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CARBON DIOXIDE EXCHANGE IN SUBARCTIC ECOSYSTEMS MEASURED BY A MICROMETEOROLOGICAL TECHNIQUE

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ACADEMIC DISSERTATION in meteorology

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Abstract

The atmospheric CO_2 concentration and the surface air temperatures have increased since the pre-industrial era, and the increase in both is predicted to continue during the 21st century. The feedback mechanisms between the changing climate and the carbon cycle are complex, and more information is needed about carbon exchange in different ecosystems. Northern Finland lies in the transition zone between boreal forest and tundra where the ecosystems are especially sensitive to any changes in the climate. In 1995–2004, micrometeorological eddy covariance measurements were conducted to yield continuous data on the CO_2 exchange between the atmosphere and the biosphere in northern Finland on four different ecosystems: an aapa mire, a mountain birch forest, a Scots pine forest and a Norway spruce forest. A measurement system enabling year-round measurements in the harsh subarctic conditions was developed and shown to be suitable for long-term exchange studies. A comparison of the CO_2 flux components, photosynthesis and respiration, at different ecosystems in the European subarctic and arctic regions showed that the leaf area index (LAI) is the key determinant of the gross photosynthetic rates, explaining greatest part of the variation between these ecosystems. Respiration did not show such a strong correlation with LAI, but in general, high respiration rates were related to high values of LAI. The first continuous round-the-year measurements of net ecosystem CO_2 exchange on a subarctic wetland were conducted at Kaamanen. The winter-time CO_2 efflux (of about 90 g CO_2 m^{-2} yr^{-1}) was shown to constitute an essential part of the annual CO_2 balance (of -79 g CO_2 m^{-2} yr^{-1} in 1997–2002). The annual CO_2 balances at all sites in northern Finland were relatively small compared with those in lower latitudes. The interannual variation of the CO_2 balance at Kaamanen was marked (-15 to -195 g CO_2 m^{-2} yr^{-1}) during the years 1997–2002. The most important factor determining this variation was the timing of the snow melt and the related temperatures. A warm spring and an early start to the growing season lead to a greater annual CO_2 sink term. The hydrometeorological conditions during the growing season had only a minor effect on the annual balances. These results suggest that the predicted climate warming would benefit rather than threaten the carbon pool in such northern wetlands.

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Mikrometeorologisia mittauksia subarktisten ekosysteemien hiilidioksidivaihdosta

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Tiivistelmä

Ilmakehän hiilidioksidipitoisuus ja ilman pintalämpötila ovat kohonneet esiteollisesta ajasta lähtien, ja tämän kehityksen uskotaan jatkuvan myös tulevaisuudessa. Takaisinkytkentämekanismit muuttuvan ilmaston ja hiilen kierron välillä ovat monimutkaisia, minkä vuoksi tarvitaan lisää tietoa ilmakehän ja eri ekosysteemien välisestä hiilivaihdosta. Pohjois-Suomi sijaitsee kahden kasvillisuusvyöhykkeen, boreaalisen metsän ja tundran, välissä. Tällaisella siirtymäalueella ekosysteemit ovat erityisen herkkiä ympäristötekijöiden muutoksille. Ilmakehän ja biosfäärin välistä CO_2-vaihtoa mitattiin mikrometeorologisella kovarianssimenetelmällä vuosina 1995–2004 neljässä pohjoissuomalaisessa ekosysteemissä (aapasuo, tunturikoivumetsä, mäntymetsä ja kuusimetsä). Työssä käytetty, ympärivuotisen mittauksen mahdollistava mittausjärjestelmä osoittautui toimivaksi subarktisissa oloissa. Kovarianssimenetelmällä mitattava CO_2-vuo koostuu kahdesta vastakkaisesta komponentista, hiilidioksidin sidonnasta biosfääriin (fotosynteesi) ja sen vapautumisesta takaisin ilmakehään (respiraatio). Näitä komponentteja ja niiden ympäristövasteita verrattiin eri ekosysteemeissä subarktisella ja arktisella alueella. Lehtipinta-ala (LAI) osoittautui keskeiseksi ekosysteemien välisen yhteytyskyvyn vaihtelun selittäjäksi. Respiraatiossa ei havaittu yhtä vahvaa korrelaatiota, mutta keskimäärin suuret respiraatiovuot liittyivät kuitenkin suuriin LAI-arvoihin. Ensimmäinen jatkuvatoiminen, ympärivuotinen CO_2-vuomittaus subarktisella suolla Kaamasessa osoitti talviajan respiraation (noin 90 g CO_2 m^{-2} yr^{-1}) muodostavan merkittävän osan suon vuositaseesta (-79 g CO_2 m^{-2} yr^{-1} vuosina 1997–2002). Hiilidioksidin vuositaseet olivat kaikilla Pohjois-Suomen mittauspaikoilla suhteellisen pieniä eteläisempien ekosysteemien taseisiin verrattuna. Vuosien välinen vaihtelu Kaamasessa oli merkittävää (-15 – -195 g CO_2 m^{-2} yr^{-1}). Tärkein yksittäinen vuositaseeseen vaikuttava tekijä oli lumen sulamisaika ja siihen liittyvä ilman lämpötila; lämmin kevät ja aikainen kasvukauden alku johtavat voimakkaaseen hiilidioksidin sidontaan myös vuositasolla. Hydrometeorologisilla olosuhteilla kasvukauden aikana oli vähäisempi vaikutus vuositaseeseen. Näiden tulosten mukaan ilmaston lämpeneminen edistäisi hiilen sidontaa tutkitun kaltaisilla pohjoisilla soilla.

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Definitions

Eddy covariance (EC)	A micrometeorological method for measuring mass and energy exchange between the atmosphere and the biosphere
Global warming potential (GWP)	A measure of the radiative warming effect of a given substance relative to that of CO_2 integrated over a specified time horizon
Leaf area index (LAI)	A unitless measure of the surface area of leaves per unit ground area, in this work defined as one-sided or projected area
Photosynthetic photon flux density (PPFD)	The incident photon flux density in the 0.4–0.7 μm waveband
Phytomass index (PI)	An empirical measure of the photosynthetic capacity of the ecosystem

Mire is a general term for the peat-forming wetlands, which may be divided into bogs and fens. On **bogs** the peat accumulation is usually dominated by mosses. Bogs receive water and nutrients only as direct precipitation, which leads to a low pH and low nutrient levels. On **fens** the peat accumulation is typically dominated by sedges and shrubs. Fens receive water and nutrients both from precipitation and the surrounding mineral soils, and have a higher pH and a moderate-to-high nutrient level. **Aapa mire** is a patterned wetland complex with dry **strings** (ridges of peat or hummocks) alternating with wet **pools** (flarks or hollows). The pools are typically covered with sedges and have the characteristics of a fen, while the strings may act more as bogs.

Carbon dioxide exchange, or the **net ecosystem CO_2 exchange** (**NEE**), refers to the exchange of CO_2 between the atmosphere and the biosphere. In this study this exchange is measured as the vertical mass flux density (in the text referred to as the **CO_2 flux**) using the EC method. According to the micrometeorological convention the fluxes from the biosphere to the atmosphere are positive. These positive fluxes are sometimes called **respiration (R)** or **efflux** to emphasize the outflow of CO_2 from the biosphere. Strictly speaking, respiration refers to the biological processes producing CO_2 and thus slightly differs from the efflux observed above ground. **Gross photosynthesis (GP)** is the negative component of the CO_2 flux, which is not measurable with the EC method, but is separated from the total flux by modelling. **Maximal gross photosynthesis (GP_{max})** is a model parameter describing the light-saturated gross photosynthetic capacity of the ecosystem. **Carbon dioxide balance** is another term for the net exchange of CO_2, but it is typically used in the context of a longer period (day, week, month, year), whereas the former terms are used for short-term (e.g., 30-min) averages. For the balances, the sign convention is the same as for the short-term fluxes, and the **sink** and **source** terms mean downward and upward net fluxes, respectively.

Contents

List of publications

This thesis consists of an introductory review, followed by six research articles. The papers are reproduced with the kind permission of the journals concerned.

I Aurela, M., Tuovinen, J.-P., and Laurila, T., 1998. Carbon dioxide exchange in a subarctic peatland ecosystem in northern Europe measured by the eddy covariance technique. *Journal of Geophysical Research*, *103*, 11289–11301.

II Aurela, M., Laurila, T., and Tuovinen, J.-P., 2001. Seasonal CO_2 balances of a subarctic mire. *Journal of Geophysical Research, 106,* 1623–1638.

III Aurela, M., Tuovinen, J.-P., and Laurila, T., 2001. Net CO_2 exchange of a subarctic mountain birch ecosystem. *Theoretical and Applied Climatology, 70,* 135–148.

IV Laurila, T., Soegaard, H., Lloyd, C. R., Aurela, M., Tuovinen, J.-P., and Nordstroem, C., 2001. Seasonal variations of net CO_2 exchange in European Arctic ecosystems. *Theoretical and Applied Climatology*, *70,* 183–201.

V Aurela, M., Laurila, T., and Tuovinen, J.-P., 2002. Annual CO_2 balance of a subarctic fen in northern Europe: Importance of the winter-time efflux. *Journal of Geophysical Research*, *107*, 4607, doi: 10.1029/2002JD002055.

VI Aurela, M., Laurila, T., and Tuovinen, J.-P., 2004. The timing of snow melt controls the annual CO_2 balance in a subarctic fen. *Geophysical Research Letter*, *31,* L16119, doi: 10.1029/2004GL020315.

Author's contribution

Papers I, II, III, V and VI: The author of this thesis was responsible for setting up and conducting the field measurements and for the data analysis, and bore the main responsibility for writing the papers. He participated in the development of the data acquisition programs and the post-processing procedures that are used throughout this work.

Paper IV: The author prepared all the figures and was responsible for the related data analysis. He was involved in the interpretation of the results and the writing of the paper.

Review of the papers

Paper I covers a one-month measurement campaign at the Kaamanen fen (11 August – 15 September 1995). In retrospect, the main outcome of the paper was the description and analysis of the measurement technique (e.g., spectral analysis) and measurement site (e.g., footprint considerations). The first version of the gap-filling model used throughout this work was presented.

Paper II presents a six-month measurement period at Kaamanen including the growing season in 1997. The main interest was in CO_2 fluxes, but some energy balance considerations were also included. The CO_2 analysis focuses on seasonal variations. A detailed description of the gap-filling model was presented. The model included a new feature, the phytomass index. By using the modelled winter-time fluxes, the first estimate of an annual balance was presented.

Paper III reports the growing season CO_2 flux measurements on a mountain birch forest at Petsikko in 1996. The CO_2 exchange model was operated on daily mean values in estimating the growing season balances for 15 years (1984–1998) in order to examine the representativeness of the one-year measurements.

Paper IV compares the CO_2 fluxes of various ecosystems in subarctic and arctic Europe. The maximum gross photosynthetic and respiration rates were analyzed during the peak summer period, and the diurnal CO_2 cycles were studied during different seasons.

Paper V presents the first continuous round-the-year CO_2 flux measurements on subarctic wetlands. Special emphasis was placed on the winter-time respiration and the mechanisms behind it. The carbon balances during different seasons were compared and their influence on the annual balance was considered. A detailed error analysis was performed on the CO_2 annual balance.

Paper VI reports the first continuous multi-year measurements of the CO_2 exchange on a subarctic fen. The annual CO_2 balances during the six years 1997–2002 were presented, and the factors behind the interannual variability were explored using correlation analysis. The climatic responses of the carbon balance variations were considered.

1. Introduction

The atmospheric CO_2 concentration has increased since the pre-industrial era by almost 100 ppm, and it continues increasing at a present rate of 1.5 ppm yr^{-1}, mainly due to anthropogenic emissions (IPCC, 2001a). During the same period the global average surface temperature has increased by 0.6 °C, and the predictions for future warming over the period 1990–2100 range between 1.4–5.8 °C (IPCC, 2001a). The regional variations for both observed and predicted warming are marked, but in Finland the rates are close to the global estimates (Tuomenvirta, 2004; Jylhä *et al.*, 2004). The predicted global warming is likely to alter the distribution and functioning of different ecosystems, but the feedback mechanisms between the changing climate and the carbon cycling are complex, and more information about carbon exchange and its climate responses is required (IPCC, 2001b; Callaghan *et al.*, 2004b).

Northern Finland lies in the transition zone between two major vegetation zones, boreal forest and tundra (Seppä, 1996). It contains the tree lines of various tree species (spruce, pine and birch) (Seppä, 1996) and also the southern border of the permafrost region (King and Seppälä, 1987). The ecosystems in such a transition zone are sensitive to changes in the climate, and the warming has been predicted to be especially great at these high latitudes (IPCC, 2001b; Callaghan *et al.*, 2004b). Wetlands are common in northern Finland, covering about 30% of the total area (Lappalainen, 1996). Globally, the northern peatlands contain 20–30% of the total terrestrial organic carbon, thus constituting a significant carbon reservoir accumulated during the Holocene (e.g., Gorham, 1991; Turunen *et al.*, 2002).

In order to better understand the carbon budget of the northern ecosystems, long-term measurements of the CO_2 exchange are needed. The micrometeorological eddy covariance method enables such long-term balance measurements on an ecosystem scale, providing direct information on the CO_2 exchange between the atmosphere and the ecosystem (Baldocchi, 2003). These measurements, relying on fast observations of vertical wind and CO_2 concentration, have become common during the most recent decade, and there have been various extensive research projects on CO_2 exchange in different ecosystems and in different areas in Europe (e.g., CARBOEUROFLUX, CARBOMONT, GREENGRASS), mainly funded by the European Union (EU). Together with similar projects conducted on other continents (e.g., AMERIFLUX, FLUXNET-CANADA, ASIAFLUX), these projects form a global network of micrometeorological measurements, FLUXNET (Baldocchi *et al.*, 2001).

This work describes the CO_2 flux measurements conducted in four different ecosystems in northern Finland during the years 1995–2004. The CO_2 and supporting momentum and sensible and latent heat fluxes were measured using the eddy covariance method. The main focus of the study is on a six-year dataset collected on a subarctice wetland.

The additional sites cover the most important forest ecosystems of northern Finland: mountain birch, Scots pine and Norway spruce. The measurements have been part of three EU projects: LAPP, CARBOEUROFLUX and CARBOEUROPE-IP.

The aims of this work were

- to develop a measurement system that enables continuous year-round measurements in difficult conditions in subarctic Finland, and to develop analysis methods and tools for collecting and further processing the flux data measured;

- to assess the environmental responses of the CO_2 exchange to different meteorological and hydrological factors and to evaluate their differences between the most common northern ecosystems;

- to determine the carbon balance of different ecosystems on daily, weekly, monthly and annual timescales;

- to evaluate the factors behind the interannual variability of the CO_2 exchange on a subarctic wetland.

This introductory review first presents the theoretical background of eddy covariance measurements, and considers the problems and error sources of the method (Chapter 2). Chapter 3 introduces the measurement sites and the measurement systems used throughout this work. The main results of the included research articles are reviewed in Chapter 4. Some new data from two coniferous forests are included in the study in order to broaden the scope of the work and to better cover the major ecosystems in northern Finland.

2. Micrometeorological theory

2.1 Atmospheric boundary layer

The troposphere may be divided into two parts, the atmospheric boundary layer (ABL) close to the earth’s surface and the free atmosphere above it (Stull, 1988; Kaimal and Finnigan, 1994). The ABL is defined as the part of the troposphere that is directly influenced by the earth’s surface and responds to surface forcing within a timescale of an hour. This surface forcing (friction and heating) induces vertical mixing of the horizontal flow, resulting in a three-dimensional swirling motion on different size scales that effectively mixes the air in the ABL. These swirls are often called turbulent eddies.

The existence of turbulence is another way of defining the ABL. In the free troposphere the turbulence is absent or it is significantly weaker than in the ABL.

The height of the ABL varies from 0.1 to 2 km, depending mainly on the atmospheric stability (Stull, 1988; Kaimal and Finnigan, 1994). During summer days with solar radiation heating the surface, the boundary layer is unstable and vigorous convection mixes the air. In such conditions the height of the ABL is typically 1–2 km. During the night the surface cools down and the ABL becomes stable, suppressing the turbulence. In a stable ABL, weak turbulence may be developed by wind shear. The situation is similar in winter-time, particularly above snow.

Turbulent mixing is an important transport mechanism for energy and matter in the vertical direction, in which the mean wind component is typically small compared with the turbulent one (Stull, 1988; Kaimal and Finnigan, 1994). In the lowest part of the boundary layer the turbulent fluxes vary only little vertically. This layer is called the surface layer (SL) or the constant flux layer. The height of the SL varies correspondingly with the variations in the ABL, having a height of approximately 10% of the ABL height. The vertical invariability of the fluxes means that a flux measured at an arbitrary height inside the SL equals that at the surface. This feature is utilized in different micrometeorological techniques developed for surface flux measurements.

2.2 Micrometeorological measurement techniques

Micrometeorology is concerned with atmospheric processes near the ground at scales from tens of metres up to several kilometres and from fractions of a second to hours. Micrometeorological measurements provide methods for analyzing the characteristics of turbulence and for measuring turbulent fluxes in the surface layer. The turbulent vertical flux of a constituent measured at some height above the surface represents the exchange between the atmosphere and the surface over a larger area upwind of the measurement mast. This source area is called the footprint (e.g., Schmid, 2002). The size of the footprint depends mainly on the atmospheric stability, measurement height, surface roughness and the canopy structure. At a low measurement height (2–3 m), 80% of the flux may originate from within the nearest 100 m, but at a higher measurement level (20–30 m) the corresponding area may extend to several kilometres, especially in stable conditions (Schmid, 1994; Rannik *et al.*, 2000).

The most direct micrometeorological method is the eddy covariance (EC) technique. In this technique the vertical flux of a scalar constituent is obtained as (e.g., Baldocchi, 2003)

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

where w is the vertical wind speed and c is the quantity of interest (e.g., temperature, humidity or gas concentration). The overbar denotes the time average, and a prime denotes the fluctuation of an instantaneous value from this average, e.g.,

$$w' = \overline{w} - w. \tag{2}$$

With the eddy covariance technique the measurements are carried out using fast-response instruments sampled typically at 10–20 Hz in order to cover the entire frequency range of turbulent variations. For CO_2 flux such measurements are feasible using a sonic anemometer and a fast infrared gas analyzer. In a typical CO_2 exchange study setup, the fluxes of sensible and latent heat, momentum and CO_2 are nowadays predominantly measured using the eddy covariance technique (Baldocchi, 2003; Aubinet *et al.*, 2000).

For many chemical compounds of ecological interest, fast-response instruments either do not exist at all, or are expensive and possibly laborious to operate (e.g., for CH_4, NO_2, O_3 or volatile organic compounds). The fluxes of these constituents may be measured by alternative, more indirect, methods that allow for slower instruments (Fowler *et al.*, 2001). With the aerodynamic gradient and Bowen ratio methods, the concentration is measured at different heights and the vertical flux is derived from this profile and some additional information on the state of the surface layer. This information may be obtained by measuring simultaneously the profiles of temperature and wind speed, but it is also possible to complete the gradient measurement with turbulence measurements using a fast sonic anemometer/thermometer (e.g., Rinne *et al.*, 2000).

The combination of a fast sonic anemometer and a slow gas analyzer is also utilized in the relaxed eddy accumulation (REA) and the disjunct eddy covariance (DEC) methods. In the REA method the air sample is collected in two reservoirs depending on the direction of the vertical wind. These two samples are analyzed afterwards and the vertical flux is estimated from the concentration difference between the upward and downward samples (Businger and Oncley, 1990). In the DEC method the flux is calculated similarly to the EC method as the covariance of w and c, but instead of the time average of a continuous time series, an ensemble average of short separate samples with time intervals of 1 to 30 s is used (Rinne *et al.*, 2001).

The main advantage of micrometeorological methods over the alternative enclosure methods is their ability to continuously measure the surface exchange of matter and energy. This makes it possible to study both the short-term variations (e.g., diurnal cycle) and the long-term balances. The micrometeorological measurements do not disturb the surface under investigation and provide fluxes on an ecosystem scale, thus avoiding the difficult up-scaling problems. The markedly smaller target area of chamber measurements, however, enables a spatially detailed study on different components of the ecosystem, which could complement the micrometeorological measurements (e.g., Fowler *et al.*, 2001).

2.3 Eddy covariance method in theory

Eddy covariance measurements provide us with the vertical turbulent flux at the measurement point. However, we are typically interested in the exchange between the ecosystem and the atmosphere. The assumption that these two fluxes are equal is correct in ideal conditions, but in practice they may differ. The factors behind the difference may be studied by investigating the law of conservation of mass (e.g., Stull, 1988)

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial u\rho_s}{\partial x} + \frac{\partial v\rho_s}{\partial y} + \frac{\partial w\rho_s}{\partial z} = S\,, \tag{3}$$

where ρ_s is the scalar density, S is the sink/source term and u, v and w are the wind velocity components in the x, y and z directions of a rectangular coordinate frame, respectively.

Molecular diffusion is significant only in the molecular sublayer, within the first centimetre of the surface (Stull, 1988). In this examination, the molecular sublayer is considered as part of the surface and is thus included in the sink/source term. Using the Reynolds decomposition (e.g., Garratt, 1992), the instantaneous values of u, v, w and ρ_s are divided into an average and a fluctuation (Eq. 2). Averaging over time and assuming that air is incompressible, we obtain

$$\underset{\text{I}}{\frac{\partial \overline{\rho_s}}{\partial t}} + \underbrace{\overline{u}\frac{\partial \overline{\rho_s}}{\partial x} + \overline{v}\frac{\partial \overline{\rho_s}}{\partial y}}_{\text{II}} + \underset{\text{III}}{\overline{w}\frac{\partial \overline{\rho_s}}{\partial z}} + \underbrace{\frac{\partial \overline{u'\rho_s'}}{\partial x} + \frac{\partial \overline{v'\rho_s'}}{\partial y}}_{\text{IV}} + \underset{\text{V}}{\frac{\partial \overline{w'\rho_s'}}{\partial z}} = \underset{\text{VI}}{S}\;, \tag{4}$$

where I represents the temporal variation of ρ_s, II and III are the horizontal and vertical advective fluxes of ρ_s, respectively, IV and V are the horizontal and vertical flux divergences, respectively, and VI represents the sources and sinks of the constituent. The horizontal flux divergence (IV) is significantly smaller than the vertical flux divergence (V) and may be neglected (Finnigan, 1999). By integrating from the surface ($z = 0$) to the measurement height ($z = z_m$) and setting $\overline{w'\rho_s'} = 0$ at the surface we obtain

$$\underset{\text{V}}{\overline{w'\rho_s'}_{z=z_m}} = \underset{\text{VI}}{\int_0^{z_m} S dz} - \underset{\text{I}}{\int_0^{z_m} \frac{\partial \overline{\rho_s}}{\partial t} dz} - \underbrace{\int_0^{z_m} \overline{u}\frac{\partial \overline{\rho_s}}{\partial x} dz - \int_0^{z_m} \overline{v}\frac{\partial \overline{\rho_s}}{\partial y} dz}_{\text{II}} - \underset{\text{III}}{\int_0^{z_m} \overline{w}\frac{\partial \overline{\rho_s}}{\partial z} dz}\,. \tag{5}$$

The assumptions made above are usually valid, and are generally believed to cause no significant error in using the EC method (Aubinet *et al.*, 2000; Finnigan, 1999). The stationarity and the horizontal homogeneity are additional assumptions that are usually stated as prerequisites for eddy covariance measurements. Under such ideal conditions the storage term (I) and the horizontal advection term (II) are negligible. The mean vertical wind speed is typically small, especially above short vegetation, and it may be assumed that the vertical advection term (III) also vanishes. Under these conditions the turbulent flux that we obtain from the EC measurements at a height z_m would equal the integrated sources and sinks below the measurement height. In the case of CO_2 fluxes, we often define this as the net ecosystem CO_2 exchange (NEE) (Aubinet *et al.*, 2000)

$$\overline{w'\rho_s'}_{z=z_m} = \int_0^{z_m} S dz = NEE \,, \qquad (6)$$

where the source term includes the soil respiration.

2.4 Eddy covariance method in practice

2.4.1 *Night-time problems*

Ideal conditions do not always exist in the surface layer, and it is important to be aware of the possible influences of terms I, II and III in Eq. 5. Problems occur especially during the night (Katul *et al*., 2004), and these are emphasized when measuring above high vegetation (Lee, 1998). During calm nights, the surface layer becomes stable and turbulence is suppressed. The CO_2 efflux from soil and plants continues at a constant rate, but due to the damped turbulence, all the CO_2 is not transported up to the measurement level but accumulates in the air layer close to the surface. In such a situation, the turbulent flux observed at the measurement height is smaller than the ongoing exchange between the ecosystem and the atmosphere (Aubinet *et al*., 2000). Eq. 6 is thus not valid due to a non-zero storage term (VI) in Eq. 5. In the morning, during the awakening turbulence, the opposite phenomenon occurs as the CO_2-rich air is transported to the measurement level. The turbulent flux observed by the EC system is then greater than the actual NEE at that time, and this should be compensated by a negative storage term in Eq. 5. The storage term may be estimated by measuring the CO_2 concentration changes in the air space below the measurement height, typically at a few levels inside and above the canopy (Aubinet *et al*., 2000).

The CO_2 accumulation is not the only problem during stable nights. Even if the storage term were adequately taken into account, the observed fluxes may be found to correlate with the wind speed or more exactly with the friction velocity (u_*), which is a turbulent velocity scale and can be understood as a measure of the turbulence intensity (Stull, 1988). The respiration process itself should not depend on turbulence, although during strong winds the pressure pumping effect may accelerate the ventilation of CO_2 from soil pores (Massman *et al*., 1997). It seems probable that there are some additional, non-turbulent, processes removing CO_2 from the air layer below the measurement height either vertically or horizontally. Various transport mechanisms have been suggested as being possible in the stably-stratified surface layer, e.g., vertical and horizontal advection, slow diffusion or intermittent turbulence not detected by standard EC measurements (Aubinet *et al.*, 2000).

These problems are aggravated in measurements above a complex terrain (Kaimal and Finnigan, 1994). Horizontal heterogeneity of the surface may lead to horizontal advection (term II). Sloping terrain induces a non-zero mean vertical wind and thus vertical advection (term III). Slopes may also cause drainage of cool CO_2-rich air during stable nights and thus horizontal advection (term II). Whereas it is relatively easy to take the storage term into account, measuring the vertical and horizontal advection is difficult and indeed presently infeasible as a routine measurement (Aubinet *et al.*, 2005).

A widely-used solution for the night-time problem is to replace the EC observations during calm situations with estimates based on measurements during acceptable conditions. There are various methods for filling the gaps (Aubinet *et al.*, 2004). Empirical methods like look-up tables, nonlinear regressions or mean diurnal variation (Falge *et al.*, 2001) are all widely used. New methods based on a statistical approach have also been suggested, e.g., Artificial Neural Networks (Papale and Valentini, 2003) and Multiple Imputation (Hui *et al*., 2004).

2.4.2 *Coordinate rotation*

A sloping terrain or a misalignment (tilt) of the sonic anemometer will induce a non-zero mean vertical wind component (term III in Eq. 5), if the coordinate system is defined along the geopotential field (Wilczak *et al*., 2001; Finnigan *et al*., 2003). These disturbances in the *w* values are usually taken into account by rotating the coordinate system to coincide with the local streamline. Traditionally a double rotation, in which the coordinate system is rotated around the *z*-axis ($\overline{v} = 0$) and around the *y*-axis ($\overline{w} = 0$), is performed for every averaging period (e.g., 30-min). Recently, it has been suggested that a more appropriate practice would be the determination of a fixed plane for the site over a longer period (e.g., a few months). In this planar fit method, the mean vertical wind component is thus allowed to have non-zero values during individual 30-min periods, but it averages to zero during the longer period (Wilczak *et al*., 2001).

2.4.3 *Frequency range of turbulent variations*

In addition to the problems of an imperfect turbulent field, uncertainties also arise because of imperfect instrumentation. Turbulence transports CO_2 over a wide frequency range extending from approximately 0.001 to 10 Hz. In order to measure the total turbulent flux, this whole range should be covered. The response times of present sonic anemometers are satisfactory, but gas analyzers are typically slower. Even if the response time of the instrument were adequate, there are other factors that tend to limit the overall performance of the EC system (e.g., Massman and Clement, 2004). With closed-path systems, the attenuation of the concentration in the inlet tube is a potential problem, especially with long tubes. The sensor separation between the sonic anemometer and the gas analyzer and the line averaging on the measurement path of the instruments also disturb the signal. All these factors lengthen the effective response time of the EC system leading to a flux loss. However, if we can estimate this effect for the different frequencies of the flux spectrum, we can correct for the underestimated flux. This is traditionally carried out according to the theoretical co-spectra and separate transfer functions (Moore, 1986). Nowadays a practically un-attenuated reference co-spectrum is more commonly taken from the simultaneous heat flux measurements, which are assumed perfect (e.g., Aubinet *et al.*, 2000, Massman and Lee, 2002).

At low frequencies, the problem is less specific. The measured EC flux should cover the whole turbulence spectrum, but exclude the slow background variations (Moncrieff *et al.*, 2004). However, those two cannot be distinguished from each other in a unique way (Sakai and Fitzjarrald, 2001). The frequency range included in the measured flux is determined by the mean removal method and averaging period. The commonly employed methods, the recursive mean filter, linear detrending and block averaging, are typically used with a 30-min averaging period (e.g., Baldocchi, 2003; Aubinet *et al.*, 2000). If a part of the relevant frequencies are attenuated due to the averaging, the loss can be compensated for by spectral corrections similar to those for high frequencies (Moore, 1986).

2.4.4 *Density fluctuations*

Another instrument-related problem is caused by density fluctuations in the air. The infrared gas analyzers used for CO_2 measurements basically detect the molar density of CO_2. The molar density is affected not only by the number of CO_2 molecules in the air sample but also by the density of that sample. The air density fluctuates due to variations in the temperature and in the humidity of the sample, and these variations induce an apparent mean vertical wind component (Webb *et al.*, 1980). However, if the humidity and temperature variations are measured, these density changes can be taken into account in every 10-Hz observation, or as usually, the correction is applied on the 30-min averages as a function of the concurrently-measured heat and humidity fluxes (Webb *et al.*, 1980). In practice, when measuring with a closed path system, the temperature variation may be assumed to vanish in the inlet tube (Rannik *et al.*, 1997). In addition, some gas analyzers (e.g., Li-Cor LI-6262) automatically take the humidity effect into account in internal calculations (Li-Cor, 1996). With open-path instruments (e.g., Li-Cor LI-7500) the full correction is required.

3. Field measurements

3.1 Measurement sites

The carbon dioxide flux measurements considered in this work have been carried out since 1995 by the eddy covariance method at four different ecosystems in northern Finland (Fig. 1; Table 1). These ecosystems cover the four major biomes of northern Finland: an aapa mire (wetland) at Kaamanen, a mountain birch (*Betula pubescens* spp. *czerepanovii*) forest at Petsikko, a Scots pine (*Pinus sylvestris*) forest at Sodankylä and a Norway spruce (*Picea abies*) forest at Pallas. This work concentrates mainly on the six-year data set collected at Kaamanen (**Papers I, II, IV, V** and **VI**). The CO_2 balance over a growing season was obtained at the Petsikko mountain birch forest (**Papers III** and **IV**). The data from the Sodankylä Scots pine forest (Suni *et al*., 2003; Laurila *et al*., 2005b) and Pallas Norway spruce forest (Aurela *et al*., 2004; Hatakka *et al*., 2003) are included here for comparison in order to obtain a general view of the important ecosystems in northern Finland. During the LAPP project, the Finnish sites were compared to five other ecosystems in European arctic and subarctic regions. These ecosystems include wetland, heathland and willow sites at Zackenberg (Greenland), a polar semi-desert at Ny-Ålesund (Svalbard) and a wetland at Kevo (Finland) (Fig. 1).

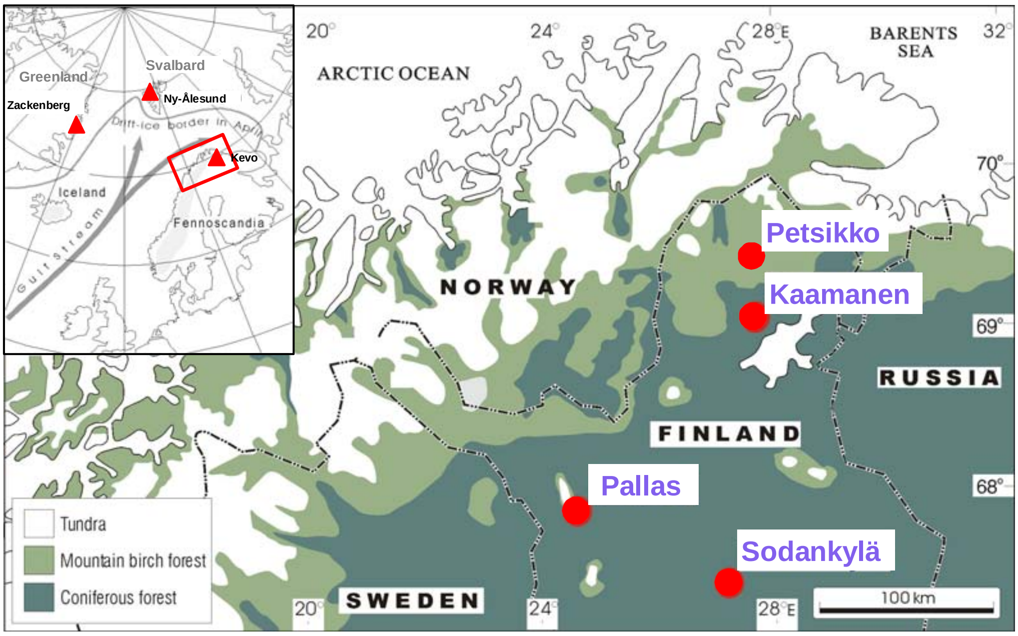

Figure 1. Distribution of mountain birch and coniferous forests in northern Fennoscandia (Seppä and Hammarlund, 2000). The flux measurement sites of the present work are shown as red circles. The additional flux measurement sites of the LAPP project are presented in the insert as red triangles.

Table 1. Flux measurement sites of this work

	Kaamanen	Petsikko	Sodankylä	Pallas
Ecosystem	Subarctic fen	Mountain birch forest	Scots pine forest	Norway spruce forest
Geographic coordinates	69°08’N 27°17’E	69°28’N 27°14’E	67°21’N 26°38’E	67°59’N 24°15’E
Height above sea, m	155	280	179	347
Mean annual temperature, °C	-1.0[a]	-2.0[b]	-1.0	-1.7[c]
Mean annual precipitation, mm	395[a]	395[b]	499	451[c]
Measurement height, m	5	8.5	22.5	23
Vegetation height, m	0.4	3.5	12	13
Tree density, trunk ha^{-1}	-	n.a.	2100	1050
Tree age, yr	-	n.a.	50– 160	70– 160
Leaf area index, m^2 m^{-2}	0.7	2.5	1.2	2.2
Measurement periods	Aug.–Sept. 1995 Apr.–Oct. 1997 Since Apr. 1998	Jun.–Sept. 1996	Since Jan. 2000	Since Jan. 2003
References	**Papers I, II, IV,V** and **VI**	**Papers III** and **IV**	Suni *et al.*, 2003 Laurila *et al.*, 2005b	Hatakka *et al.*, 2003 Aurela *et al.*, 2004

Long-term data from [a]Ivalo airport, [b]Utsjoki-Kevo and [c]Muonio weather stations are from the Finnish Meteorological Institute (1991).

3.2 Measurement system

The measurement system used for the CO_2 flux measurements was developed in the Finnish Meteorological Institute in the 1990s. The first eddy covariance flux measurements, of the O_3 flux, were carried out in 1993 on an agricultural field in southern Finland (Aurela, 1995); in 1994–95 O_3 flux measurements complemented by the CO_2 flux component were conducted in a Scots pine forest in south-eastern Finland (Aurela *et al.*, 1996; Tuovinen *et al.*, 2001). The measurement system was further developed in order to enable measurements in northern Finland, first on a campaign basis (**Paper I;** Tuovinen *et al.*, 1998), then over the growing seasons (**Papers II** and **III**) and finally on a continuous basis including the harsh winter conditions (**Paper V** and **VI**).

The measurement system has slightly varied during the years at the different measurement sites. At Kaamanen and Petsikko the basic system has been the same. The instrumentation included an SWS-211 (Applied Technologies, Inc., ATI) three-axis sonic anemometer/thermometer and a LI-6262 (Li-Cor, Inc.) CO_2/H_2O analyzer. At Sodankylä and Pallas, the ATI SWS-211 was replaced by a Metek USA-1, and the LI-6262 was replaced by a new model, the LI-7000 (Aurela *et al.*, 2004). A sampling rate of 10 Hz has been used for all data collection in the EC system. Synthetic air with a known CO_2 concentration is used as the reference gas (e.g., **Paper II**). Supporting meteorological measurements include, e.g., the air temperature and humidity, soil temperature and various radiation measurements (net radiation, global radiation and photosynthetic photon flux density (PPFD)) (**Papers II and III**).

The EC data acquisition has been carried out by in-house programs, originally based on a program by McMillen (1986). The programs have experienced some changes, but the main features have remained the same. A 30-min averaging period has been used together with an autoregressive running-mean filter with a 200-s time constant. A double rotation (DR) of the coordinate system was performed according to McMillen (1988). A comparison of the two rotation methods presented in Chapter 2.4.2, the DR and the planar fit, showed no significant difference between the resulting turbulent fluxes (Tuovinen *et al.*, 2005). The lag between the time series resulting from the transport through the inlet tube is taken into account in the on-line calculation of the flux quantities. The lag time is determined separately for each component for every 30-min period by maximizing the absolute value of the covariance in question (**Paper V**).

A series of further manipulations and corrections are performed on the collected data off-line (**Papers I** and **II**; Tuovinen *et al.*, 1998). The density corrections related to the heat and water vapour fluxes (Chapter 2.4.4) were not necessary for the CO_2 and H_2O fluxes at Kaamanen and Petsikko, as the LI-6262 corrects the CO_2 concentrations proportional to dry air, and the temperature fluctuations can be assumed to vanish in the tubing (Rannik *et al.*, 1997). The new CO_2/H_2O analyzer, LI-7000, on the other hand, does not take into account the humidity variations, and thus a partial density correction is required at Pallas and Sodankylä. Corrections for the systematic flux loss owing to the imperfect properties and setup of the sensors (insufficient response time, sensor separation, damping of the signal in the tubing and averaging over the measurement paths) (Chapter 2.4.3) were formerly performed according to the procedures suggested by Moore (1986) (**Paper II**). At Sodankylä and Pallas the transfer function was determined empirically by comparing the CO_2 flux spectrum to the heat flux spectrum (e.g., Aubinet *et al.*, 2000).

The night-time problem discussed in Chapter 2.4.1 was addressed by discarding the data during calm periods ($u_* < 0.1$ m s^{-1} at the Kaamanen wetland, $u_* < 0.2$ m s^{-1} at the Sodankylä pine forest and the Petsikko birch forest and $u_* < 0.25$ m s^{-1} at the Pallas spruce forest) and then filling the gaps by modelled values. At Kaamanen and Petsikko, a non-linear regression model was used, while the preliminary analysis of the data from Sodankylä and Pallas was conducted using the mean diurnal variation method. The storage term (I in Eq. 5) was estimated at Sodankylä and Pallas from CO_2 concentration profiles, resulting in a significant influence in the annual balances for these sites. At lower measurement heights over a short canopy, the influence of storage is markedly smaller. At Kaamanen, the storage term is presently included in the data processing routines, but it was not considered in **Papers I-VI**. In this work it was calculated for the most recent years, showing that the influence of storage is minor on the short-term balances (<1.5% in a typical monthly balance), while the relative contribution to the annual balance is somewhat larger and is considered in the error analysis of the annual balances.

3.3 Data analysis

The eddy covariance system provides us with a direct means of calculating the CO_2 balance of the ecosystem on different time scales. For certain purposes, however, it is useful to obtain more detailed ecosystem responses for the two contrasting NEE components, photosynthesis and respiration. Such flux partitioning was performed in **Paper IV** by parameterizing the irradiance response of the gross photosynthesis using a rectangular hyperbola (e.g., Whiting, 1994) and then fitting the sum of the modelled gross photosynthesis and the ecosystem respiration (R) to the observed 30-min flux data,

$$\mathrm{NEE} = \left(\frac{\alpha \cdot \mathrm{PPFD} \cdot GP_{\max}}{\alpha \cdot \mathrm{PPFD} + GP_{\max}} \right) + R\,. \tag{7}$$

Here $GP_{\max}$ is the gross photosynthesis rate in optimal light conditions (in mg CO_2 m^{-2} s^{-1}), PPFD is the measured photosynthetic photon flux density (in μmol m^{-2} s^{-1}), and α is the initial slope of NEE versus PPFD (in g CO_2 mol^{-1}).

The ecosystem respiration rate R is often modelled separately by a temperature response function, e.g., the commonly-used formula proposed by Lloyd and Taylor (1994),

$$R = R_0 \exp\left\{ E \left(\frac{1}{T_0} - \frac{1}{T - T_1} \right) \right\}, \tag{8}$$

where R_0 is the rate of the ecosystem respiration at 10 °C (in mg CO_2 m^{-2} s^{-1}), T is the measured air temperature (in K), E = 308.56 K, T_0 = 56.02 K and T_1 = 227.13 K. At Petsikko (**Paper III**), the ecosystem respiration was modelled as the sum of the soil respiration (R_s) and the plant dark respiration (R_d). At Kaamanen (**Papers I**, **II**, **V** and **VI**), the soil respiration was further divided into respiration from wet pools and from dry strings in order to take into account their contrasting characteristics. The model obtained was used to patch the gaps in the time series when estimating the long-term CO_2 balances. The same model structure was also used in a long-term model which is run using daily mean meteorological data. This version was used for estimating the long-term variability of CO_2 balances and representativeness of the measured CO_2 balances (**Paper III**; Aurela *et al*. 2005).

An additional parameter, the phytomass index (PI), was introduced in **Paper II**, and it is utilized throughout this work. The PI is an empirically-determined measure of the photosynthetic capacity of the ecosystem. It is used in the NEE-model, in the same way as the leaf area index (LAI), for taking into account the seasonal courses of the gross photosynthesis and plant respiration (NEE = $PI \cdot GP + PI \cdot R_d + R_s$). In principle the PI could be determined as the GP_{max} (in Eq. 7), but in practice it is evaluated as the difference between the daytime and night-time fluxes. Typically, the PI is assigned in 3 to 7 days periods and is normalized to unity at its maximum. The PI may be used to improve the temporal accuracy of the gap-filling model by covering the synoptic-scale variations in the environmental conditions (e.g., water vapour pressure deficit, soil moisture, water table, and temperature), even when Eq. 7 is fitted in longer time steps for the sake of stability (**Paper VI**). The PI also has an important role in the long-term model, in which its seasonal cycle is modelled separately according to the effective temperature sums and possibly other temperature and humidity functions during the growing season (**Paper II**; Aurela *et al.*, 2005).

4. Results

4.1 Seasonality of CO_2 exchange

The seasonal cycle of the CO_2 exchange in northern ecosystems is distinctly divisible into the growing season and the non-growing season. This division is ultimately determined by the availability of solar energy. The annual courses of the incident radiation (represented by PPFD), the actually-available energy (net radiation), and the resulting photosynthetical activity (CO_2 flux) decrease almost simultaneously in autumn (Fig. 2). In spring, on the other hand, there is a marked phase difference between these three quantities (**Paper V**). The lag between the net radiation and the CO_2 flux is basically the time the plants need to develop biomass. The phase difference between PPFD and net radiation, on the other hand, is caused by the energy loss due to the high albedo of the snow cover (**Paper II**).

The difference between spring and autumn may have a significant influence in a warming climate. During the spring an increase in temperature will advance the snow melt. Under the photosynthetically-favourable temperature and radiation conditions the growing season will probably lengthen, leading to an increase in the annual gross photosynthesis. In the autumn the case is different. Even if the higher temperatures were to promote a longer growing season, the decreasing radiation would initiate senescence. In addition, the shortening of the day further decreases the daily CO_2 uptake. Actually, a higher temperature in autumn will result in higher soil respiration, possibly leading to a net decrease in the annual CO_2 uptake.

The growing season at these northern sites is short, as it directly depends on the latitude. In northern Finland the growing season lasts about 3 months, while in northern Greenland and Svalbard it is even shorter. In ecosystems dominated by annual plants, this leads to a rather clear peak in the daily maximum photosynthetic rates, typically occurring in late July (e.g., **Papers II** and **III**). Coniferous forests have the advantage of a perennial phytomass, and they already reach their maximum uptakes in early July.

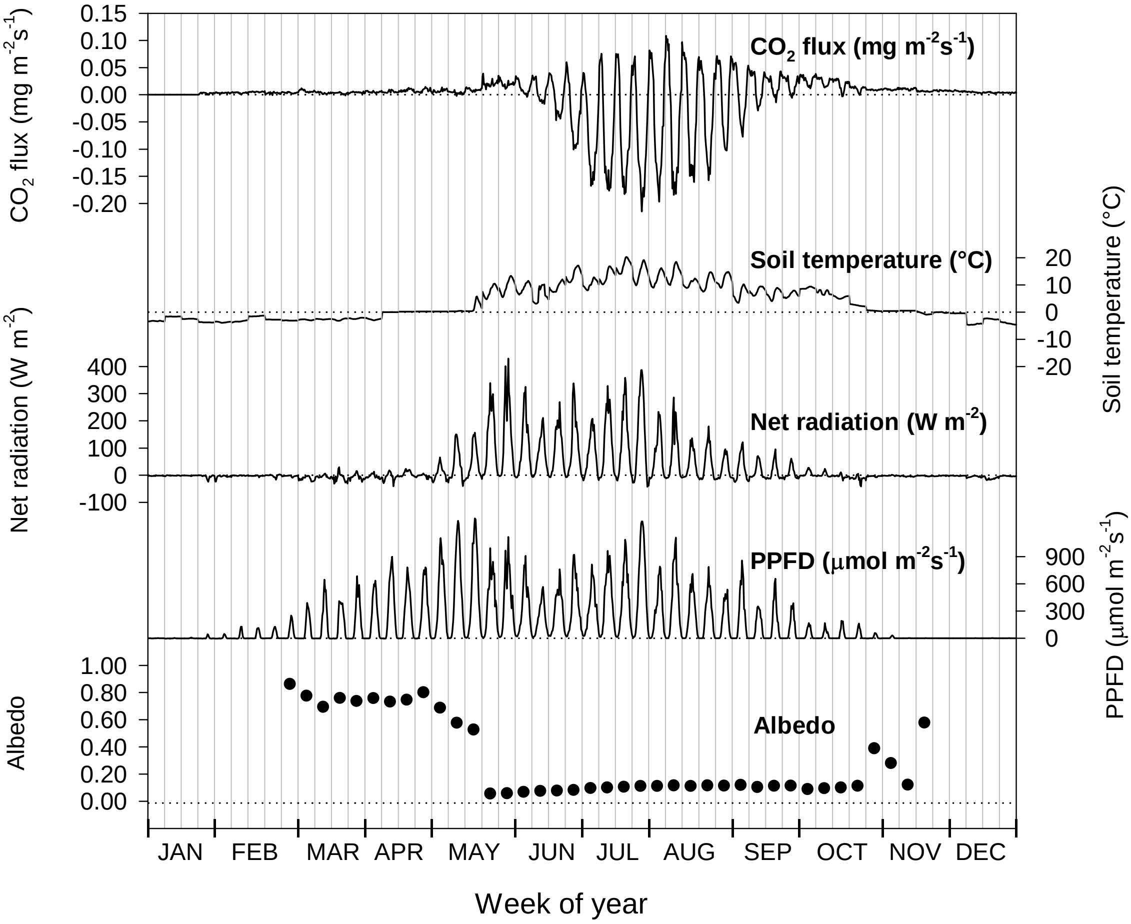

Figure 2. Consecutive 7-day average diurnal cycles of CO_2 exchange, soil temperature, net radiation and PPFD, together with the midday (12–15, local time) albedo at a wetland in Kaamanen in 2002.

4.2 Gross photosynthesis

The most important determinants of the annual gross photosynthetic sum are the length of the growing season and the high summer maximum photosynthetic rates. As discussed above, the length of the growing season is largely controlled by the available energy, and thus depends on the latitude. The latitude may also influence the maximum photosynthesis rates, but this is a secondary factor. The gross photosynthetic capacities at different arctic and subarctic sites were compared in **Paper IV**. Here the exercise is extended to cover the coniferous forests in northern Finland. The light response parameterization (Eq. 7) was fitted to the data during the maximum uptake period at the different sites (Table 2).

Table 2. Parameters for Eq. 7 estimated for different sites, together with the latitude (λ), the leaf area index (LAI) and the soil type of each measurement site

	λ	LAI	Soil type	Period	$\alpha \times 10^3$	GP_{max}	R	r^2
					g mol^{-1}	mg m^{-2} s^{-1}	mg m^{-2} s^{-1}	
FMI sites								
Kaamanen – wetland	69°N	0.7	Peat	20–29 Jul.	-1.17	-0.31	0.08	0.84
Petsikko – mountain birch	69°N	2.5	Mineral	25–31 Jul.	-1.80	-0.68	0.10	0.88
Sodankylä – Scots pine	67°N	1.2	Mineral	1–31 Jul.	-1.62	-0.37	0.18	0.59
Pallas – Norway spruce	68°N	2.2	Mineral	1–31 Jul.	-3.16	-0.55	0.21	0.69
Reference LAPP sites								
Zackenberg – wetland	74°N	1.1	Peat	25–31 Jul.	-1.18	-0.44	0.10	0.87
Zackenberg – willow	74°N	0.5	Mineral	25–31 Jul.	-0.441	-0.33	0.04	0.83
Zackenberg – heath	74°N	0.2	Mineral	25–31 Jul.	-0.698	-0.11	0.04	0.72
Kevo Skalluvaara – wetland	69°N	0.7	Peat	22–28 Jul.	-1.50	-0.30	0.06	0.76
Ny-Ålesund – semidesert	79°N	0.2	Mineral	31 Jul.–6 Aug.	-0.147	-0.039	0.008	n.a.

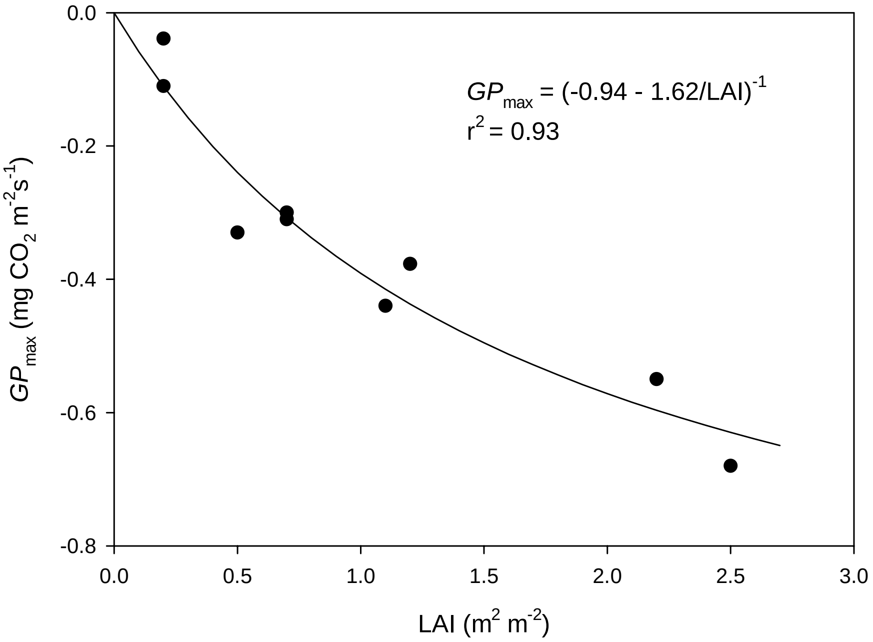

Figure 3. Maximal gross photosynthesis (GP_{max}) versus projected leaf area index (LAI) at various sites in subarctic and arctic Europe. See Table 2 for details.

The highest photosynthetic capacity was observed in the subarctic mountain birch ecosystem. The coniferous forests and the wetlands also had a relatively high potential for photosynthesis, while the arctic heathland ecosystems, and especially the polar semidesert at Ny-Ålesund, had a lower CO_2 uptake capacity. A number of other parameters, such as leaf temperature, air and soil humidity, CO_2 and nutrient concentrations, also have their influences on the maximum gross photosynthesis (GP_{max}) rates. However, when comparing different sites, the leaf area index (LAI) alone was found to explain a great part of the variation in $GP_{\max}$ (Fig. 3). The $GP_{\max}$ values increase with increasing LAI, but the slope of the response is smaller at LAI values higher than 1. This is probably caused by shading effects in an ecosystem with a higher vegetation density.

4.3 Respiration

The autotrophic respiration of plants is closely linked to their photosynthesis, while the heterotrophic soil respiration is influenced by litter production. Thus we might expect that respiration would partly share the correlation between photosynthesis and LAI, and indeed this is observed. On the average, sites with high LAIs show strong respiration and vice versa (Table 2). However, this dependency is weaker than that between LAI and $GP_{\max}$, because the complex soil respiration processes are not directly related to the LAI. The soil type, nutrient level, humidity, and above all, the soil temperature are all parameters that are important to soil respiration but are not considered here. However, such a correlation with LAI, even a weak one, might prove usable when estimating carbon balances using remote sensing. The LAI and the soil surface temperature are readily-available satellite data products, whereas the other soil properties probably more directly controlling the soil respiration are more difficult to obtain (e.g., Wan *et al.*, 2004; Tan *et al.*, 2005).

In winter the CO_2 efflux of northern ecosystems is relatively stable, irrespective of the meteorological conditions (Fig. 2). A closer look at the data, however, reveals some temporal variation, mainly controlled by the soil temperature (**Paper V**). During early winter, with shallow snow cover, the soil temperature and thus the respiration are directly linked with the air temperature. This link gradually weakens due to increasing snow cover, and the late winter respiration is practically detached from the air temperatures. The winter-time fluxes exhibit a weak seasonal course with the minimum respiration occurring in January–February. This mid-winter efflux at Kaamanen is 5.5 $\mu g\ CO_2\ m^{-2}\ s^{-1}$, which is about 5% of the typical summertime respiration. When integrated over the six-month winter period, the small but constant respiration totalled about 90 $g\ CO_2\ m^{-2}$ in 1998.

The mid-winter fluxes observed at Kaamanen are similar to the winter fluxes at other northern ecosystems. In **Paper V** we collated data on winter-time minimum fluxes at different cold ecosystems, which are shown in Fig. 4 together with the Finnish data introduced in this study. The data are consistent with a rough climatic zone distribution: effluxes from arctic and alpine ecosystems are mainly in the range 0.1 to 3 $\mu g\ CO_2\ m^{-2}\ s^{-1}$, those from the subarctic and subalpine typically within 3–10 $\mu g\ CO_2\ m^{-2}\ s^{-1}$, while in the boreal ecosystems they are somewhat higher still. Weak respiration seems to take place even if the soil surface temperature is below -10 °C, but substantially higher fluxes are observed at temperatures close to 0 °C (Fig. 4).

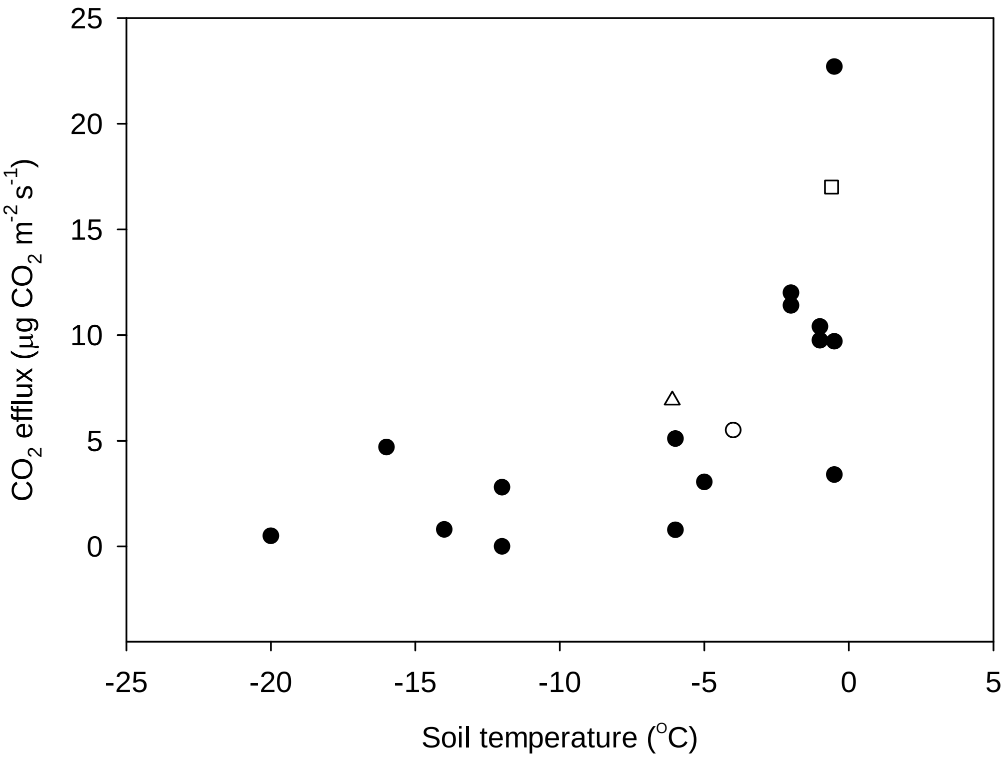

Figure 4. Mid-winter CO_2 efflux versus soil temperature in various snow-covered ecosystems (closed circles). The Finnish measurement sites of the Kaamanen wetland (open circle), the Sodankylä Scots pine forest (open triangle) and the Pallas Norway spruce forest (open square) are here added to the data collated and discussed in ***Paper V****.*

4.4 Annual CO_2 balances

The summertime CO_2 exchange measurements yield important information about the ecosystem functions and the short-term processes controlling the CO_2 exchange. Regarding carbon balances and their role in global change, the shortest meaningful measurement period is one year. In **Paper V** we presented the first annual CO_2 balance measured on a subarctic wetland. During the year 1998, with moderate meteorological conditions and a relatively short growing season, the mire was found to be a sink for CO_2 with an annual NEE of -78 g CO_2 m^{-2} yr^{-1} (re-calculated from **Paper V**). The winter-time efflux was shown to be an essential part of the annual balance, with an average efflux of 91 g CO_2 m^{-2} yr^{-1} during the period from November to April (Table 3). The annual balance obtained is close to the 6-year (1997–2002) average of -79 g CO_2 m^{-2} yr^{-1} reported for the mire in **Paper VI**.

Table 3. The annual CO_2 balances and their uncertainty range (UR) together with the seasonal balances during summer (May–October) and winter (January–April + November–December) periods at Kaamanen

	Year g CO_2 m^{-2}	UR* g CO_2 m^{-2}	Summer g CO_2 m^{-2}	Winter g CO_2 m^{-2}
1997	-15	-40..-4	-104	89
1998	-78	-109..-62	-171	92
1999	-30	-54..-22	-124	93
2000	-23	-43..-18	-121	97
2001	-134	-160..-125	-220	87
2002	-195	-215..-183	-278	85
Average	-79		-169	91

* The uncertainty range is based on the error analysis performed in **Paper VI** and described in detail in **Paper V**. The storage term is not taken into account in the annual balance calculations, but it was here estimated that the inclusion of storage would increase the sink term for about 10 g CO_2 m^{-2} yr^{-1}. This value was subtracted from the lower limit of the uncertainty ranges presented in **Paper VI**.

The comparison of the results at Kaamanen (a subarctic fen) with other wetlands is difficult due to the scarcity of continuous round-the-year measurements. Lafleur *et al.* (2003) observed an average annual CO_2 balance of -248 g CO_2 m^{-2} yr^{-1} from their multi-year measurements on Mer Bleue bog in central Canada (45.40°N, 75.50°W). Balances between -55 and -90 g CO_2 m^{-2} yr^{-1} were obtained on a subarctic mire in northern Sweden (68°21'N, 19°02'E) (Callaghan *et al.*, 2004b). At some sites, the lacking data on the winter-time efflux have been estimated using modelling or extrapolation of existing winter measurements. Arneth *et al.* (2002) reported annual balances from -80 to -130 g CO_2 $m^{-2}yr^{-1}$ on a boreal bog in central Siberia (60.45°N, 89.23°E). Nordstroem *et al.* (2001) estimated a small sink of -20 g CO_2 m^{-2} yr^{-1} on a high arctic fen in north-east Greenland (75°N, 8°E) (Fig. 5).

Among the upland ecosystems, the closest comparison is provided by the coniferous forests in northern Finland. The preliminary results show annual balances of -175 g CO_2 m^{-2} yr^{-1} (in 2003) and 125 g CO_2 m^{-2} yr^{-1} (average in 2001–2004) in the Pallas spruce forest and the Sodankylä Scots pine forest, respectively. As the balances are close to zero, the variation between the sites seems marked, but on a broader scale the fluxes are relatively small. A comparison of annual CO_2 balances in various European forests shows a clear latitude dependency, with higher uptake at lower latitudes (Fig. 5) (Valentini *et al.*, 2000).

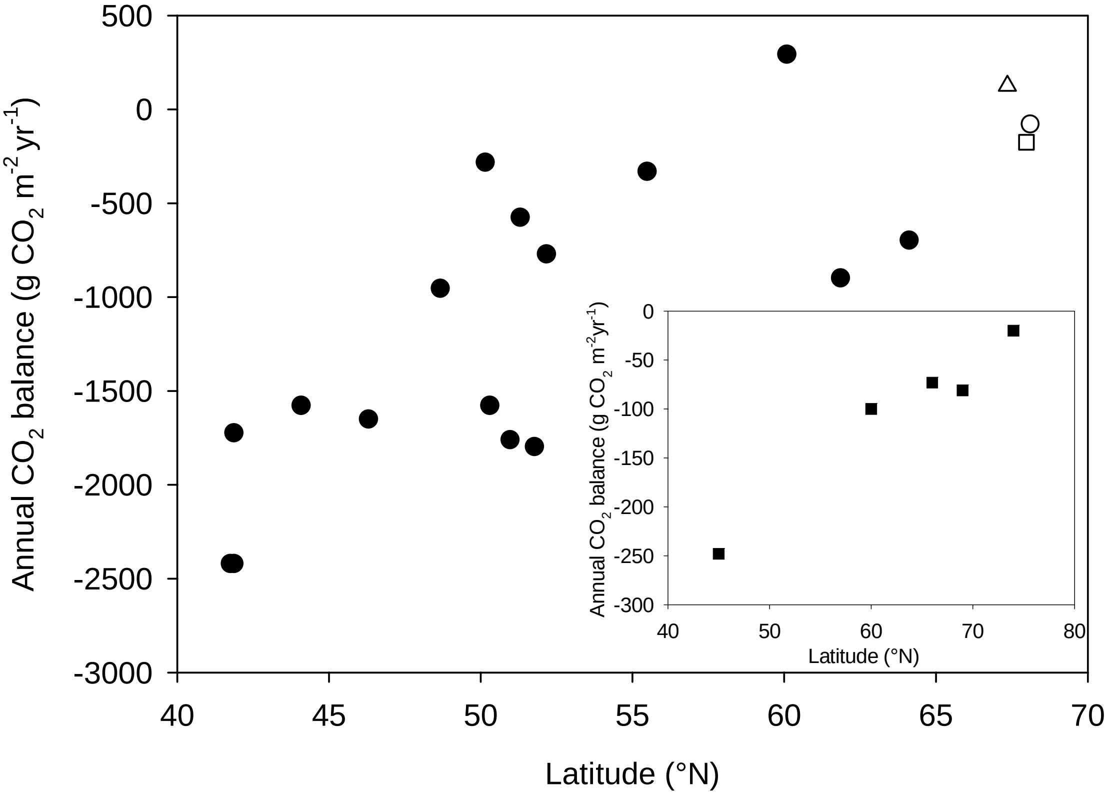

Figure 5. The annual CO_2 balance of various European sites plotted against latitude (filled circles). The figure is based on a similar figure by Valentini et al. (2000). Intensively-managed plantations are omitted, each site is represented by only one value, and data from the wetland at Kaamanen (open circle), the Scots pine forest at Sodankylä (open triangle) and the Norway spruce forest at Pallas (open square) have been added. In the insert the corresponding data are presented for the five wetland ecosystems discussed in the text.

The annual balances on wetlands are generally weaker than those obtained for forests, but a similar behaviour was found for the few wetland sites available, discussed above (Fig. 5). In **Paper V** we compared the Kaamanen fen to the Mer Bleue bog in Canada and suggested that the greater uptake at the bog is mainly due to its more southernly location and consequently longer growing season. The Mer Bleue bog was a net sink for over 200 days, whereas the Kaamanen fen was only a net sink for 70 days. The highest instantaneous uptake values were higher at Mer Bleue, but the maximum daily net uptake was actually slightly higher at Kaamanen (Lafleur *et al.*, 2001; **Paper V**).

Due to their location in the transition zone between boreal forest and the tundra, the ecosystems in northern Finland are especially sensitive to any changes in the environmental conditions. Because of their small annual balances such changes may relatively easily turn these ecosystems from a net sink to a source of CO_2. The Sodankylä Scots pine forest, for example, has been a source of CO_2 during recent years. According to a forest inventory data, however, the forest trees are growing normally and are a sink for carbon (Jarno Kallonen, unpublished data of Finnish Meteorological

Institute). It may be speculated whether this discrepancy could be related to the changes observed in the ground vegetation. The white reindeer-lichen (*Cladonia* spp.), typical for the area, has markedly decreased during the recent decades, causing changes in the albedo and the insulating properties of the forest floor. The resulting influence on the soil temperature and respiration rates is now under investigation (Laurila *et al.*, 2005b).

Changes in the environmental conditions and the CO_2 balances have been reported in different subarctic and arctic ecosystems (Callaghan *et al.*, 2004b, Oechel *et al.*, 1993; IPCC, 2001b). There has been discussion as to whether this northern region as a whole is becoming a carbon source due to the predicted and partly observed climate warming and the consequent drying of the soil and partial melting of the permafrost (Callaghan *et al.*, 2004a). Some sites have been observed to act as a net source of CO_2 (e.g., Griffis *et al.*, 2000; Heikkinen *et al.*, 2004; Welker *et al.*, 2000), but some sites have remained as a CO_2 sink (e.g., Soegaard and Nordstroem, 1999; Harazono *et al.*, 2003; **Paper V**). There are currently too few full annual datasets available to provide a solid answer about the present carbon balance of these arctic and subarctic areas at the landscape scale, but the data collected so far suggest that the dry areas may already have become a source of carbon, whereas the wetter areas are believed to continue as a carbon sink, the strength of which may even be increasing (Callaghan *et al.*, 2004a; Harazono *et al.*, 2003; **Paper VI**; Heikkinen *et al.*, 2004).

4.5 Interannual variation

At the Kaamanen fen during the years 1997–2002, the annual balances ranged from -15 to -195 g CO_2 m^{-2} yr^{-1} (Table 3). Lafleur *et al.* (2003) reported quite a similar variation range (-37 to -278 g CO_2 m^{-2} yr^{-1}) on a boreal bog, although the average annual uptake is higher on their site. Such relatively great variation is typical for wetlands, and it has been shown that the annual balances actually often change from a sink to a source from year to year, depending on the meteorological conditions (e.g., Shurpali *et al.*, 1995; Joiner *et al.*, 1999).

The interannual variation at Kaamanen originated almost completely from the variations occurring during the snow-free period (Table 3). Even though the efflux in the winter-time (November–April) constituted an important part of the annual balance as discussed above, its contribution to the interannual variation was small.

Using correlation analysis, we studied which hydrometeorological factors are the most important determinants of the carbon balance at Kaamanen (**Paper VI**). We found no significant correlation between the annual CO_2 balance and the annual means of key hydrometeorological quantities. The correlations were also poor for the summer (June–August) means of most variables. By contrast, the annual balance correlated well with various characteristics of the spring conditions, including the beginning of the growing season, the start of the sink period and the water table level during the spring flood. The strongest correlations were found with the snow-melt date and the associated mean temperature (Fig. 6a; **Paper VI**).

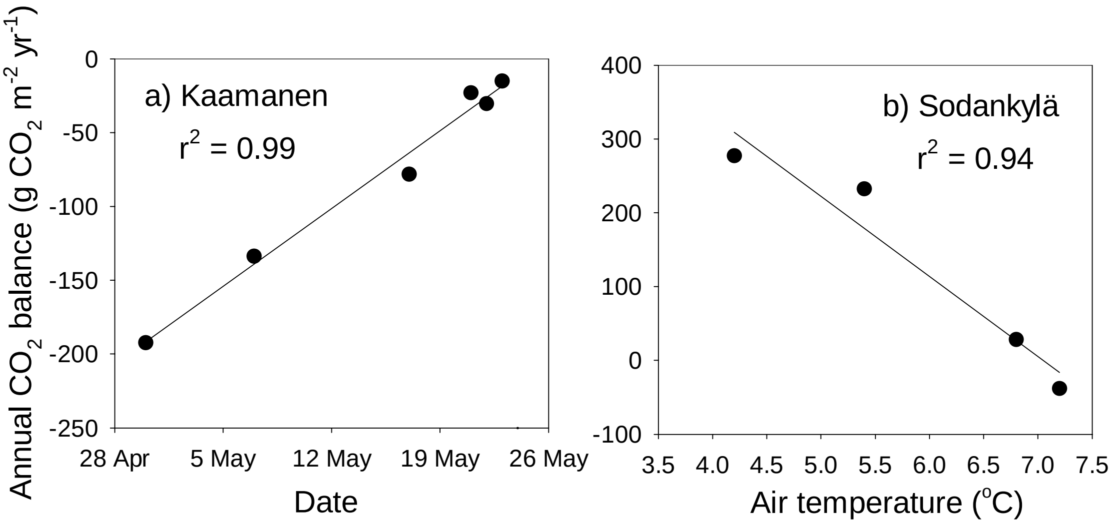

Figure 6. The annual CO_2 balances plotted against a) a snow-melt date at Kaamanen in 1997–2002 and b) an average May temperature at Sodankylä in 2001–2004.

The observed monthly CO_2 balances further demonstrate the significance of the spring phenology at Kaamanen (**Paper VI**). The highest uptake rates are regularly observed in July, but the year-to-year variation of the monthly balances was very low. In June, the mean net uptake is 28% of that in July, but the range of variation is over four times as high as in July. This was suggested as promoting the importance of the onset of spring to the annual balance. The study years were meteorologically quite well representative of a longer period over several decades. The period contains, for example, the extremely dry summer of 1997 (lowest precipitation in 1961–2002) and the early spring of 2002 (second earliest snow melt date in 1961–2002). The mean July temperature, however, showed surprisingly little variation during the six measurement years. More changeable July temperatures would probably enhance the variation in the July CO_2 balances and could possibly also have an effect on the variation of the annual balances. That would not, however, reduce the significance of the springtime conditions (**Paper VI**; Aurela *et al.*, 2005).

The preliminary annual CO_2 balances from the Sodankylä Scots pine forest also exhibit a dependency on springtime temperatures (Fig. 6b), suggesting that a warm spring also promotes CO_2 uptake at a site that predominantly acts as a source of CO_2. These results support the general hypothesis that advancing the beginning of the growing season effectively increases the annual net carbon gain in northern high latitudes, as has been previously suggested, based on atmospheric CO_2 data (Keeling *et al.*, 1996), satellite measurements (Myneni *et al.*, 1997) and ecosystem-scale flux measurements (Black *et al.*, 2000).

4.6 Carbon balance and global warming potential

The carbon balance of a wetland ecosystem differs from the CO_2 balance. The measured annual CO_2 balance at Kaamanen does not include the carbon lost in the efflux of methane and in the carbon leaching by lateral water flow. An annual CH_4 efflux of 5.5 g CH_4 m^{-2} yr^{-1} (4 g C m^{-2} yr^{-1}) was estimated for the Kaamanen fen based on three measurement campaigns covering different seasons (Hargreaves *et al.*, 2001). The leaching of carbon (8 g C m^{-2} yr^{-1}) was estimated from the studies by Kortelainen *et al.* (1997) and Sallantaus (1994) at different ecosystems in Finland (**Paper V**). If these fluxes are subtracted from the mean annual CO_2 balance of -79 g CO_2 m^{-2} yr^{-1} (-22 g C m^{-2} yr^{-1}) we obtained for Kaamanen, the fen results in being a carbon sink of 10 g C m^{-2} yr^{-1}.

The estimated carbon balance is consistent with the long-term carbon accumulation rates estimated for Finnish peatlands. The Kaamanen fen is about 7000 years old and a long-term accumulation rate of 11 g C m^{-2} yr^{-1} has been observed for it (Jukka Turunen, unpublished data). This is slightly lower than the average of 16 g C m^{-2} yr^{-1} estimated for other similar aapa mires in Finland (Turunen *et al.*, 2002).

As regards climate change considerations, the role of CO_2 exchange appears to be slightly different. The concept of a Global Warming Potential (GWP) has been developed for evaluating the ability of each greenhouse gas to trap heat in the atmosphere relative to CO_2. The GWP depends on the time horizon adopted, and for a 100-year time-horizon the GWP of CH_4 is 23 (IPCC, 2001a). Using this factor, the annual balance obtained for methane (127 g CO_2-eq m^{-2}) exceeds the annual CO_2 balance (-79 g CO_2 m^{-2}) at Kaamanen. This means that, even if the fen were a net sink of CO_2 during the measurement years, its carbon balance has a potentially warming influence on the atmospheric on a 100-year time-horizon (**Paper V**; Laurila *et al.*, 2005a). This is typical for northern fens, whereas the more southern wetlands often exhibit an opposite effect (Whiting and Chanton, 2001). Over a longer (500-year) time-horizon, the northern wetlands predominantly act as net greenhouse gas sinks, due to the domination of the long-lived CO_2 molecules (Whiting and Chanton, 2001).

5. Summary and conclusions

Carbon dioxide exchange between the atmosphere and different ecosystems was measured in northern Finland during 1995–2004. The measurements covered four major biomes in northern Finland: an aapa mire, a mountain birch forest, a Scots pine forest and a Norway spruce forest. The measurements were conducted using the eddy covariance method, which provides continuous CO_2 exchange data on an ecosystem scale. A measurement system enabling year-round measurements in the harsh subarctic conditions was shown to be suitable for long-term exchange studies in different ecosystems. The development of data analysis tools, such as the data screening procedures and the gap-filling model including the *PI*-term, was essential for determining the long-term CO_2 balances.

The high summer CO_2 exchange was compared at nine sites in the European arctic and subarctic regions. The leaf area index was found to be the most important determinant of the gross photosynthetic rates in these contrasting ecosystems. The highest uptake was observed in the mountain birch forest and the lowest in the arctic desert at Svalbard. Respiration did not show such a monotonic dependence on LAI, but on the average, the highest respiration rates were related to the highest LAI and the lowest respiration to the lowest LAI.

The first continuous round-the-year measurements of net ecosystem CO_2 exchange on a subarctic wetland were conducted at the Kaamanen fen. The fen was a net sink for CO_2 during the years 1997–2002, with an average annual balance of -79 g CO_2 m^{-2} yr^{-1}. Due to its northern location the growing season at Kaamanen is relatively short. The average duration of the sink period is about 3 months. The fen showed continuous respiration throughout the winter with an average mid-winter respiration rate of about 5 μg CO_2 m^{-2} s^{-1}, about 5% of the typical summertime values. During the 6-month snow cover period, the fen releases about 90 g CO_2 m^{-2}, making the winter-time respiration a highly important part of the annual CO_2 balance.

The interannual variation of the CO_2 balance was studied at Kaamanen. The balances varied from -15 to -195 g CO_2 m^{-2} yr^{-1} during the years 1997–2002. The most important factors determining this variation were found to be the snow-melt timing and the related temperatures. The warmer the spring was, the greater the sink. The hydrometeorological conditions during the growing season had only a minor effect on the annual balance. These results suggest that the predicted climate warming would benefit rather than threaten the carbon pool in such a northern wetland.

The measured annual CO_2 balance at Kaamanen (-22 g C m^{-2}) does not include the carbon lost through methane efflux and carbon leaching. An annual methane efflux of 4 g C m^{-2} has been earlier determined for the fen. Assuming a leaching of total organic carbon of 8 g C m^{-2} yr^{-1}, an annual carbon balance of -10 g C m^{-2} is obtained for the fen. This is close to the long-term carbon accumulation rate estimated for the fen from peat core analysis. Recognizing the higher global warming potential of CH_4 compared with CO_2, it can be concluded that even if the fen were a small sink for CO_2, the carbon balance has a potentially warming influence on the atmosphere over a 100-year time-horizon.

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