Carbon dioxide exchange above a 30-year-old Scots pine plantation established on organic-soil cropland

Annalea Lohila[1], Tuomas Laurila[1], Lasse Aro[2], Mika Aurela[1], Juha-Pekka Tuovinen[1], Jukka Laine[2], Pasi Kolari[3] and Kari Minkkinen[4]

[1] *Finnish Meteorological Institute, Climate and Global Change Research, P.O. Box 503, FI-00101 Helsinki, Finland (annalea.lohila@fmi.fi)*

[2] *Finnish Forest Research Institute, Parkano Research Unit, Kaironiementie 54, FI-39700 Parkano, Finland*

[3] *Department of Forest Ecology, APFE Group, P.O. Box 27, FI-00014 University of Helsinki, Finland*

[4] *Department of Forest Ecology, Peatland Ecology Group, P.O. Box 27, FI-00014 University of Helsinki, Finland*

In the boreal zone, large areas of natural mires have been drained and used for agriculture, resulting in net carbon dioxide (CO_2) emissions and increased nitrous oxide emissions but decreased methane emissions. However, due to structural changes in agriculture, a substantial area of cropland on organic soil has been afforested. In order to estimate the carbon balance of afforested organic-soil cropland, we measured CO_2 and water vapour (H_2O) fluxes during year above a Scots pine plantation (*Pinus sylvestris*) in the middle-boreal zone, using the micrometeorological eddy covariance method. We observed CO_2 uptake by the Scots pine stand from late April to mid-October with a daily average net uptake from May to the beginning of October. However, there were also periods of daily net efflux. High ecosystem respiration rates continued throughout the winter (mean winter respiration 0.036 mg CO_2 m^{-2} s^{-1}). As an annual average, the 30-year-old pine stand was a small source of CO_2 (+50 g m^{-2} a^{-1}) to the atmosphere, showing that the CO_2 sequestration into the ecosystem was able to compensate for most of the carbon that was released by heterotrophic respiration from the drained soil.

Introduction

Worldwide, peatlands store large amounts of carbon (C), accounting for about 20%–35% of the global soil C reservoirs (Gorham 1991, Eswaran *et al.* 1993). Natural wetland ecosystems fix atmospheric carbon dioxide (CO_2) into biomass, which accumulates in humid and cool conditions. This is because, in the anoxic conditions below the water table, the rate of heterotrophic respiration is lower than the input of carbon as plant residues. However, in the absence of oxygen, methane (CH_4) is produced by methanogenic bacteria, and part of the C that was fixed by plants from atmospheric CO_2 is thus emitted back into the atmosphere as CH_4.

In mineral soils, agricultural activities, such as tillage and fertilization, are known to enhance

the soil carbon loss due to erosion, leaching, and accelerated organic matter mineralization (Sampson *et al.* 2000). In peat soils brought into agricultural use, the same mechanisms contribute to an increased C loss. In addition, the mineralization of organic matter is further enhanced following the drawdown of the water table. The thicker aerobic layer increases heterotrophic respiration, but CH_4 emissions cease following the higher oxygen availability in the peat (Nykänen *et al.* 1995). There is strong evidence that the carbon loss in cultivated peat soils is considerable (Armentano and Menges 1986, Maljanen *et al.* 2001b, Lohila *et al.* 2003, Lohila *et al.* 2004). While in natural mires emission of nitrous oxide (N_2O) is minor (Martikainen *et al.* 1993), cultivated organic soils are known to be significant sources of N_2O, a powerful greenhouse gas (Kasimir-Klemedtsson *et al.* 1997, Regina *et al.* 2004).

Roughly estimated, the area of peatlands that have been drained for agriculture in Europe amounts to 43 000 km², which is about 5% of its total peatland area (Penman *et al.* 2003). In Russia, Malaysia, Indonesia and China the corresponding area of such soils is about 17 000 km² (Penman *et al.* 2003). In Finland, the area of croplands that have soil organic matter concentrations exceeding 20% is presently about 300 000 ha (Myllys and Sinkkonen 2004). This is much less than the area originally drained for agriculture (about 700 000 ha), reflecting the general policy to reduce the total farmed land area. The afforestation of organic croplands has become increasingly important during recent decades. According to the Kyoto Protocol of the United Nations Framework Convention on Climate Change, afforestation of agricultural land is recommended, in order to increase or at least preserve the soil carbon stock, and it is an accepted way of improving the greenhouse gas budget of a country (Sampson *et al.* 2000, Schulze *et al.* 2002). However, it is not known whether the rate of decomposition of soil C on drained peatlands will change after changing the land use from agriculture to forestry.

Measurements of gas exchange and carbon stock changes in organic soils are scarce. The change in the carbon balance following the conversion of a natural wetland to a forested peatland

has been estimated by measuring the changes in biomass and peat C after drainage (Minkkinen and Laine 1998a). The results suggested that the soil carbon store increased in some peat soil forest types after the forestry drainage, due to the enhanced root and needle litter production. Measurements have also indicated that afforested organic croplands may act as a significant source of N_2O into the atmosphere and that their CH_4 fluxes differ from those of pristine mires (Maljanen *et al.* 2001a, Mäkiranta *et al.* 2007). However, CO_2 flux measurements above an afforested organic-soil cropland, which would make possible the estimation of the whole-ecosystem CO_2 balance, have not been done earlier.

CO_2 flux measurements conducted with the micrometeorological eddy covariance method above a forest canopy give the net ecosystem exchange (NEE) of the ecosystem (Baldocchi 2003). NEE may be separated into two components, GPP and R_{tot}. GPP denotes the gross primary production of the ecosystem, i.e., the CO_2 assimilated by the trees and forest floor vegetation, while R_{tot} is the sum of heterotrophic (R_h) (mainly soil and litter) and autotrophic (R_a) (plant-derived) respiration. Net primary production (NPP), on the other hand, is defined as GPP $- R_a$, and denotes the plant biomass gain or loss by the vegetation. However, when assessing the ecosystem C balance in peat soils, we need to consider the net ecosystem production (NEP), which, in addition to NPP, also accounts for the C gain or loss taking place in peat, owing to, e.g., litter input, heterotrophic respiration or carbon leaching. NEP is defined as NPP $- R_h$. Finally, when looking at the C balance in managed forests in the long run, the part played by forest management, encompassing the rotation length, has to be accounted for. When the carbon removed in harvesting or logging (or other processes leading to loss of living or dead organic matter) is subtracted from the NEP, the net biome production (NBP) is obtained.

Here we present data on CO_2 and water vapour (H_2O) exchange measurements conducted above an afforested organic-soil cropland. To our knowledge, these are the first published year-round NEE data on this type of ecosystem. The data cover one year from September 2002 to September 2003. In this paper we examine the

seasonal CO_2 and H_2O exchange rate of the eco-system and the factors controlling NEE. We also report monthly evapotranspiration (ET) rates because they are, most probably, increased due to afforestation. Finally, we estimate the annual CO_2 balance of the organic cropland 30 years after its afforestation, and make a coarse estimate of the carbon fluxes in this type of ecosystem.

Material and methods

Site description

The study site was a ca. 30-year-old Scots pine (*Pinus sylvestris*) plantation at Alkkia, in Finland (62°10.586′N, 22°47.021′E, elevation 159 m a.s.l.). The site is situated in the middle boreal climatic zone (Solantie 1990). The original site type was *Sphagnum fuscum* bog which was drained in 1936–1938, after which, in 1940, a mineral soil admixture was introduced into the soil. This was a typical practice in peat soils to improve them for cultivation. Following this, from 1940 until 1969, the area was in agricul-tural use, meaning regular fertilization and soil preparation measures. In 1971, the field was fer-tilized with potassium (87 kg ha⁻¹) and phospho-rus (73 kg ha⁻¹) and planted with Scots pine with 3, 5, and 8 m row spacings. Naturally-generated birch (*Betula bendula*, *B. pubescens*) trees are observed in plots where the row spacing of pines is wide. In 1991, the site was refertilized with 0–45 kg P and 0–131 kg K per hectare.

The CO_2 flux measurement mast was located close to a ditch which divided the forest into two management types. The afforested organic crop-land was located in the sector 270° through N to 135°, whereas in other directions the site had no agricultural history. The size of the afforested area was approximately 20 ha. In this paper we concentrate only on the data measured for the sector with an agricultural history.

The leaf area index (LAI) of the forest canopy was determined by taking photos with a camera equipped with a fish-eye objective (6 mm, Canon) and analyzing the photos with Gap Light Analyzer (GLA) software, Version 2.0 (Simon Fraser University, Burnaby, British Columbia, Canada, and Institute of Ecosystem

Studies, Millbrook, New York, U.S.A). The LAI of the forest floor vegetation was measured five times between June and August with an LAI-2000 Plant Canopy Analyser (LI-COR, Inc, NE) at about 40 points located within 200 m of the measurement mast. The ground vegetation reflected the agricultural history and improved fertility. Common species included *Rubus idaeus*, *Epilobium angustifolium, Urtica dioica, Cirsium arvense, Galeopsis* spp., *Filipendula ulmaria, Ranunculus acris, Geranium sylvaticum, Athy-rium filix-femina, Agrostis* spp., *Deschampsia* spp. and *Calamagrostis* spp.

Trees were measured from 40 circular plots (r = 7.07 m, A = 157 m²) located systematically around the mast within a 200-m radius, the area considered to be the most significant flux source area. The measured quantities were the diameter at breast height (DBH), height, height growth, and lower limit of living crown. Wood samples for determining radial growth were taken from sample trees of pine (every sixth measured pine). The tree stand characteristics (e.g. mean DBH, height, annual diameter and height growth, stand volume) were calculated with a KPL computer programme package developed for computing stand and single tree characteristics from sample plot measurements (Heinonen 1994). Because annual diameter and height growth were not determined from sample trees of birch, their average growth rate was assumed to be the same as for pine. Based on the annual growth rates, DBH and tree height were calculated for years preceding the stand measurements. The biomass of the various tree stand components (stems, branches with needles, dead branches, stumps, coarse and fine roots) at the beginning and end of the CO_2 flux measurement period was esti-mated with biomass functions for pine published by Marklund (1988), generating a dry mass accumulation in the tree stand during the study period. Using the pine functions for birch may have resulted in a potential under-estimation of the dry mass accumulation for birch. The carbon content of the dry mass was assumed to be 50%.

The mean depth of the peat layer was meas-ured with a sonde at 12 points located within a 200-m radius of the mast. The physical and chemical properties of the soil were measured as averages of 10 cm soil layers down to 50 cm.

The organic matter content was determined as loss on ignition (550 °C) and the C and N concentrations using LECO CHN-2000. Element concentrations (K, Ca, Mg, Fe, Mn) were measured by flame atomic spectrophotometry (Varian AA-30) after dry combustion and HCl extraction, and P spectrophotometrically. Total dissolved nitrogen (TDN), ammonium (NH_4-N) and nitrate (NO_3-N) concentrations were determined by flow injection analysis (FIA Star 5020, Tecator).

Instrumentation

CO_2, H_2O and sensible heat exchange rates were measured with the eddy covariance technique. The instrumentation, mounted on the top of an 18 m telescopic mast, included an SWS-211 three-axis sonic anemometer (Applied Technologies, Inc.) and an LI-7000 CO_2/H_2O analyzer (Li-Cor, Inc.). The heated inlet tube for the LI-7000 was 14 m in length, a flow rate of 6 l min^{-1} being used to maintain turbulent flow. The LI-7000 was operated in absolute mode using CO_2-free synthetic dry air as a reference gas. A two-point calibration (0 and 391 ppm) was conducted typically once a month.

The CO_2 flux measured above the forest canopy is not always equal to the net flux density of CO_2 moving into and out of the plant–soil system. In certain conditions, e.g., nights with a stable temperature stratification, CO_2 is stored in the air column below the measurement height, and is released later. The significance of this so called storage flux decreases with increasing turbulence. The storage flux of CO_2 was calculated from the concentration data measured at a height of 18 m and added to the measured NEE (hereafter NEE refers to the sum of turbulent and storage fluxes). In this paper, we use the convention that a positive value of NEE indicates flux from the ecosystem into the atmosphere, while a negative value indicates uptake of CO_2 from the atmosphere into the ecosystem.

Ancillary meteorological measurements were conducted at the study site as follows: air temperature and humidity at 3 and 18 m (Vaisala HMP230), soil temperature at depths of 0.05, 0.30, and 0.50 m (PT100), soil moisture at depths of 0.07 and 0.30 m (ThetaProbe ML2x, Delta-T Devices Ltd), soil heat flux at a depth of 0.15 m (HFP01), net radiation (Kipp&Zonen NR Lite), global radiation, reflected global radiation (LI-200SZ), photosynthetic photon flux density (PPFD) and reflected PPFD (Licor LI-190SZ) at the top of the mast at 18 m, below-canopy PPFD at 1m, and precipitation at 12 m. The data were acquired using a Vaisala QLI 50 sensor collector and stored as 30-min averages by a PC. The snow depth and the precipitation data were taken from the Alkkia weather station operated by the Finnish Meteorological Institute and located about 5 km to the west of the study site. In cases of data collection failure, the air temperature data of the weather station were also utilized. During July–August 2003 meteorological data break, the radiation data were obtained from the Närpiö weather station about 75 km to the west of Alkkia. The data were utilized as daily averages as explained later.

Data processing

The eddy covariance data acquisition was carried out by a LabView-based program BAR-FLUX. Coordinate rotation and data detrending by an autoregressive running-mean filter with a 200-s time constant were performed according to McMillen (1988). The lag between the time series resulting from the transport through the inlet tube was taken into account in the on-line calculation of the flux quantities. A series of further manipulations and corrections to the collected data were performed off-line. The instrumentation and the data processing procedures have been presented in more detail by Lohila *et al.* (2004) and Aurela (2005).

The flux data were screened for spikes in the anemometer data, high sensor variance, insufficiently turbulent conditions, and an abnormally high difference in the temperature measured with the sonic anemometer and the HMP230. When the friction velocity (u_*) was smaller than 0.2 m s^{-1}, we considered turbulence to be inadequate, and deleted the observations (Fig. 1). In addition to these situations, there were several gaps in the data due to the limited measurement sector. As mentioned above, only the data from the sector

Fig. 1. Half-hourly NEE *vs*. friction velocity at Alkkia during four winter months (Nov. 2002–Feb. 2003). The curve shows the smoothed data using a polynomial regression and weights computed from the Gaussian density function (sampling proportion = 0.05; polynomial degree = 1). The broken line shows the limit below which the data were discarded.
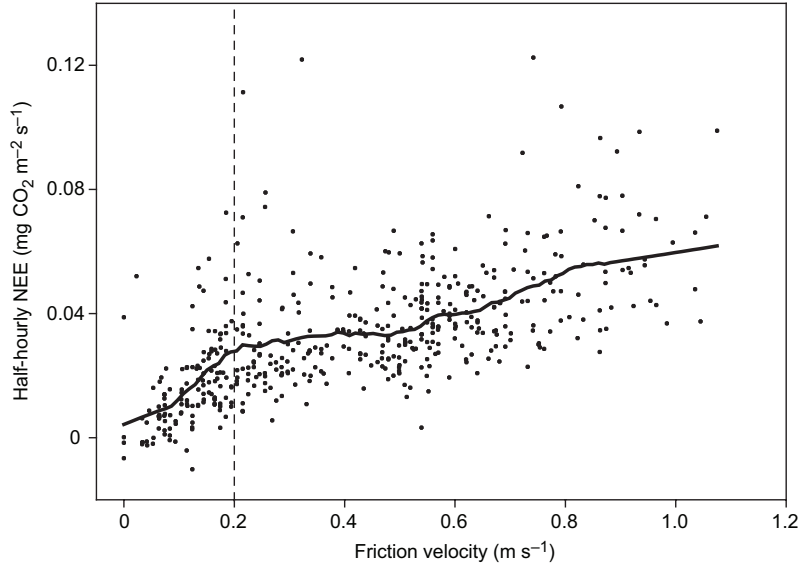
> 270° and < 135° were used. Altogether, 4632 observations (26.4% of the year) were obtained from the afforested organic cropland during the study period. Most of the data gaps occurred during the winter (17 Oct. 2002–10 Apr. 2003; here defined as the period when the daily mean air temperature was below zero) mainly due to the anemometer icing up. Due to this, the data coverage during the winter was only 10%. However, the days with accepted observations were relatively evenly distributed, and no marked seasonal variability in NEE during the winter months was seen. Outside the winter season, when the variation in daily and seasonal NEE was more pronounced, the data coverage was better, about 45%. There were two longer data gaps, one in April (13 days) and another in July (8 days).

Gap filling of the flux data

In order to calculate the CO_2 balances for longer periods, the gaps in the data had to be filled. During the winter, the gap-filling for the total ecosystem respiration (R_{tot}) was done with the empirical equation of Lloyd and Taylor (1994) using the air temperature at 3 m:

$$R_{tot} = R_{ref} \times \exp\left[E_0 \times \left(\frac{1}{56.02} - \frac{1}{T - 227.13} \right) \right] \quad (1)$$

In this equation, R_{ref} is a parameter describing the total ecosystem respiration (mg CO_2 m^{-2} s^{-1}) at the reference temperature (0 or 10 °C), T is the air temperature (K), and E_0 is a parameter describing the temperature response of the respiration. In winter, the reference temperature was set to 0 °C. Although the correlation between the soil temperature and NEE was slightly better, the air temperature was chosen because a continuous time-series was available from the nearby Alkkia weather station.

As regards the non-winter periods, the total ecosystem respiration was parameterized by means of Eq. 1 using the air temperature and nocturnal NEE observations as input values. The parameterization was done separately for four periods: the autumn period in 2002, and in 2003 from mid-April till the middle of May, from then till the beginning of July, and from then till September. The model was fitted to the data, and values of E_0 and R_{tot} were derived from this fitting using a reference temperature of 10 °C. NEE was then parameterized for the same periods by using PPFD and the gap-filled R_{tot} as input values to the following equation:

$$NEE = PI \times \left(\frac{\alpha \times PPFD \times GP_{max}}{\alpha \times PPFD + GP_{max}} \right) + R_{tot} \quad (2)$$

where α is the apparent quantum yield (mg μmol^{-1}) and GP_{max} is the full daylight asymptotic value of NEE after subtracting R_{tot}.

In the gap-filling of the data, a term called the Phytomass Index (PI), originally developed by Aurela *et al.* (2001), was used to account for the seasonal development of the photosynthesis. This is an empirically-determined coefficient, calculated from the NEE data as the difference between the nighttime respiration and the daytime photosynthetic uptake of CO_2 (when PPFD > 700 μmol m^{-2} s^{-1}) (Aurela *et al.* 2001). PI was normalised to unity at its maximum.

Between 17 and 25 July, when due to an equipment malfunction NEE or meteorological data were not measured, we employed a different method for the gap filling. Half-hourly gross primary production and R_{tot} were first estimated for the days before and after the gap with existing NEE data based on Eqs. 1 and 2. From these, daily GPP, R_{tot} and NEE were obtained. We then took the PPFD data from the Närpiö weather station and formed a linear regression between the daily GPP at Alkkia and the daily PPFD at Närpiö (R^2 was 0.39). Using this regression, we estimated the daily GPP at Alkkia for the period with missing NEE data. For the same period we made a regression between the daily air temperature and the respiration. The daily respiration for the missing period was calculated from this regression using the air temperature measured at the nearby Alkkia weather station. Finally, NEE for this period was calculated as the sum of GPP and $R_{tot.}$.

We estimated the monthly evapotranspiration (ET) rates by calculating the monthly averages of the measured latent heat (LH) flux for each half hour of the day (48), and then multiplying these averages by the number of days in a month and finally summing the resulting values. The monthly evapotranspiration was compared with ET measurements above a Scots pine forest growing on mineral soil at SMEAR II research station at Hyytiälä, located about 100 km to the east of Alkkia. The site belongs to the CARBOEUROPE flux network, and has similar climatic conditions, tree age, height and LAI with the Alkkia site. Eddy covariance measurements and site characteristics at Hyytiälä were documented by e.g. Markkanen *et al.* (2001) and Suni *et al.* (2003).

Results

Tree stand and soil characteristics

The mean DBH of the trees was 14.8 cm and height 12.1 m. The total stand density was 977 trees ha^{-1} and stand volume 126 m^3 ha^{-1}. The average annual dry mass accumulation in the below- and above-ground parts of the trees was 0.472 kg m^{-2} (equal to 865 g CO_2 m^{-2}). The LAI of the tree canopy varied between 0.7 and 2 m^2 m^{-2} depending on the row spacing, the average being 1.6 m^2 m^{-2}. The average forest floor vegetation LAI was 2.0 m^2 m^{-2} during the growing season. No seasonal variation was observed in the ground vegetation LAI data.

The mean depth of the peat layer ($\pm$ SD) was 1.56 $\pm$ 0.13 m. The mineral soil admixture, fertilization and the afforestation had increased the bulk density, pH and element concentrations and decreased the C/N of the topmost 0–30 cm peat layer (Table 1). 42% of the total dissolved nitrogen existed in mineralised form. Below 30 cm the soil consisted almost exclusively of peat material only, as is indicated by the high organic matter concentration (94%–98%).

Table 1. Soil characteristics and element concentrations at the Scots pine plantation established on former organic-soil cropland at Alkkia.

Soil layer	Bd	pH	C (%)	N (%)	Org (%)	C/N	P[1]	Ca[1]	Fe[1]	K[1]	Mg[1]	Mn[1]	NH$_4$$^+$[1]	NO$_3$$^-$[1]	TDN[1]
Litter + humus		5.4	31	1.45	61	21	1460	7200	2150	1320	1250	450	257	31	520
0–10 cm	0.65	4.8	12	0.55	23	22	730	3430	5900	600	1080	73	35	0.95	71
10–20 cm	0.59	4.5	20	0.65	39	31	810	3560	4750	470	930	34	25	0.49	78
20–30 cm	0.28	4.2	41	1.11	75	37	630	4080	3390	330	840	21	21	0.27	118
30–40 cm	0.22	4.0	53	1.43	94	37	490	2470	2300	200	580	21	54	0	133
40–50 cm	0.22	4.0	57	1.33	98	43	450	1440	1970	180	410	20	64	0	134

Bd = bulk density. TDN = total dissolved nitrogen. [1] total amount of the element in mg kg^{-1}.
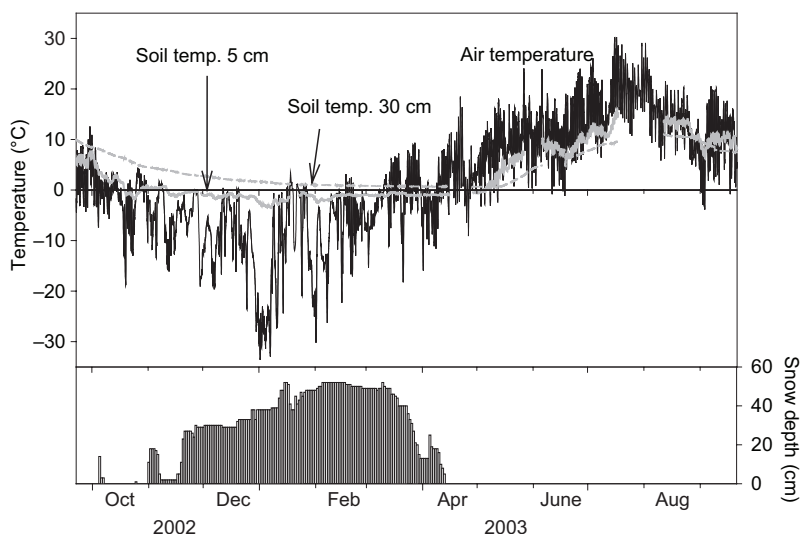
Fig. 2. Half-hourly air (18 m) and soil temperatures (at depths of 5 and 30 cm) at the flux site, and the snow depth at the Alkkia meteorological station over the period 22 Sep. 2002–21 Sep. 2003.

Meteorology

The years 2002 and 2003 were warmer than average, but, interestingly, the study period from 22 Sep. 2002 to 21 Sep. 2003 was slightly cooler than normal with the mean of 2.2 °C as compared with the long-term (1961–1990) annual mean of 2.8 °C (Finnish Meteorological Institute 1991). The summer of 2002 was very warm, the mean temperature for April–September being 2 °C higher than normal. In the autumn of 2002 and in the following winter (October 2002–January 2003) the monthly temperatures were markedly lower than those indicated by the long-term data. The average temperature during the period October 2002–March 2003 was –6.2 °C. The top soil layer froze in October and thawed in April. Despite the daily air temperature temporarily falling to ca. –30 °C during winter, the snow cover effectively insulated the soil so that the temperature at a depth of 5 cm only dropped a few degrees below zero, while at a depth of 30 cm the soil stayed unfrozen (Fig. 2). The first snow appeared at the beginning of November 2002, while the thickest snow cover, about 50 cm, was measured in January–March 2003. The snow thawed by mid-April.

The annual precipitation was 504 mm during the measurement period. As there were no long-term data on precipitation for the Alkkia weather station, the data from three other nearest weather stations were used for comparison. According to these data, the long-term annual precipitation varied from 611 to 641 mm a⁻¹, indicating that the study year was drier than normal. Precipitation in the late summer and autumn of 2002 was much smaller than normal. During August–September it was only 47% of the 1961–1990 average (results not shown). The dry conditions during the late summer of 2002 were amplified by the high temperatures in the summer of 2002. The precipitation in May 2003 was three times the average value, but in June and July close to normal (Table 2). Again, August–September of that year was very low in precipitation, being only 44% of the long-term average (Table 2). During the 2003 growing season, the ground water level varied between 40–60 cm, showing a decreasing trend towards the end of the summer.

Ecosystem CO₂ and H₂O fluxes

The NEE data measured in the sector > 270° and < 135° between 22 Sep. 2002 and 21 Sep. 2003 are shown in Fig. 3. In autumn 2002, there was a clear diurnal cycle in the NEE, indicating photosynthetic activity by trees and the understorey. On 17 October, a few days after the daily air temperatures had dropped below zero, the diurnal cycle was attenuated following the cessation of assimilation. Some photosynthetic activity was,
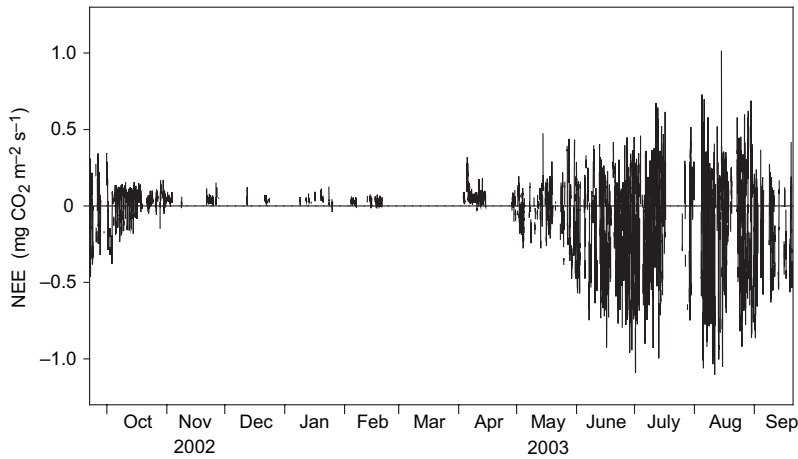
Fig. 3. Accepted NEE data between 22 Sep. 2002 and 21 Sep. 2003 measured over a 30-year-old Scots pine plantation established on former organic-soil cropland at Alkkia.

however, observed later in October, and also in mid-winter when the daily air temperature rose above zero. The winter total ecosystem respiration was weakly correlated with air temperature (Fig. 4). The average mid-winter CO_2 flux (from December to March) was 0.036 mg m^{-2} s^{-1}.

The diurnal variation in NEE was absent in April, despite a relatively high PPFD and positive midday air and soil temperatures (Figs. 3 and 5). Daily average temperatures rose at the beginning of May above +5 °C, a temperature which is often considered to mark the start of the thermal growing season. During the first few weeks the minimum daytime NEE fluctuated around –0.2 mg m^{-2} s^{-1}, but after a warm day on 25 May, on which the air temperature exceeded 25 °C, the photosynthesis increased rapidly (Fig. 3). As the summer progressed, both the nighttime respiration and the daytime CO_2 uptake increased (Figs. 3 and 5). The nighttime respiration and daytime net uptake were highest in August, although from April onwards the median diurnal PPFD was smaller than that in other months (Fig. 5). In the

latter half of August the diurnal amplitude of NEE started to decrease along with the decreasing temperature and lower PPFD (Figs. 3 and 5). The photosynthetic parameters α and GP_{max} were also at their maximum in August (Table 3). The median vapour pressure deficit (VPD), a measure expressing the potential of the air to take up more moisture, was then low (Fig. 5).

The lowest 0–50 m layer of the atmosphere is called the atmospheric surface layer in which the energy flux components should balance each other. The major components in the surface are the solar and long-wave radiations — whose balance is measured by the net radiometer — the turbulent sensible (SH) and latent heat (LH) fluxes, the heat flux to the soil and the heat storage in the biomass above the ground. LH is equal to the evapotranspiration but is expressed in energy units. In April, when the soil was mostly snow-covered, most of the incoming radiation was dissipated as SH flux, although a small diurnal variation in the LH flux could be observed (Fig. 5). The midday Bowen ratio, describing

Table 2. Long-term monthly precipitation in 1961–1990 and monthly precipitation in 2003 at the Alkkia weather station and evapotranspiration in 2003 from April to September at the Alkkia and Hyytiälä flux sites. All values have been expressed in mm.

	April	May	June	July	August	September	Total
Normal precipitation 1961–1990[1]	36	37	52	74	82	71	352
Precipitation in 2003 at the Alkkia weather station	20	109	69	65	57	10	330
Evapotranspiration at the Alkkia flux site in 2003	10	59	94	103	62	64	392
Evapotranspiration at the Hyytiälä flux site in 2003	13	48	65	72	64	29	291

[1] The data were taken from the three weather stations nearest to Alkkia.

Fig. 4. The winter (15 Oct. 2002–10 Apr. 2003) total ecosystem respiration (measured using the eddy covariance method) plotted against the air temperature. The solid line is the fitted equation of Lloyd and Taylor (1994).
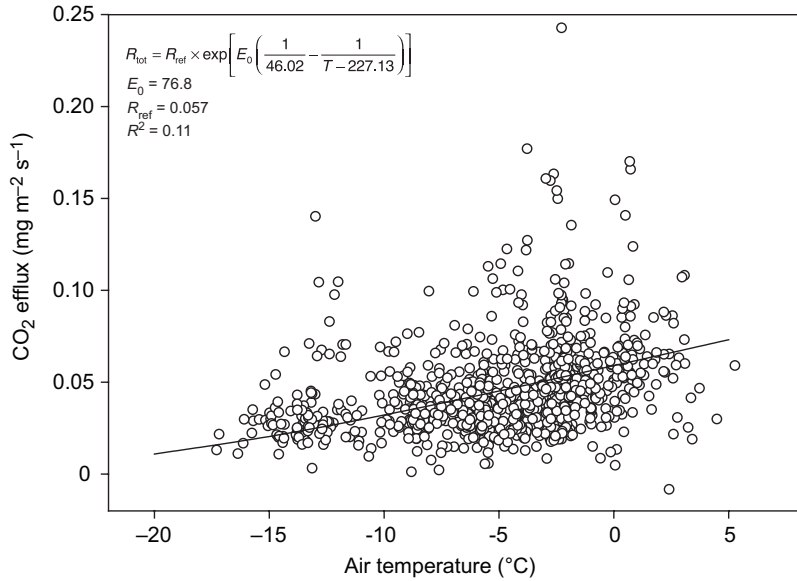
the partitioning between the sensible and latent heat fluxes (SH/LH), was about 10. The midday Bowen ratio was close to 2 in May, when the LAI of the ground vegetation and birch were low. It gradually decreased from values above 1 in June to about 0.7 in August, showing the increasing importance of evapotranspiration towards the late summer when the leaf area of birch and forest floor vegetation were at their maximum. The highest average values of SH were measured in May, when the evapotranspiration was still small and a large part of the incoming radiation was dissipated as sensible heat.

The monthly evapotranspiration rates at the Alkkia Scots pine plantation exceeded the precipitation during the summer period (Table 2). In April and May, the monthly precipitation was roughly double the ET rate, but during the later part of the growing season ET exceeded precipitation and in September it was greater by a factor of six due to the low precipitation. Over the summer period, the ET was 20% higher than the precipitation.

## Daily and annual CO_2 balances and carbon balance

The daily NEE varied from about +13 to –25 g CO_2 m^{-2} d^{-1} (negative values indicating net CO_2 uptake by the forest ecosystem). While there were a few days in September and at the beginning of October 2002 with a small net CO_2 uptake, the drop in the daily mean air temperature to close to zero caused the assimilation activity to cease. From mid-October 2002 to the end of March 2003, the daily NEE was on average +3.5 g CO_2 m^{-2} d^{-1}, showing no great seasonal variation. The first days of daily net uptake by the forest ecosystem were observed at the beginning of May, at about the same time as the thawing of the soil surface (Fig. 6).

Table 3. Monthly values of the parameters in Eq. 2, when PI is constant (= 1) for the NEE data from May to September 2003 as measured at the Alkkia flux site.

	May	June	July	August	September
α (× 10^{-3}) (μg CO_2 μmol^{-1})	−0.91	−1.94	−2.35	−2.75	−1.37
GP$_{max}$ (mg CO_2 m^{-2} s^{-1})	−0.56	−1.07	−1.18	−1.53	−1.25
R_{tot} (mg CO_2 m^{-2} s^{-1})	0.140	0.225	0.315	0.290	0.151
Coefficient of determination (R^2)	0.72	0.84	0.82	0.87	0.75
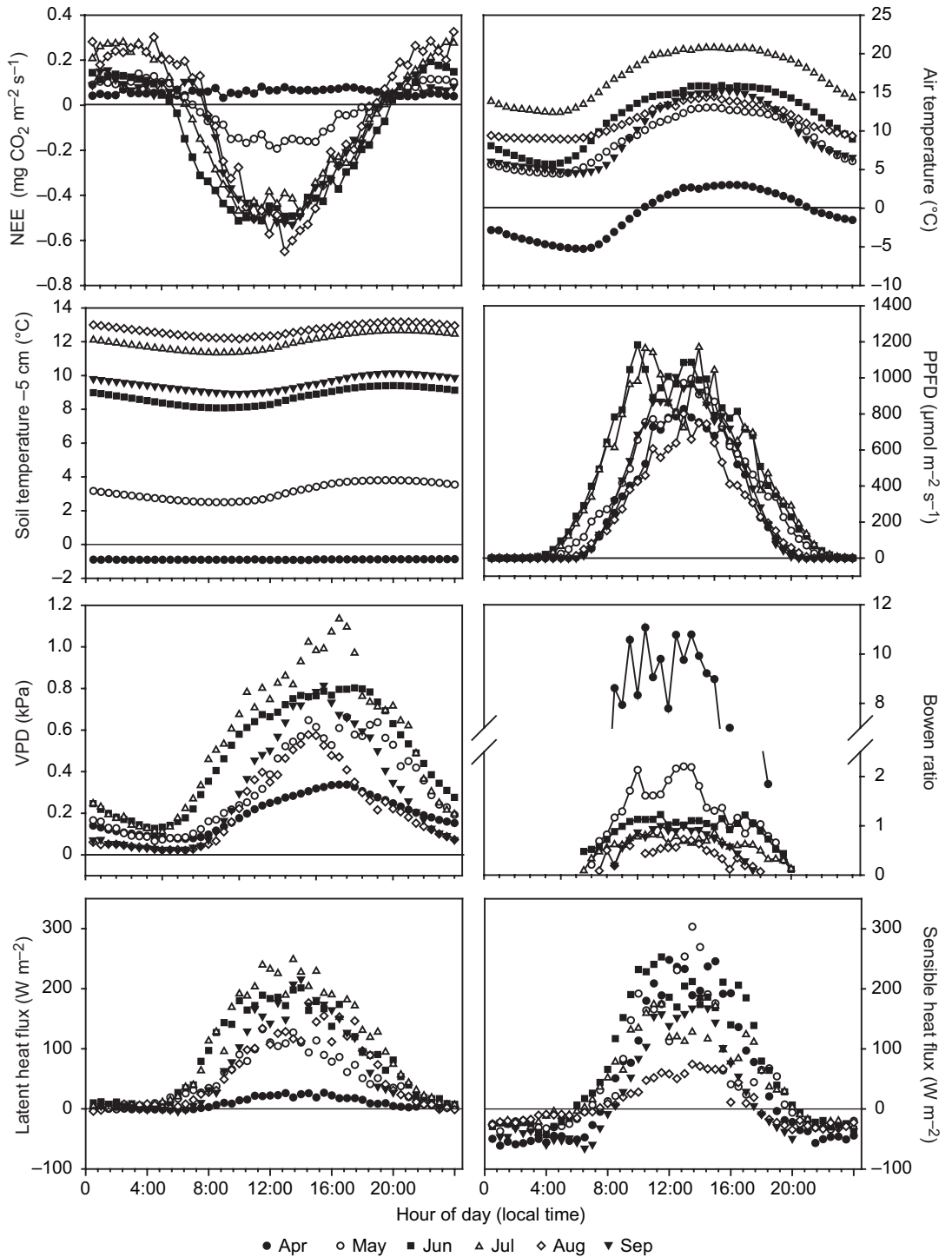
Fig. 5. Monthly averages of half-hourly NEE, air temperature, soil temperature and the medians of photosynthetic photon flux density, vapour pressure deficit, Bowen ratio, latent heat, and sensible heat from April to September, 2003, at the Alkkia flux site.
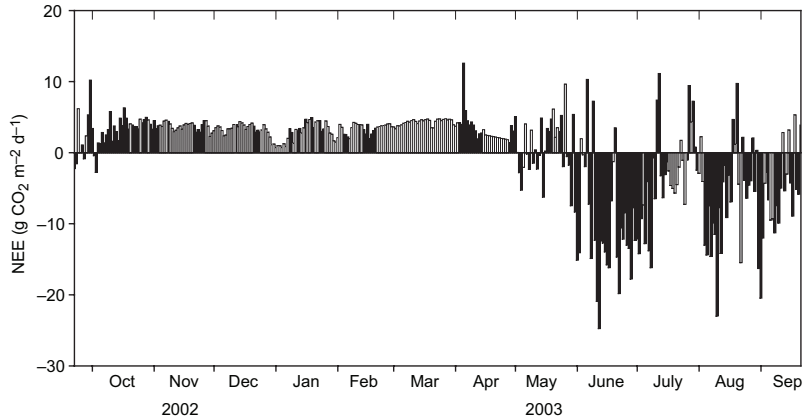
Fig. 6. Daily NEE from 22 Sep. 2002 to 21 Sep. 2003 measured over a Scots pine plantation established on former organic-soil cropland at Alkkia. White bars denote days with only gap-filled NEE data.

The highest CO_2 loss from the forest to the atmosphere was typically observed on cloudy and rainy summer days (Fig. 6). The greatest CO_2 sink was measured in June and August, whereas during a 2-week warm and dry period in July the forest was a daily CO_2 source or only a very small CO_2 sink. By summing up the daily CO_2 balances, an annual balance of +50 g CO_2 m^{-2} a^{-1} was obtained.

The annual CO_2 balance measured with the eddy covariance method should equal the sum of all separate CO_2 sinks and sources in our ecosystem. From these, the tree biomass net accumulation and the microbial peat decomposition were measured (Fig. 7). The annual net accumulation of CO_2 into tree biomass was about –870 g CO_2 m^{-2} a^{-1}, which was probably an underestimate, because fine roots were not included

in the calculation. According to the chamber measurements conducted at the Alkkia site, the underlying peat was losing carbon at an average rate of +1760 g CO_2 m^{-2} a^{-1} (Mäkiranta *et al.* 2007). Then, as the measured NEE was only +50 g CO_2 m^{-2} a^{-1}, an additional imbalance of –840 g CO_2 m^{-2} a^{-1} was obtained (Fig. 7). In other words, this amount of CO_2 should have been bound up somewhere else in the ecosystem.

Discussion

Soil characteristics

The agricultural history of the site was reflected in the physical and chemical properties of the soil. Amongst the afforested agricultural histosol
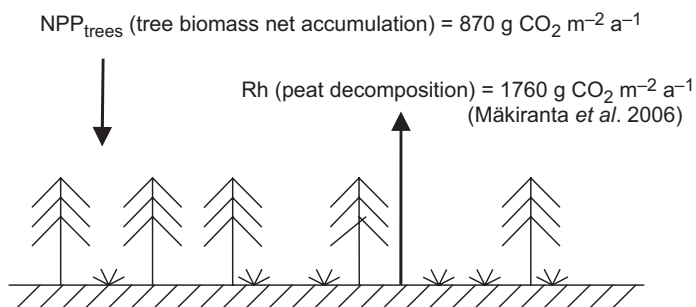
▲ NEE = 50 g CO_2 m^{-2} a^{-1}

NPP_trees	–870
Rh	+1760
Imbalance	–840
NEE	+50 g CO_2 m^{-2} a^{-1}

Fig. 7. Schematic representation of the carbon fluxes in the afforested organic cropland at Alkkia. To obtain the measured annual NEE of +50 g CO_2 m^{-2} a^{-1}, measurements indicate an additional sink of about 840 g CO_2 m^{-2} a^{-1} (Imbalance) in the ecosystem not accounted for by our measurements

NPP_{trees} (tree biomass net accumulation) = 870 g CO_2 m^{-2} a^{-1}

Rh (peat decomposition) = 1760 g CO_2 m^{-2} a^{-1}
(Mäkiranta *et al.* 2006)

sites reported by Mäkiranta *et al.* (2007), the Alkkia site had the highest bulk density and ash content, indicating a high amount of mineral soil admixture. Minkkinen and Laine (1998b) reported peat bulk densities for forestry-drained pine mires in Finland. This bulk density was on average 0.133 g cm^{-3} in the 0–80 cm layer with no significant vertical variation. At Alkkia, the bulk densities were much higher, on average 0.62 g cm^{-3} in the 0–20 cm layer and 0.22 g cm^{-3} in the 30–50 cm layer (Table 1). The high density close to the surface was probably mostly a result of the mineral soil addition, but high peat oxidation may have contributed to the compaction of the peat as well. The density close to the surface was even higher than at a histosol cropland site in southern Finland (0.48 g cm^{-3}), but not as high as in the mineral-soil croplands (1.06–1.26 g cm^{-3}) observed by Lohila *et al.* (2003). The addition of mineral soil had increased the soil pH, which was 4.65 (0–20 cm) as compared with the more acidic 2.66–3.30 (0–20 cm) drained forested peatlands in the Lakkasuo mire complex in central Finland (Minkkinen *et al.* 1999). At the Alkkia site, the C concentration in the 0–10 cm layer was only 12%, which was much less than the corresponding values in the Lakkasuo drained forested mires, where C concentrations were about 50%. The C/N ratio (22) close to the surface (0–10 cm) showed relatively high N concentrations at Alkkia as compared with those at the Lakkasuo drained sites (about 33). The high mineral concentrations and pH at our site indicated favourable conditions for high C-mineralization rates.

Estimation of the magnitude of error in the annual CO$_2$ balance

There were several possible error sources in the study, which may have affected the instantaneous fluxes and especially the annual CO$_2$ balance. First of all, there is uncertainty in the measured fluxes themselves, and secondly, a further error arises from the gap-filling of the data. Here we will only deal with the uncertainties arising from the two different sources we consider the most important, both related to the gap-filling. Perhaps the greatest error source in this study

resulted from the replacement of the nighttime fluxes measured during inadequate turbulence with modelled values (the so-called u_* correction). We estimated this uncertainty by studying the effect on the annual balance of selection of the u_* level for valid observations. With a u_* limit of 0.1 ms^{-1}, the annual CO$_2$ balance would have been –93 g m^{-2}, whereas with a limit of 0.3 it would have been +107 g m^{-2}. Another marked error source was the break in the data in the summer of 2003. We assessed this error by calculating the difference between the measured and modelled NEE during 18 days before and after the gap, a time-period equal to the gap in the summer data. When the daily modelled and measured balances were compared, the difference varied between –70 and +47 g CO$_2$ m^{-2}. The total error from these two sources was estimated by summing up the individual errors, resulting in a lower, –163 g CO$_2$ m^{-2} a^{-1}, and an upper, +154 g CO$_2$ m^{-2} a^{-1}, limit for the annual balance. This short exercise gives a rough and conservative impression of the range of uncertainty associated with the annual CO$_2$ balance measured with the eddy covariance technique.

CO$_2$ and H$_2$O fluxes and annual CO$_2$ balance

The highest half-hourly CO$_2$ uptake values were measured in August, coincidentally with the photosynthetic parameters α and GP$_{max}$ (Table 3). Generally, the relationship between these is not quite straightforward, since e.g. radiation and VPD greatly affect the instantaneous fluxes. Instead, the photosynthetic parameters derived from the data are better indicators of the assimilation ability of the ecosystem, since these are not dependent on the temporary radiation conditions. There are some explanations available for the high parameter values in August. First of all, though we failed to find any significant change in the LAI of the forest floor vegetation due to the high spatial variation, there must have been a seasonal trend with a maximum in August. Most probably, the same was true for birch leaves, albeit the contribution of the birches to the total LAI was minor. Second, the pine trees may also have had their maximum photosynthetic capacity

and LAI at that time. In addition, one explanation for the high uptake rates may have been the low VPD in August (Fig. 5). VPD and NEE (in full radiation) were linearly correlated, so that the higher the VPD, the lower the CO_2 uptake (data not shown). In general, the lower the VPD, the more advantageous it is for the plant. This in turn results from the stomata dynamics: the drier the air, the greater the stomatal closure, thus preventing the loss of water from the plant cells, and at the same time preventing the diffusion of CO_2 into the stomata.

The value for the annual CO_2 balance of +50 g m^{-2} (from –160 to +150 g m^{-2}) indicates that the NPP by the trees and the forest floor vegetation roughly balanced the oxidation of the underlying peat layer. The peat oxidation measured by the chamber method at the same site (Mäkiranta *et al.* 2007) was 1760 g m^{-2}, of which 200 g m^{-2} took place during the November–April winter period. According to the micrometeorological measurements the net emission during the same winter period was 620 g m^{-2}, showing the dominant role of respiration compared with the other components of the ecosystem, and suggesting that the contribution of the R_a to the R_{tot} is highly significant even during the winter.

It must be emphasized that the late summers of both 2002 and 2003 were low in precipitation, which may have affected the fluxes and the annual balance. According to the direct measurements the ET during the summer of 2003 was higher than the precipitation (Table 2), amplifying the effect of low precipitation. As could be expected, during the growing season the ET was 35% higher at Alkkia as compared to Hyytiälä (Table 2). Since the meteorological conditions at the two sites were quite similar, it is presumably the amount of soil water above the wilting point that explains the difference in ET. In peatland forests, evapotranspiration is one of the key factors regulating the greenhouse gas dynamics. High ET rates maintain a low water table level, which in turn has important effects on soil microbial processes. The peat decomposition at Alkkia site may possibly have been enhanced due to the lower water table and thicker aerobic peat layer. Furthermore, the dry conditions may possibly have led to a lower assimilation and an increased needle litter production.

As the imbalance of ca. –840 g CO_2 m^{-2} a^{-1} between the NEE measured above the forest canopy and that measured using individual CO_2 fluxes suggests (Fig. 7), there were CO_2 flux components inside the Alkkia ecosystem that were not measured and accounted for. First of all, the annual net accumulation of CO_2 into tree biomass (–870 g CO_2 m^{-2} a^{-1}) was probably a low estimate of the actual tree biomass accumulation because fine roots were not included in the calculation. As was mentioned in the Material and methods section, the birch dry mass accumulation may also have been underestimated. However, tree growth was comparable to growth of Scots pine stands growing on mineral soil (Koivisto 1959). Possible pools for additional carbon fixation and accumulation, which were not measured in this study, were the ground vegetation biomass and belowground litter production. Substantial above- and below-ground litter production was reported by Laiho *et al.* (2003) in drained organic-soil pine forests. In general, data reporting the net uptake of the boreal forest understorey is scarce. Medlyn *et al.* (2005) estimated by means of modelling that the contribution of the ground vegetation to the annual NEP in a spruce forest in Sweden was 330 g CO_2 m^{-2} yr^{-1}. However, the soil type at their study site was a sandy podzolic glacial till. Kolari *et al.* (2006) measured the cumulative GPP of the understorey at the Hyytiälä site during the snowless period. The result, 480 g CO_2 m^{-2} a^{-1}, suggests that the NEP at Hyytiälä is probably much smaller than that in the Swedish site estimated by Medlyn *et al.* (2005). In order to gain a more reliable insight into the forest carbon balance of this ecosystem type, the different components of the carbon cycle, especially the net carbon accumulation into the ground vegetation and above- and below-ground litter, should be studied in more detail, particularly in peatland forests.

Comparison of CO_2 fluxes with other sites

Comparison with similar ecosystems is difficult, as published year-round eddy covariance data from any type of forested histosol croplands do not exist. Based on measurements and modelling, an undisturbed peatland in Scotland became

a sink of CO_2 about 4 years after its afforestation (Hargreaves *et al.* 2003). After 26 years, the upper limit of the annual forest CO_2 uptake rate was estimated to be about 1800 g m^{-2}. It was estimated that the annual peat decomposition rate was only about 370 g CO_2 m^{-2} a^{-1}, which is clearly less than that at our forest site, 1760 g CO_2 m^{-2} (Mäkiranta *et al.* 2007). This difference may be due to the different management history of the sites; in afforested agricultural organic soil the conditions favour microbial activity more than in a pristine peat soil, even 30 years after its afforestation.

The annual emission from this afforested organic-soil cropland was, however, smaller than that measured in an organic cropland still under cultivation. Spring barley growing on peat soil in southern Finland emitted 790 g CO_2 m^{-2} a^{-1}, whereas grass growing at the same site resulted in an emission of 290 g m^{-2} a^{-1} (Lohila *et al.* 2004). Despite the differences in site characteristics and measurement years, this result suggests that afforestation is a reliable means of reducing the climatic forcing caused by organic croplands, at least in the short run, when the fate of the carbon accumulated in the woody biomass is not accounted for. Afforestation of a cultivated histosol does not change the methane fluxes very much, because both of these drained land uses are small sinks of CH_4 from the atmosphere (Martikainen *et al.* 2002, Mäkiranta *et al.* 2007). The high N_2O emissions observed at afforested agricultural peatland sites (Maljanen *et al.* 2001a, Pihlatie *et al.* 2004, Mäkiranta *et al.* 2007), including our site, reflect the high level of microbial activity and mineralization. Afforestation does not seem to affect N_2O emissions very much, because the emission rates at Alkkia, over 30 years after afforestation, are of about the same magnitude as those observed for farmed peat soils. Obviously the climatic forcing due to N_2O from both cultivated (Regina *et al.* 2004) and afforested organic soils is very important.

An interesting comparison can be made between the Alkkia and Hyytiälä sites. The most profound difference between the sites is the underlying soil type; while the Alkkia site has a thick, drained peat layer with a lowered water table, the Hyytiälä soil type is haplic podzol and the soil material is coarse, silty, glacial till. According to the multiyear eddy covariance measurements there, the Hyytiälä forest has proved to be a sink of CO_2, with annual uptake rates varying approximately from –600 to –900 g CO_2 m^{-2} a^{-1} (Suni *et al.* 2003). Presumably the difference in annual balances between Alkkia and Hyytiälä can be largely explained with the absence of thick, aerobic peat layer at Hyytiälä.

During the high summer months, both the gross primary production and the total ecosystem respiration (estimated from the light-response curve according to the Eq. 2) were high at Alkkia when compared to the other peatland and forest ecosystems (Table 4). As compared with that at Hyytiälä, the high summer GPP_{1200} (gross primary production at full daylight, PPFD = 1200 μmol m^{-2} s^{-1}) was larger at Alkkia, which may be due to the abundant forest floor vegetation resulting from the agricultural past of the site. Both the winter and high summer respirations were greater at the Alkkia site than at Hyytiälä (Table 4), reflecting the high heterotrophic respiration of the thick peat layer with a lowered water table at the Alkkia Scots pine plantation. We can make the rough assumption that the difference between the Hyytiälä and Alkkia winter respiration, 0.017 mg m^{-2} s^{-1} (or 1.5 g m^{-2} d^{-1}), equals the magnitude of the winter peat oxidation rate at the Alkkia site. The direct chamber measurements of peat respiration at the site indeed support this result, giving a winter peat oxidation rate of 1.1 g m^{-2} d^{-1} (Mäkiranta *et al.* 2007).

Comparison with another Scots pine forest, Huhus, located in eastern Finland (Zha *et al.* 2004), supports the assumption that the soil type and condition strongly affect the annual CO_2 balance and the ecosystem gas exchange parameters. At Huhus the winter respiration and the high summer R_{tot} were markedly lower than at Alkkia (Table 4). Despite the much lower high summer GPP_{1200}, the annual balance at Huhus was negative, indicating a significant sink of CO_2 there. The LAI of the Scots pine at the Huhus site was 2, resembling that of Alkkia. Again, the dense forest floor vegetation at the Alkkia site probably explains the higher GPP_{1200} there.

The average winter respiration at Alkkia was also higher than that of an organic cropland at Jokioinen in southern Finland (Table 4). This difference might be related to the higher amount

of respiring biomass, such as trunks and roots, at Alkkia, since there was no significant difference in the soil temperature between these sites. At a natural subarctic *aapa* mire north of the Arctic Circle, the average winter respiration rate was much lower than at Alkkia (Table 4; Aurela 2005). This natural wetland was accumulating carbon in spite of the short growing season and low GPP_{1200}; this emphasizes the importance of respiration processes in the annual carbon balance of peatlands.

Conclusions

These first published year-round measurements of the CO_2 exchange above an afforested organic cropland show that the ecosystem is close to balance 30 years after the afforestation, i.e. the peat decomposition nearly equals the net C uptake by the vegetation. Leaching of C was not studied here. With the present data, however, it was impossible to estimate the interannual variability of the CO_2 exchange and to judge how representative the obtained result was in the long run. In order to reveal the effect of the longer-term weather conditions on the carbon balance, and to find out the source of the released carbon and the factors causing the imbalance in the fluxes, more measurements on NEE and on single C fluxes inside the ecosystem are needed. During the summer, the monthly evapotranspiration in the afforested organic-soil cropland exceeded the precipitation amount. It was also higher than that in a nearby Scots pine forest, the soil type of which was podzolic till, showing that the transpiration of the trees strongly controls the hydrological conditions in organic-soil forests. The effect of the water table dynamics on the GPP and respiration processes should be further studied in afforested peatland ecosystems. In comparing the annual NEE of cultivated and afforested organic croplands, it seems that the tree growth was able to compensate the C loss from the peat, at least during the first 30 years after the afforestation. However, over a longer time period, e.g. several rotations, the lifecycle of the timber removed from the site must be taken into account in the ecosystem NBP estimate. The afforested organic cropland is then, most probably, a source of CO_2.

Table 4. Winter respiration, high summer total respiration (R_{tot}) and gross primary production in full daylight (GPP_{1200}, PPFD = 1200 μmol m⁻² s⁻¹), and annual NEE and the high summer period used to calculate the respective CO_2 flux components in five different boreal ecosystems measured by the eddy covariance technique.

Site/Location in Finland	Soil type	Vegetation type	Winter respiration[1]	High summer R_{tot}[1]	High summer GPP_{1200}[1]	Annual NEE[2]	Reference: the high summer period
Jokioinen 61°N, 23°E/South	Cultivated histosol	Forage grass	0.015	0.24	–0.74	+290	Lohila et al. (2004): 29 June–16 July
Jokioinen 61°N, 23°E/South	Cultivated histosol	Spring barley	0.015	0.30	–0.95	+770	Lohila et al. (2004): 27 June–20 July
Alkkia 62°N, 23°E/West	Afforested histosol	Scots pine forest	0.036	0.30	–0.89	+50	This study: July–August 2003[3]
Kaamanen 69°N, 27°E/North	Flark fen histosol	Aapa mire vegetation	0.0055	0.08	–0.25	–80	Aurela et al. (2005): 20–29 July
Hyytiälä 62°N, 24°E/Central	Podzolic till	Scots pine forest	0.019	0.27	–0.80	–800	Markkanen et al. (2001): 16 °C < air temp < 18 °C
Huhus 63°N, 31°E/East	Sandy podzol	Scots pine forest	0.025	0.22	–0.47	–580	Zha et al. (2004): July (1999–2002)

[1] mg CO_2 m⁻² s⁻¹. [2] g CO_2 m⁻² a⁻¹. [3] no data from 18 July to 10 Aug. 2003.

References

Armentano T.V. & Menges E.S. 1986. Patterns of change in the carbon balance of organic soil — wetlands of the temperate zone. *J. Ecol.* 74: 755–774.

Aurela M. 2005. *Carbon dioxide exchange in subarctic ecosystems measured by a micrometeorological technique*. Finnish Meteorological Institute Contributions 51.

Aurela M., Tuovinen J.-P. & Laurila T. 2001. Net CO_2 exchange of a subarctic mountain birch ecosystem. *Theor. Appl. Climatol.* 70: 135–148.

Baldocchi D.D. 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global Change Biol.* 9: 479–492.

Eswaran H., Van Den Berg E. & Reich P. 1993. Organic carbon in soils of the world. *Soil Sci. Soc. Am. J.* 57: 192–194.

Finnish Meteorological Institute 1991. *Climatological Statistics in Finland 1961–1990, Supplement to the Meteorological Yearbook of Finland*.

Gorham E. 1991. Northern peatlands: Role in the carbon cycle and probable responses to climate warming. *Ecol. Appl.* 1: 182–195.

Hargreaves K.J., Milne R. & Cannell M.G.R. 2003. Carbon balance of afforested peatland in Scotland. *Forestry* 76: 299–317.

Heinonen J. 1994. Koealojen puu- ja puustotunnusten laskentaohjelma KPL. Käyttöohje. *Metsäntutkimuslaitoksen tiedonantoja* 504: 1–80.

Kasimir-Klemedtsson Å., Klemedtsson L., Berglund K., Martikainen P., Silvola J. & Oenema O. 1997. Greenhouse gas emissions from farmed organic soils: a review. *Soil Use Manage.* 13: 245–250.

Koivisto P. 1959. Kasvu- ja tuottotaulukoita. *Communicationes Instituti Forestalis Fenniae* 51: 1–44.

Kolari P., Pumpanen J., Kulmala L., Ilvesniemi H., Nikinmaa E., Grönholm T. & Hari P. 2006. Forest floor vegetation plays an important role in photosynthetic production of boreal forests. *For. Ecol. Manage.* 221: 241–258.

Laiho R., Vasander H., Penttilä T. & Laine J. 2003. Dynamics of plant-mediated organic matter and nutrient cycling following water-level drawdown in boreal peatlands. *Global Biogeochem. Cycles* 17(2), 1053, doi:10.1029/2002GB002015.

Lohila A., Aurela M., Regina K. & Laurila T. 2003. Soil and total ecosystem respiration in agricultural fields: Effect of soil and crop type. *Plant Soil* 251: 303–317.

Lohila A., Aurela M., Tuovinen J.-P. & Laurila T. 2004. Annual CO_2 exchange of a peat field growing spring barley or perennial forage grass. *J. Geophys. Res.* 109(D18116), doi:10.1029/2004JD004715.

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

Mäkiranta P., Hytönen J., Aro L., Maljanen M., Pihlatie M., Potila H., Shurpali N.J., Laine J., Lohila A., Martikainen P.J. & Minkkinen K. 2007. Soil greenhouse gas emissions from afforested organic soil croplands and cutaway peatlands. *Boreal Env. Res.* 12: 159–175.

Maljanen M., Hytönen J. & Martikainen P.J. 2001a. Fluxes of N_2O, CH_4 and CO_2 on afforested boreal agricultural soils. *Plant Soil.* 231: 113–121.

Maljanen M., Martikainen P.J., Walden J. & Silvola J. 2001b. CO_2 exchange in an organic field growing barley or grass in eastern Finland. *Global Change Biol.* 7: 679–692.

Markkanen T., Rannik Ü., Keronen P., Suni T. & Vesala T. 2001. Eddy covariance fluxes over a boreal Scots pine forest. *Boreal Env. Res.* 6: 65–78.

Marklund L.G. 1988. *Biomass functions for pine, spruce and birch in Sweden*. Swedish University of Agricultural Sciences, Department of Forest Survey, Report 45. [In Swedish with English summary].

Martikainen P.J., Nykänen H., Crill P. & Silvola J. 1993. Effect of a lowered water table on nitrous oxide fluxes from northern peatlands. *Nature* 366: 51–53.

Martikainen P.J., Regina K., Syväsalo E., Laurila T., Lohila A., Aurela M., Silvola J., Kettunen R., Saarnio S., Koponen H., Jaakkola T., Pärnä A., Silvennoinen H., Lehtonen H., Peltola J., Sinkkonen M. & Esala M. 2002. Agricultural soils as sinks and sources of greenhouse gases: A research consortium (AGROGAS). In: Käyhkö J. & Talve L. (eds.), *Understanding the global system, the Finnish perspective*, Painosalama, Turku, pp. 55–68.

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

Medlyn B.E., Berbigier P., Clement R., Grelle A., Loustau D., Linder S., Wingate L., Jarvis P.G., Sigurdsson B.D. & McMurtrie R.D. 2005. The carbon balance of coniferous forests growing in contrasting climatic conditions: a model-based analysis. *Agric. For. Met.* 131: 97–124.

Minkkinen K. & Laine J. 1998a. Long-term effects of forest drainage on the peat carbon stores of pine mires in Finland. *Can. J. For. Res.* 28: 1267–1275.

Minkkinen K. & Laine J. 1998b. Effect of forest drainage on the peat bulk density of pine mires in Finland. *Can. J. For. Res.* 28: 178–186.

Minkkinen K., Vasander H., Jauhiainen S., Karsisto M. & Laine J. 1999. Post-drainage changes in vegetation composition and carbon balance in Lakkasuo mire, Central Finland. *Plant Soil* 207: 107–120.

Myllys M. & Sinkkonen M. 2004. The area and distribution of cultivated peat soils in Finland. *Suo* 55: 53–60. [In Finnish with English summary].

Nykänen H., Alm J., Lång K., Silvola J. & Martikainen P.J. 1995. Emissions of CH$_4$, N$_2$O and CO$_2$ from a virgin fen and a fen drained for grassland in Finland. *J. Biogeography* 22: 351–357.

Penman J., Gytarsky M., Hiraishi T., Krug T., Kruger D., Pipatti R., Buendia L., Miwa K., Ngara T., Tanabe K. & Wagner F. (eds.) 2003. *Good practice guidance for land use, land-use change and forestry*. Published for the IPCC by the Institute for Global Environmental Strategies, Hayama, Japan.

Pihlatie M., Rinne J., Lohila A., Laurila T., Aro L. & Vesala T. 2004. Nitrous oxide emissions from an afforested peat soil using eddy covariance and enclosure techniques. In: Päivänen J. (ed.), *Wise use of peatlands*, *Proceedings of the 12th International Peat Congress*, vol. 2, International Peat Society, Jyväskylä, pp. 1010–1014.

Regina K., Syväsalo E., Hannukkala A. & Esala M. 2004. Fluxes of N$_2$O from farmed peat soils in Finland. *Eur. J. Soil Sci.* 55: 591–599.

Sampson N.L. & Scholes R.J. 2000. Additional human-induced activities. In: Watson R.T., Noble I.R., Bolin B., Ravindranath N.H., Verardo D.J. & Dokken D.J. (eds.), *Land use, land use change and forestry*, Cambridge University Press, pp. 181–281.

Schulze E.-D., Valentini R. & Sanz M.-J. 2002. The long way from Kyoto to Marrakesh: Implications of the Kyoto Protocol negotiations for global ecology. *Global Change Biol.* 8: 505–518.

Solantie R. 1990. *The climate of Finland in relation to its hydrology, ecology and culture*. Finnish Meteorological Institute Contributions 2.

Suni T, Rinne J., Reissell A., Altimir N., Keronen P., Rannik Ü., Dal Maso M., Kulmala M. & Vesala T. 2003. Long-term measurements of surface fluxes above a Scots pine forest in Hyytiälä, southern Finland, 1996–2001. *Boreal Env. Res.* 8: 287–301.

Zha T., Kellomäki S., Wang K.-Y. & Rouvinen I. 2004. Carbon sequestration and ecosystem respiration for 4 years in a Scots pine forest. *Global Change Biol.* 10: 1492–1503.