Since respiratory processes are sensitive to temperature, annual NEE could be sensitive to a change in temper-

ature. A sensitivity test was made by adding 1 °C to all half-hourly temperatures, then using the nighttime $F_{NEE}$ temperature response equations to estimate RE, the total annual ecosystem respiration (Lindroth et al., 1998). This rough estimate indicated a 79 g C m$^{-2}$ per year increase in RE (5-year average) due to a 1 °C increase in temperature. To estimate the effect on NEE, we should also consider the effect of temperature on GPP, but this is not trivial, as it largely depends on the distribution of temperature within the year. In fact, higher temperatures can increase GPP by causing an earlier start of the growing season, but can also decrease GPP by occasionally limiting photosynthesis during warm days (stomatal closure). Assuming that the effect of increased temperature on GPP is smaller than on RE, NEE should be more negative (more uptake by the ecosystem) in "normal" years. The yearly total incoming global radiation was not higher than the long-term normal (5-year average was 3535 MJ m$^{-2}$ per year and normal is 3598 MJ m$^{-2}$ per year). It also suggests that NEE should be more negative during "normal" years, as annual global radiation and GPP can be supposed to be positively correlated, although they are not expected to be strongly correlated on a yearly scale.

#### 5.4.2.2. Forest management practices

The observed net C losses from the forest may also be partly due to the legacy of past management practices. Until the 1980s, the forest was privately owned and not exploited for wood production but for hunting purposes. The original, homogeneous stocking density was very high and thinning was neglected (1390 tree ha$^{-1}$ in pine stands in 1980; Cermak et al., 1995), resulting in tall, slender stems. Furthermore, *Rhododendron ponticum* and *Prunus serotina* proliferated and established a 3 m tall undergrowth. Biomass of this dense undergrowth was on average 7 t ha$^{-1}$ where *Rhododendron* dominated (15% of the forest area), and 35 t ha$^{-1}$ where *Prunus* dominated (30% of the forest area). During the 1980s, the forest became property of the Flemish region and a new management policy was implemented, including intensive thinning and removal of invasive species such as *Rhododendron* and *Prunus*. Due to this recent intensive thinning, some forest patches are approaching their degradation stage; more openings in the canopy create better light conditions triggering decomposition of the thick

forest floor and consequently enhancing respiration losses.

Based on detailed information on the harvested stems (number and DBH), and applying site-specific allometric relationships (Xiao et al., 2003), we calculated that since 1987 an average of $80 \, \mathrm{g\,C\,m^{-2}}$ per year of slash was added to the forest floor as a consequence of the thinning of pines and oaks. Decomposition of this slash remaining after the thinning was estimated to have released about $50 \, \mathrm{g\,C\,m^{-2}}$ per year during the 1997–2001 period (based on exponential decay model with different parameterization for woody tissues and foliage/fine roots; Janssens et al., unpublished results). Removal of *Rhododendron* and *Prunus*, could therefore easily have doubled the C efflux due to decomposition of slash. The resulting enhancement of the C efflux from the soil, could therefore have increased ecosystem respiration by about $100 \, \mathrm{g\,C\,m^{-2}}$ per year, contributing to the observed positive NEE.

This situation was possibly exacerbated by the removal of *Rhododendron* from large areas in the forest. *Rhododendron* inhibits germination of seeds, as well as decomposition of litter (Cross, 1975; Rotherham, 1983). Therefore, the prevalence of *Rhododendron* may have resulted in retarded decomposition rates, and thus higher equilibrium soil organic C (SOC) contents. Since the removal of *Rhododendron*, the organic molecules retarding decomposition may have been broken down or leached out of the system, which may have restored the original, lower SOC equilibrium content. Thus, the forest floor may have been losing C during the late 1990's, and thus have contributed to the observed positive C fluxes.

However, the effects of this change in management should be transient. Now that the forest has been intensively thinned and most *Rhododendron* has been cleared, soil C losses should be reduced and also NEE should go down. At this site, continued, long-term eddy flux measurements could therefore clarify whether our speculated management effect is indeed transient and over which time period these management effects are prolonged.

### 5.5. Annual respiration estimates

The annual ecosystem respiration (RE) was estimated using the $F_{\mathrm{NEE}}$ nighttime temperature response functions (Eq. (3)) and, optionally the ecosystem respiration rate during daytime $F_{\mathrm{RE,day}}$ from the light response relationships Eq. (4). We found a 5 years average of 1300 ($\pm40$) $\mathrm{g\,C\,m^{-2}}$ per year (the standard error represents only the two different computation methods). This mean RE is close to the highest RE estimates reported within the EUROFLUX network sites (RE between 600 and $1400 \, \mathrm{g\,C\,m^{-2}}$ per year, mean value $1100 \, \mathrm{g\,C\,m^{-2}}$ per year; Janssens et al., 2001). This agreed with our hypothesis that the positive NEE observed at our site could be due to a high ecosystem respiration, potentially caused by management and climate.

The annual soil respiration (SR) of the entire forest was estimated to 650 ($\pm60$) $\mathrm{g\,C\,m^{-2}}$ per year in 2001 (Curiel Yuste et al., unpublished results) using soil efflux measurements made in different patches. According to these estimates, soil respiration would account for about 63% of the total ecosystem respiration (RE = $1030 \, \mathrm{g\,C\,m^{-2}}$ in 2001), which is slightly below the mean SR/RE-ratio observed within the EUROFLUX network (69%; Janssens et al., 2001). However, these soil respiration measurements were made on collars that did not contain slash remaining after thinning. Therefore, the true contribution of the soil to RE could be higher than 63%.

## 6. Conclusions

As observed by previous similar studies, the $u_*$-correction strongly affected the NEE annual sums, increasing the annual NEE by $+61 \, \mathrm{g\,C\,m^{-2}}$ per year on average. For the same data pre-treatment, the uncertainty in annual NEE associated with the gap filling strategy was found to be up to $130 \, \mathrm{g\,C\,m^{-2}}$ per year (in year with large gap). Studies on inter-annual variability in NEE should therefore avoid potential confounding effects by the gap filling methodology.

Over the 5 years of measurements, the uncertainty associated with the different gap filling methods was reduced and the studied forest appeared to be a consistent net source of $CO_2$ $110 \, \mathrm{g\,C\,m^{-2}}$ per year (on average for 1997–2001). This is different from the results of the other CARBOEUROFLUX forest ecosystems under influence of similar temperate climate, which appeared to be net sinks. Forest management practices and unusually elevated temperatures are suspected to have increased the ecosystem

respiration, and thereby the NEE, over the 5 years of measurement.

## References

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

Aubinet, M., Chermanne, B., Vandenhaute, M., Longdoz, B., Yernaux, M., Laitat, E., 2001. Long-term carbon dioxide exchange above a mixed forest in the Belgian Ardennes. Agric. For. Meteorol. 108, 293–315.

Aubinet, M., Heinesh, B., Longdoz, B., 2002. Estimation of the carbon sequestration by a heterogeneous forest: night-flux corrections, heterogeneity of the site and inter-annual variability. Global Change Biol. 8, 1–19.

Baeyens, L., Van Slycken, J., Stevens, D., 1993. Description of the soil profile in Brasschaat. Internal research paper. Institute for Forestry and Game Management, Geraardsbergen, Belgium.

Baldocchi, D.D., Valentini, R., Oechel, W., Dahlman, R., 1996. Strategies for measuring and modeling carbon dioxide and water vapor fluxes over terrestrial ecosystems. Global Change Biol. 2, 159–168.

Baldocchi, D.D., Hicks, B.B., Meyers, T.P., 1988. Measuring biosphere–atmosphere exchange of biologically related gases with micrometeorological methods. Ecology 69, 1331–1340.

Baldocchi, D.D., Falge E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Mahli, Y., Meyers, T., Munger, W., Oechel, W., Paw, U.K.T., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K., 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. 82, 2415–2434.

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

Blanken, P.D., Black, T.A., Neumann, H.H., Den Hartog, G., Yang, P.C., Nesic, Z., Staebler, R., Chen, W., Novak, M.D., 1998. Turbulent flux measurements above and below the overstorey of a boreal aspen forest. Boundary-Layer Meteorol. 89, 109–140.

Ceulemans, R., Kowalski, A.S., Berbigier, P., Dolman, A.J., Grelle, A., Janssens, I.A., Lindroth, A., Moors, E., Rannik, U., Vesala, T., 2003. Coniferous forests (Scots and Maritime Pine): carbon and water fluxes, balances, ecological and ecophysiological determinants. In: Valentini, R. (Ed.), Fluxes of Carbon, Water and Energy of European Forests. Ecological Studies, vol. 164, Springer-Verlag, Berlin, Heidelberg, pp. 71–97.

Ciais, P., Tans, P.P., White, J.C., Francey, R.J., 1995. A large northern hemisphere terrestrial $CO_2$ sink indicated by the $^{13}C/^{12}C$ ratio of atmospheric $CO_2$. Science 269, 1098–1102.

Cross, J.R., 1975. Biological flora of the British Isles. List Br. Vasc. Pl. (1958) No. 345.1: *Rhododendron ponticum* L. J. Ecol. 63, 345–364.

Curiel Yuste, J., Janssens, I.A., Carrara, A., Meiresonne, L., Ceulemans, R., 2003. Interactive effects of temperature and precipitation on soil respiration in a temperate maritime pine forest. Tree Physiol., in press.

Dabberdt, W.F., Lenschow, D.H., Horst, T.W., Zimmerman, P.R., Oncley, S.P., Delany, A.C., 1993. Atmosphere–surface exchange measurements. Science 260, 1472–1480.

de Pury, D.G.G., Ceulemans, R., 1997. Scaling-up carbon fluxes from leaves to stands in a patchy coniferous/deciduous forest. In: Mohren, G.M.J., Kramer, K., Sabaté, S. (Eds.), Impacts of Global Change on Tree Physiology and Forest Ecosystems. Kluwer Academic Publishers, Dordrecht, pp. 263–272.

Desjardins, R.L., 1985. Carbon dioxide budget of maize. Agric. For. Meteorol. 36, 29–41.

Dolman, A.J., Moors, E.J., Elbers, J.A., 2001. The carbon uptake of a mid latitude pine forest growing on sandy soil. Agric. For. Meteorol. 111, 157–170.

EC-UN/ECE, 1996. European programme for the intensive monitoring of forest ecosystems. General information on the permanent observation plots in Europe (Level II). European Commission, DG VI F.II.2, in cooperation with ICP forests of UN/ECE.

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

Falge, E., Tenhunen, J., Baldocchi, D.D., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C., Bonnefond, J.-M., Burba, G., Clement, R., Davis, K.J., Elbers, J.A., Falk, M., Goldstein, A.H., Grelle, A., Granier, A., Grunwald, T., Gudmundsson, J., Hollinger, D., Janssens, I.A., Keronen, P., Kowalski, A.S., Katul, G., Law, B.E., Malhi, Y., Meyers, T., Monson, R.K., Moors, E., Munger, J.W., Oechel, W., Paw, U.K.T., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Thorgeirsson, H., Tirone, G., Turnipseed, A., Wilson, K., Wofsy, S., 2002. Phase and amplitude of ecosystem carbon release and uptake potentials as derived from FLUXNET measurements. Agric. For. Meteorol. 113, 75–95.

Foken, T., Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements. Agric. For. Meteorol. 78, 83–105.

Gond, V., de Pury, D.G., Eerens, H., Veroustraete, F., Ceulemans, R., 1999. Seasonal variation of leaf-area index, leaf chlorophyll and water content scaled up to fAPAR to estimate the carbon balance of a temperate multi-layer, multi-species forest. Tree Physiol. 19, 673–679.

Goulden, M.L., Munger, J.W., Fan, S.M., Daube, B.C., Wofsy, S.C., 1996. Measurements of carbon storage by long-term eddy correlation: methods and a critical assessment of accuracy. Global Change Biol. 2, 169–182.

Greco, S., Baldocchi, D.D., 1996. Seasonal variations of $CO_2$ and water vapor exchange rates over a temperate deciduous forest. Global Change Biol. 2, 183–197.

Hollinger, D.Y., Kelliher, F.M., Byers, J.N., Hunt, J.E., McSeveny, T.M., Weir, P.L., 1994. Carbon dioxide exchange between an undisturbed old-growth temperate forest and the atmosphere. Ecology 75, 134–150.

Houghton, R.A., Davidson, E.A., Woodwell, G.M., 1998. Missing sinks, feedbacks, and understanding the role of terrestrial ecosystems in the global carbon balance. Global Biogeochem. Cycles 12, 25–34.

Janssens, I.A., Sampson, D.A., Cermak, J., Meiresonne, L., Riguzzi, F., Overloop, S., Ceulemans, R., 1999. Above- and below-ground phytomass and carbon storage in a Belgian Scots pine stand. Ann. For. Sci. 56, 81–90.

Janssens, I.A., Meiresonne, L., Ceulemans, R., 2000. Mean soil $CO_2$ efflux from a mixed forest: temporal and spatial integration. In: Ceulemans, R., Veroustraete, F., Gond, V., Van Rensbergen, J. (Eds.), Forest Ecosystem Modeling, Upscaling and Remote Sensing. SPB Academic Publishing, The Netherlands, pp. 19–33.

Janssens, I.A., Lankreijer, H., Matteucci, G., Kowalski, A.S., Buchmann, N., Epron, D., Pilegaard, K., Kutsch, W., Longdoz, B., Grunwald, T., Dore, S., Montagnani, L., Rebmann, C., Moors, E.J., Grelle, A., Rannik, U., Morgenstern, K., Oltchev, S., Clement, R., Gudmundsson, J., Minerbi, S., Berbigier, P., Ibrom, A., Moncrieff, J., Aubinet, M., Bernhofer, C., Jensen, N.O., Vesala, T., Granier, A., Schulze, E.D., Lindroth, A., Dolman, A.J., Jarvis, P.G., Ceulemans, R., Valentini, R., 2001. Productivity overshadows temperature in determining soil and ecosystem respiration across European forests. Global Change Biol. 7, 269–278.

Kaimal, J.C., Wyngaard, J.C., Izumi, Y., Cote, O.R., 1972. Spectral characteristics of surface layer turbulence. Q. J. R. Meteorol. Soc. 98, 563–589.

Keeling, R.F., Piper, S.C., Heimann, M., 1996. Global and hemispheric $CO_2$ sinks deduced from changes in atmospheric $O_2$ concentration. Nature 381, 218–221.

Kowalski, A.S., Overloop, S., Ceulemans, R., 2000. Eddy fluxes above a Belgian, Campine forest and their relationship with predicting variables. In: Ceulemans, R., Veroustraete, F., Gond, V., Van Rensbergen, J. (Eds.), Forest Ecosystem Modeling, Upscaling and Remote Sensing. SPB Academic Publishing, The Hague, pp. 3–17.

Kristensen, L., Mann, J., Oncley, S., Wyngaard, J.C., 1997. How close is close enough when measuring scalar fluxes with displaced sensors? J. Atm. Oceanic Technol. 14, 814–821.

Lee, X.H., 1998. On meteorological observations of surface–air exchange above tall vegetation. Agric. For. Meteorol. 91, 39–49.

Leuning, R., Judd, M.J., 1996. The relative merits of open- and closed-path analysers for measurements of eddy fluxes. Global Change Biol. 2, 241–254.

Leuning, R., King, K.M., 1992. Comparison of eddy-covariance measurements of $CO_2$ fluxes by open- and closed-path $CO_2$ analysers. Boundary-Layer Meteorol. 59, 297–311.

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

Lloyd, J., Taylor, J.A., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8, 315–323.

McMillen, R.T., 1988. An eddy correlation technique with extended applicability to non-simple terrain. Boundary-Layer Meteorol. 43, 231–245.

Meiresonne, L., Sampson, D.A., Kowalski, A.S., Janssens, I.A., Nadezhdina, N., Cermak, J., Van Slycken, J., Ceulemans, R., 2003. Water flux estimates from a Belgian Scots pine stand: a comparison of different approaches. J. Hydrol. 270, 230–252.

Michaelis, L., Menten, M.L., 1913. Die Kinetik der Invertinwirkung. Biochemisches Zeitschrift 49, 333.

Moncrieff, J.B., Malhi, Y., Leuning, R., 1996. The propagation of errors in long-term measurements of land–atmosphere fluxes of carbon and water. Global Change Biol. 2, 231–240.

Moncrieff, J.B., Massheder, J.M., de Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Soegaard, H., Verhoef, A., 1997. A system to measure surface fluxes of momentum, sensible heat, water vapor and carbon dioxide. J. Hydrol. 188–189, 589–611.

Moore, C., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorol. 37, 17–35.

Neirynck, J., Van Ranst, E., Roskams, P., Lust, N., 2002. Impact of decreasing throughfall depositions on soil solution chemistry at coniferous monitoring sites in northern Belgium. For. Ecol. Manage. 160, 127–142.

Overloop, S., Meiresonne, L., 1999. Basiskarakteristieken van het proefvlak Brasschaat, domeinbos de Inslag. Mededelingen van het Institut voor Bosbouw en Wildbeheer 1, 11–21 (in Dutch).

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

Reich, P.B., Bolstad, P., 2001. Productivity of evergreen and deciduous temperate forests. In: Roy, J., Saugier, B., Mooney, H.A. (Eds.), Terrestrial Global Productivity. Physiological Ecology. Academic Press, San Diego, pp. 245–283.

Roskams, P., Sioen, G., Overloop, S., 1997. Meetnet voor de intensieve monitoring van het bosecosysteem in het Vlaamse Gewest-resultaten 1991–1992. Institute for Forestry and Game Management, Ministry of the Flemish Community (in Dutch).

Rotherham, I.D., 1983. The ecology of *Rhododendron ponticum* with special reference to its competitive and invasive capabilities. Ph.D. Thesis, University of Scheffield, UK.

Sakai, R.K., Fitzjarrald, D.R., Moore, K.E., 2001. Importance of low-frequency contributions to eddy fluxes observed over rough surfaces. J. Appl. Meteorol. 40, 2178–2192.

Sarmiento, J.L., Gruber, N., 2002. Sinks for anthropogenic carbon. Phys. Today 208, 30–36.

Saxén, B., Saxén, H., 1995. NNDT—A Neural Network Development Tool, Version 1.2. Åbo Akademi University, Åbo, Finland.

Schimel, D.S., 1995. Terrestrial ecosystems and the carbon cycle. Global Change Biol. 1, 77–91.

Schmid, H.P., Grimmond, C.S.B., Cropley, F., Offerle, B., 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.

Stull, R.B., 1988. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, The Netherlands.

Suni, T., Berninger, F., Markkanen, T., Keronen, P., Rannik, U., Vesala, T., 2003. Inter-annual variability and timing of growing-season $CO_2$ exchange in a boreal forest. J. Geophys. Res. 108, No. D9-10.1029/2002JD002381.

Swinbank, W.C., 1951. The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere. J. Meteorol. 8, 135–145.

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., Grunwald, T., Aubinet, M., Ceulemans, R., Kowalski, A.S., Vesala, T., Rannik, U., Berbigier, P., Loustau, D., Gudmundsson, J., Thorgeisrsson, H., Montagnani, L., Minerbi, S., Jarvis, P.G., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861–865.

Verma, S.B., Baldocchi, D.D., Anderson, D.E., Matt, D.R., Clement, R.J., 1986. Eddy fluxes of $CO_2$, water vapor and sensible heat over a deciduous forest. Boundary-Layer Meteorol. 36, 71–91.

Vickers, D., Mahrt, L., 1997. Quality control and flux sampling problems for tower and aircraft data. J. Atm. Oceanic Technol. 14, 512–526.

Webb, E.K., Pearman, G.I., 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.

Xiao, C.W., Curiel Yuste, J., Janssens, I.A., Roskams, P., Nachtergale, L., Carrara, A., Sanchez, B.Y., Ceulemans, R., 2003. Above- and belowground biomass and net primary production in a 73-year-old Scots pine forest. Tree Physiol. 23, 505–516.