

Annual CO₂ exchange of a peat field growing spring barley or perennial forage grass

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[1] We report on net ecosystem CO₂ exchange (NEE) measurements conducted with the eddy covariance method over agricultural peat soil in the 2-year period between October 2000 and October 2002. In 2001, spring barley and undersown grass were sown on the site. After the barley harvest, the perennial forage grass was left to grow, so that in 2002 the field was growing grass. A higher maximum net CO₂ uptake was observed for barley than for grass during the height of the summer, peaking at about -1.0 and -0.75 mg CO₂ m⁻² s⁻¹, respectively. The maximum nighttime total ecosystem respiration was measured in July and was similar for both crops, about 0.35 mg CO₂ m⁻² s⁻¹. During the growing season the field acted as a daily CO₂ sink for only 40 days in barley versus 84 days in grass. In the winter the average carbon dioxide efflux varied from 15.6 to 16.5 μg CO₂ m⁻² s⁻¹. The annual NEE of the agricultural peat soil growing barley and grass was 771 ± 104 and 290 ± 91 g CO₂ m⁻², respectively. The longer net CO₂ uptake period was the main reason for the lower annual NEE for grass; however, owing to the higher amount of grass biomass produced the net ecosystem production (NEP), calculated as the sum of NEE and removed biomass, was slightly larger for grass (452 g C m⁻²) than for barley (336 g C m⁻²). These results show that the organic peat is still undergoing rapid decomposition after more than 100 years of cultivation activity. In addition, switching from an annual to a perennial crop did not turn the field into a CO₂ sink, at least during a 1-year period.

INDEX TERMS: 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805); **KEYWORDS:** carbon dioxide balance, drained peatland, eddy covariance method, NEE, NEP

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1. Introduction

[2] Currently, the carbon balances of different ecosystems and the factors controlling the dynamics of the net ecosystem CO₂ exchange (NEE) are being actively studied around the world in e.g., forests [e.g., Goulden *et al.*, 1998; Valentini *et al.*, 2000], grasslands [Flanagan *et al.*, 2002], and prairie ecosystems [Suyker *et al.*, 2003]. In northern peatlands, which have been estimated to represent as much as a third of the worldwide soil carbon reservoirs [Gorham, 1991], long-term measurements have so far been concentrated mainly on pristine wetlands [e.g., Aurela *et al.*, 2002; Lafleur *et al.*, 2001]. The accumulation of carbon in these soils has been possible due to cool and humid conditions which are unfavorable for the aerobic decomposition of the plant remnants. During the last few hundreds of years, extensive areas of wetlands have been drained to make them suitable for forestry, agriculture, or peat harvesting. In Russia, for example, 71,000 km² of peatlands, comprising about 12% of the total peatland area, have been turned into

agricultural soil [Kosov and Kreshtapova, 1996]. In Finland, approximately 7000–10,000 km² of wetlands have been drained in the past for agricultural purposes, but nowadays the estimated area of cultivated histosols in Finland is about 2000 km², i.e., about 10% of the total land area under agriculture [Myllys, 1996]. Globally, the area of cultivated histosols is estimated to be only a few percent of the total amount of farmed soils; however, owing to their high C content, the amount of carbon in them may exceed 50% of that in all agricultural soils throughout the world [Paustian *et al.*, 1998]. Accordingly, it has been estimated that the amount of C lost from these soils has been among the highest in cultivated soils overall [Paustian *et al.*, 1998].

[3] In arable peat soils, the combined effects of low water table, high organic C content, mechanical disturbance and fertilization make the conditions ideal for vigorous carbon mineralization. CO₂ efflux measurements have shown that, following the drainage and subsequent water table drop, the respiration activity in cultivated peat fields increases strongly [Nykänen *et al.*, 1995]. The change in the carbon dioxide production rate is generally permanent, and still decades after the drainage higher respiration rates as compared to mineral soils have been measured [Koizumi *et al.*,

1999; Lohila *et al.*, 2003]. On the basis of soil subsidence [Armentano and Menges, 1986] and chamber CO₂ flux [Maljanen *et al.*, 2001] studies, the annual net carbon loss estimate from cultivated peat soils in the boreal zone varies from approximately 2000 to 7500 kg C ha⁻².

[4] In this study we present eddy covariance measurements conducted over agricultural peat soil in southern Finland. The 2-year study period includes one growing season with barley and another with forage ley. The objectives here were to study the seasonal CO₂ exchange of annual and perennial species growing on peat soil and to determine the annual net CO₂ balance for barley and forage grass.

2. Materials and Methods

2.1. Site Characteristics and Cultural Practices

[5] The study site was located at Jokioinen, southern Finland (60°53.932'N, 23°30.861'E, elevation 104 m). The area belongs to the southern boreal climatic zone, where the mean duration of the vegetational period is approximately 160–170 days [Solantie, 1990]. The CO₂ exchange measurements were conducted in the middle of a flat square peat field, which has been in agricultural use for about a century. This uniformly cultivated field of 17 ha (about 0.4 km × 0.4 km) was located at the edge of a larger (about 1 km²) cultivated area. In a sector of 225° to 330° from the measurement masts, the site provided at least 1000 m of upwind fetch of open agricultural field, whereas in the eastern sector the distance to a forest was about 250 m. The prevailing wind directions were southwest (15.4%) and south (13.6%), whereas least accepted data originated from the northeast (7.8%) and east (9.9%). About 30 m to the northwest of the measurement masts there was an experimental plot of 46 m × 30 m with cropped (barley, forage ley) or fallow subplots. Owing to the rather similar annual cycle in the plant cover, the effect of this plot on the observed CO₂ fluxes was of less importance. Subsurface drainage pipes were initially installed in 1954, but due to soil subsidence they were reinstalled in 1992 at a depth of 0.8–1 m. This was also the depth of the water table during the study.

[6] In the sector from about 345° through north to 180°, the soil was well-decomposed peat, classified as Terric histosol (FAO-UNESCO system) [Yli-Halla and Mokma, 2001]. Close to the flux measurement mast, the depth of the peat layer was 0.5–0.6 m. In the sector between 180° and 345°, the peat layer became gradually thinner as the soil type changed from peat to mud. Within the nearest 120 m of the measurement masts, however, the peat layer was everywhere thicker than 0.4 m. The subsoil in the study area consisted of clay. The average soil organic carbon content was determined along two transects crossing at the flux measurement point. On both transects, ten samples (core diameter 0.10 m) from two depths, 0–0.2 and 0.4–0.5 m, were taken every 40 m, each sample consisting of three subsamples. The average carbon content of the 0.5 m soil layer was 234 and 205 g kg⁻¹ at distances of 120 and 200 m from the masts, respectively. The average C/N ratio of the transect samples was 20. The soil pH in the vicinity of the measurement masts was 5.8 and the soil bulk density was 0.48 g cm⁻³ [Lohila *et al.*, 2003]. The 0.5 m peat

layer contained on average 56 kg C m⁻² at a distance of 120 m from the measurement masts. The wilting point and field capacity for the 0.1–0.2 m layer were 0.22 and 0.60 m³m⁻³, respectively (K. Regina, Agrifood Finland, personal communication, 2002).

[7] The 17 ha field was planted with perennial forage ley (a mixture of *Phleum pratense* and *Festuca pratensis*, referred to hereafter as grass) in 1996, with oats (*Avena sativa* L.), barley (*Hordeum vulgare* L.) and grass in 1997, and with barley and oats in 1998–2000. In autumn 2000, on 10 October, the field was ploughed. In the following spring the field was harrowed and immediately after that, on 25 May, was sown with spring barley (*H. vulgare* L., “Inari”) and undersown grass (76 % of *P. pratense* and 24 % of *F. pratensis*) at rates of 150 and 25 kg ha⁻¹, respectively. The row spacing was 0.125 m. At sowing the field received 42.5 kg N, 15 kg P and 25 kg K per hectare. In 2001, the barley was harvested about a month too late, on 21 September because of the wet conditions prevailing during the first half of September. In 2002, the grass was harvested twice, on 7–10 June and 5–6 August. Fertilizers were applied at rates of 91 kg N, 7 kg P and 10.5 kg K per hectare on 26 April, and at rates of 50 kg N and 37.5 kg K per hectare after the first harvest.

2.2. CO₂ Flux Measurements and Data Acquisition

[8] The CO₂ and energy fluxes were measured at a height of 3 m using the eddy covariance (EC) technique. The instrumentation included an SWS-211 (Applied Technologies, Inc.) three-axis sonic anemometer and an LI-6262 (Li-Cor, Inc.) CO₂/H₂O analyzer. The heated inlet tube for the LI-6262 was 5.6 m in length and 3.1 mm in diameter. Turbulent flow was achieved by using a flow rate of 6 L min⁻¹. The LI-6262 was operated in absolute mode using CO₂-free synthetic air as a reference gas. A two-point calibration (0 and 376 ppm) was conducted typically twice a month. The EC data acquisition was carried out by a LabView-based program BARFLUX. The coordinate rotation and the 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 online calculation of the flux quantities. A series of further calculations and corrections to the collected data were performed off-line. We corrected for the systematic flux loss due to the insufficient frequency response of the measurement system by using a modified version of the method presented by Moore [1986]. The transfer function representing the performance of the LI-6262, including tube attenuation and sensor separation effects, was determined empirically with the sensible heat cospectrum as the reference. For the transfer function we used $\exp(\ln 2 \times f^2/f_0^2)$, where f is the frequency and f_0 is the half power frequency. From the spectral analysis of in situ data we obtained $f_0 = 1.6$ Hz for the CO₂ flux. In addition to the high-frequency correction, the flux loss at low frequencies due to the data detrending was taken into account with an appropriate transfer function. No density corrections related to heat and water vapor fluxes [Webb *et al.*, 1980] were necessary for the CO₂ and H₂O fluxes, because the LI-6262 corrects the CO₂ concentrations proportional to dry air, and the

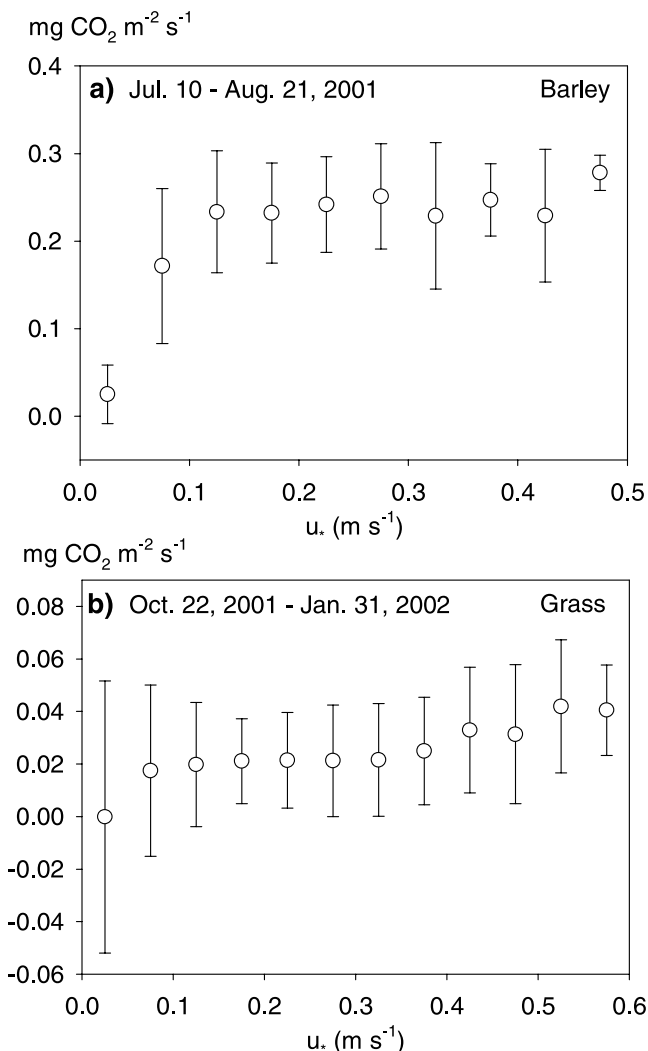


Figure 1. Medians (\pm standard deviation) of the half-hourly CO₂ flux plotted against the respective friction velocity class (a) during the growing season (nighttime data only) and (b) outside the growing season.

temperature fluctuations can be assumed to vanish in the tubing [Rannik *et al.*, 1997]. The instrumentation and the data processing procedures have been presented in more detail by Aurela *et al.* [1998, 2001b] and Tuovinen *et al.* [1998]. Throughout this paper, we use the convention that a positive flux value represents CO₂ transfer from the ecosystem into the atmosphere, whereas a negative flux means the reverse. All fluxes are expressed as CO₂ unless stated otherwise.

2.3. Supporting Meteorological and Plant Measurements

[9] Ancillary meteorological measurements were conducted on the study site with the following instruments: air temperature and humidity at canopy level (0.20 m) and at 2.5 m (Vaisala HMP230), soil temperature at depths of 0.05, 0.15, 0.30 and 0.50 m (PT100), soil humidity at depths of 0.15 and 0.30 m (ThetaProbe ML2x, Delta-T Devices Ltd), soil heat flux at a depth of 0.15 m (HFP01), net radiation, global radiation, reflected global radiation,

photosynthetic photon flux density (PPFD) and reflected PPFD (LI-COR-190SZ). The data were collected with a Vaisala QLI data logger as 30-min averages. The snow depth and the precipitation data as well as missing air temperature data were observed at the Jokioinen weather station, located 15 km to the south of the study site.

[10] During the growing season 2001, the leaf area index (LAI) was measured weekly with an LAI-2000 Plant Canopy Analyser (LI-COR, Inc.) at six points located within 100 m of the measurement towers. The aboveground plant biomass was measured by clipping the plants from two 0.125 m² areas. In 2002, LAI was measured weekly with the LAI-2000 from the middle of May until the latter half of July, and less frequently after that. Measurements were made in eight directions to a distance of about 100–150 m from the tower, making records every 1–1.5 m. Samples of aboveground biomass were collected at the harvests by clipping 5–8 quadrates (0.6 m \times 0.6 m each), oven-drying the samples at 40°C and weighing them, except in September 2002, when the biomass was estimated on the basis of LAI and the grass height. The grain yield in 2001 was determined with a threshing machine (Sampo 2055) by harvesting an area of 0.16 ha. The grains were weighed and their humidity content was measured inside the threshing machine. In 2002, the forage yield was achieved by weighing three of the trailer loads at both harvests and counting the total number of loads.

2.4. Data Screening and Gap Filling of Eddy Covariance Data

[11] There were some longer and several shorter gaps in the data, mainly caused by power breaks or instrument failure. The longest gaps, of 11 days, took place in October–November 2000 and in January 2002. Also the three other longer gaps (>6 days) occurred during the winter. The collected data were carefully screened by using strict quality criteria. High sensor variance within the 30-min averaging period, spikes in the anemometer data, abnormally high difference in the temperatures measured with the sonic anemometer and the HMP230, or inadequate turbulent conditions caused the data to be rejected.

[12] It is well known that under stable temperature stratification, typically occurring during summer nights, EC measurements may underestimate the vertical flux. To avoid this bias, we studied the dependence of the CO₂ flux on the friction velocity (u_*). As illustrated in Figures 1a and 1b, both the nighttime and wintertime fluxes measured below $u_* < 0.10$ m s⁻¹ were underestimated. Thus, during the growing season, we rejected all nighttime data with $u_* < 0.10$ m s⁻¹, and also all daytime data with $u_* < 0.05$ m s⁻¹. Similarly, outside the growing season, only data with a friction velocity above 0.10 m s⁻¹ were used in the further analysis. Furthermore, we used a stability criterion (inverse Obukhov length < 0.06 m⁻¹) to minimize the effect of the forest and adjacent fields. After fulfilling all these criteria, the data covered 49% of all half hours during the period from 13 October 2000 to 12 October 2002.

[13] In order to calculate the CO₂ balance over a longer time period, all gaps in the data had to be filled. The method of substitution for CO₂ flux data was dependent on the time of year and the number of missing values. Outside the growing season, the shorter gaps were filled using running

averages (with 3 to 9 day windows), while the longer gaps were filled using temperature response functions for the soil respiration. For the parameterization of the respiration model, the data (with $u_* > 0.15 \text{ m s}^{-1}$) preceding and following the gap were used.

[14] During the periods with photosynthetic CO₂ uptake, all the gap-filling was performed using semiempirical response functions which, for quality reasons, were only calibrated using nighttime data having $u_* > 0.15 \text{ m s}^{-1}$ and daytime data having $u_* > 0.10 \text{ m s}^{-1}$. The parameterization of gross photosynthesis (GP) was based on a commonly used nonlinear radiation response function [e.g., *Ruimy et al.*, 1995], so NEE can be written as:

$$NEE = \left(\frac{\alpha \times PPFD \times GP_{\max}}{\alpha \times PPFD + GP_{\max}} \right) + R_{\text{tot}} \quad (1a)$$

where α is the apparent quantum yield (in $\text{mg } \mu\text{mol}^{-1}$), GP_{\max} ($\text{mg m}^{-2} \text{ s}^{-1}$) is the maximum GP as $PPFD \rightarrow \infty$, and R_{tot} is the total ecosystem respiration. For filling the data gaps, the GP function was extended to explicitly account for the seasonal development in the photosynthesis and plant respiration, and for the effect of atmospheric vapor pressure deficit (VPD). The equation for NEE then takes the form:

$$NEE = VPDI \times PI \times \left(\frac{\alpha^* \times PPFD \times GP_{\max}^*}{\alpha^* \times PPFD + GP_{\max}^*} \right) + R_s + R_d \quad (1b)$$

For the seasonal effects, we employed the concept of effective phytomass index (PI) developed by *Aurela et al.* [2001a]. PI is an empirically determined coefficient, calculated as the difference between the measured average nighttime ($PPFD < 1 \mu\text{mol m}^{-2} \text{ s}^{-1}$) and daytime ($PPFD > 700 \mu\text{mol m}^{-2} \text{ s}^{-1}$) NEE. PI was normalized to unity at its annual maximum measured in about the middle of July in both years. Although LAI is an independent estimate of the canopy development, it is affected only by the biomass of the aboveground vegetation. PI also takes into account the changes in plant activity, and is able to decrease, e.g., after a cold spell. Furthermore, LAI measurements based on light penetration through the canopy may only be reliably used before the beginning of plant senescence, whereas PI also works during the senescence period. Hence PI was used in the gap-filling during both growing seasons. The effect of VPD on assimilation was taken into account during a few modeling periods in the peak growing season. The vapor pressure deficit index (VPDI) takes a value of 1 when $VPD < 0.5 \text{ kPa}$ and decreases linearly from 1 to 0.45 as VPD increases from 0.5 to 2 kPa. Since in equation (1b) the GP function is multiplied with PI and with VPDI, the explicit meaning of the parameters in equation (1b) is not same as in equation (1a), and these have been therefore marked with an asterisk (GP_{\max}^* and α^*).

[15] R_{tot} was further divided into plant dark respiration (R_d) and soil respiration (R_s) (equation (1b)). The soil respiration was calculated as done by *Lloyd and Taylor* [1994]:

$$R_s = R_{s10} \times \exp \left[E_0 \left(\frac{1}{T_1} - \frac{1}{T_s - T_0} \right) \right] \quad (2)$$

where R_{s10} is a parameter describing the soil respiration (in $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) at the reference temperature 283 K, $T_1 = 56.02 \text{ K}$, and $T_0 = 227.13 \text{ K}$. T_s is the soil temperature (in K) and E_0 is a parameter describing the temperature response of the soil respiration. Here we have used a value of $E_0 = 308 \text{ K}$ which, according to *Lloyd and Taylor* [1994], is applicable for a wide range of different soils. In the gap-filling of the growing season data we have used the average soil temperature as T_s . In wintertime, the soil temperature at a depth of 0.05 m was used, because during the longer gaps the meteorological measurements were also usually missing and soil temperatures at a depth of 0.05 m from a nearby site were used instead.

[16] A function based on the Arrhenius equation was used for the calculation of the plant dark respiration [e.g., *Baldocchi*, 1994; *Aurela et al.*, 2001a]:

$$R_d = PI \times R_{d10} \times \exp \left[\frac{E_a}{R} \left(\frac{1}{T_0} - \frac{1}{T_l} \right) \right] \quad (3)$$

where R_{d10} is the rate of plant dark respiration (in $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) at the reference temperature $T_0 = 283 \text{ K}$. T_l is the leaf temperature (in K), E_a is the activation energy and R is the universal gas constant ($8.314 \text{ J K}^{-1} \text{ mol}^{-1}$). On the basis of other studies [*Baldocchi*, 1994; *Gent and Kiyomoto*, 1992; *Kim et al.*, 1992] and initial fitting procedures on the present data, we selected a constant value of $E_a = 45,000 \text{ J mol}^{-1}$ to describe the temperature dependence of the plant dark respiration of barley and undersown grass. To limit the number of free parameters, a constant value of $R_{d10} = 0.1 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ was used.

[17] During the growing seasons the parameters for the photosynthesis and for the soil and plant dark respiration equations were derived separately for about 2- to 3-week periods. The length of these periods was determined by taking into account the timing of the cultivation practices or other factors (like phenology or drought) clearly affecting the magnitude of the fluxes.

3. Results

3.1. Meteorological Conditions

[18] The mean temperature for the year from October 2000 to September 2001 was 5.9°C , being 2.0°C above the long-term average (Table 1). The next period of one year was very similar with regard to the mean temperature (5.8°C), but the precipitation (502 mm) was only two thirds of that observed during the previous yearly period (719 mm). The most significant differences between the years were observed in autumn and at the beginning of the winter. While the period from October 2000 to January 2001 was $3^\circ\text{--}6^\circ\text{C}$ warmer than in 1961–1990, the corresponding period in 2001–2002 was closer to normal in temperature. In 2002, the mean monthly temperature for February was almost 6°C above the normal. Summer temperatures were mostly close to the long-term average. However, in both years, July was $2^\circ\text{--}3^\circ\text{C}$ warmer than normal. In autumn 2001, the monthly precipitation was above normal, while, in contrast, the period from August 2002 onward, was very dry.

[19] During the study period, the soil water content (SWC) at a depth of 0.15 m ranged from 0.28 to $0.62 \text{ m}^3 \text{ m}^{-3}$ (Figure 2f). In 2001, the minimum SWC was observed in

Table 1. Monthly Mean Temperature and Total Precipitation From October 2000 to October 2002 Together With the Corresponding Long-Term Averages (1961–1990) at a Nearby Weather Station^a

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Oct.–Sept. Averages
<i>Air Temperature, °C</i>													
2000	-	-	-	-	-	-	-	-	-	8.1	3.8	0.7	
2001	-2.3	-8.4	-4.2	5.1	8.6	13.6	18.9	15.3	11.2	7.3	-0.7	-8	5.9 ^b
2002	-4.5	-1.7	-0.5	5.2	11.3	15.3	18.2	17.9	10.1	-0.4			5.8 ^c
Long term	-7.5	-7.4	-3.5	2.4	9.4	14.3	15.8	14.2	9.4	4.7	-0.5	-4.9	3.9
<i>Precipitation, mm</i>													
2000	-	-	-	-	-	-	-	-	-	61	93	50	
2001	23	32	34	56	37	53	73	71	136	80	38	20	719 ^b
2002	71	40	33	2	32	95	66	13	12	26			502 ^c
Long term	36	24	25	31	35	47	80	83	65	58	55	42	581

^aData are from *Finnish Meteorological Institute* [1991].^bThe mean of October 2000 to September 2001.^cThe mean of October 2001 to September 2002.

late August, whereas in 2002 the SWC decreased sharply to 0.35 m³ m⁻³ in June but, following a 3-week rainy period, returned to about 0.4–0.5 m³ m⁻³. During the anomalously dry August 2002, the SWC decreased to 0.28 m³ m⁻³, but still did not reach the wilting point. However, unlike in earlier autumns, the SWC did not return close to the field capacity even in the deeper soil, being still low at the time of soil freezing. The snow cover on the site was discontinuous during both winters and relatively shallow, at most about 30 cm. In 2000 the lasting snow cover appeared late, in the last half of December, whereas in 2001 the first snow fell in October and more permanent snow in November. The final snow melt took place at the end of March.

3.2. Seasonal Periods

[20] To study the effect of different seasons and meteorology on the CO₂ exchange, as well as to compare the different years, the study period was divided into four seasons based on meteorological observations: the growing season, autumn, winter and spring (Figure 2). The growing season and winter were here defined following the practice commonly used in the Finnish Meteorological Institute [Helminen, 1988; Kolkki, 1969]. According to that, the thermal growing season begins when the daily average air temperature stays above 5°C for 5 days. In addition, the sum of the mean temperatures of the following 5 days has to be 20°C or more. Similarly, the thermal growing season ends when the daily air temperature stays below 5°C. In practice the definitions are not that straightforward, and there are several exceptions to the abovementioned definitions. For example, the occurrence of snow cover and night frosts causes deviations from the five-degree rules. The thermal winter begins when the mean daily temperature falls below 0°C, and finishes when it has steadily increased above zero. Autumn and spring were in this study determined as the seasons between the thermal growing season and the thermal winter.

3.3. Growing Season Pattern of NEE

[21] A small positive NEE, indicating a CO₂ flux from the soil into the atmosphere, was observed during a large part of the year (Figure 2a). After the start of the assimilation period, both the nighttime CO₂ release and the daytime uptake increased rapidly in concert with the leaf area

development (Figures 2a and 3). In both years the nocturnal respiration peaked at 0.35 mg m⁻² s⁻¹, and the minimum daily NEE was about -1.0 and -0.75 mg m⁻² s⁻¹ in 2001 and 2002, respectively. The highest instantaneous respiration and assimilation rates were measured in July. The strong decline in the photosynthetic CO₂ uptake may be seen in growing season 2002 after both grass harvests (indicated with “Ha” in the Figure 2a). No such decline was observed after the harvest in 2001, because the crop was already mature at harvest time and the photosynthetic activity of the barley had decreased markedly before that. The maximum values are comparable to those presented in earlier studies. *Biscoe et al.* [1975] measured similar maximum daytime uptake rates in their barley field (-1.0 mg m⁻² s⁻¹), but lower respiration rates (about 0.15 mg m⁻² s⁻¹). In wheat, twice as high uptake rates, about -2.0 mg m⁻² s⁻¹, have been measured in the peak growing season [Baldocchi et al., 1994]. Again, their nighttime respiration was lower than that in our study, about 0.15 mg m⁻² s⁻¹. The lower respiration rates are probably due to the lower soil respiration from mineral soils. In a natural northern grassland in Canada, the highest daytime CO₂ uptake values were -0.6 mg m⁻² s⁻¹ [Flanagan et al., 2002], whereas *Suyker and Verma* [2001] reported maximum daytime uptake of -1.4 mg m⁻² s⁻¹ in a tall grass prairie in the United States.

[22] In 2001, owing to the late sowing of the barley and undersown grass, the assimilation period did not start until the beginning of June, about 1.5 months after the onset of the thermal growing season. Hence the fairly long period with high PPFD and favorable air and soil temperatures could not be utilized in growth (Figures 2b–2d), as the soil was bare from the snowmelt in April until the barley emergence in early June. After that, the evolution of the daytime CO₂ uptake and the nighttime respiration rates was rapid. The assimilation intensity, represented by the phyto-mass index (PI) derived from the flux measurements, closely followed the leaf area growth (Figure 3). The decline in the assimilation was also rapid, and during the last two weeks of August the daytime NEE had already dropped to a level of -0.1 mg m⁻² s⁻¹. Barley was harvested very late, in September, due to rainy weather. Finally the photosynthesis of the undersown grass ceased at the beginning of October when the surface soil froze.

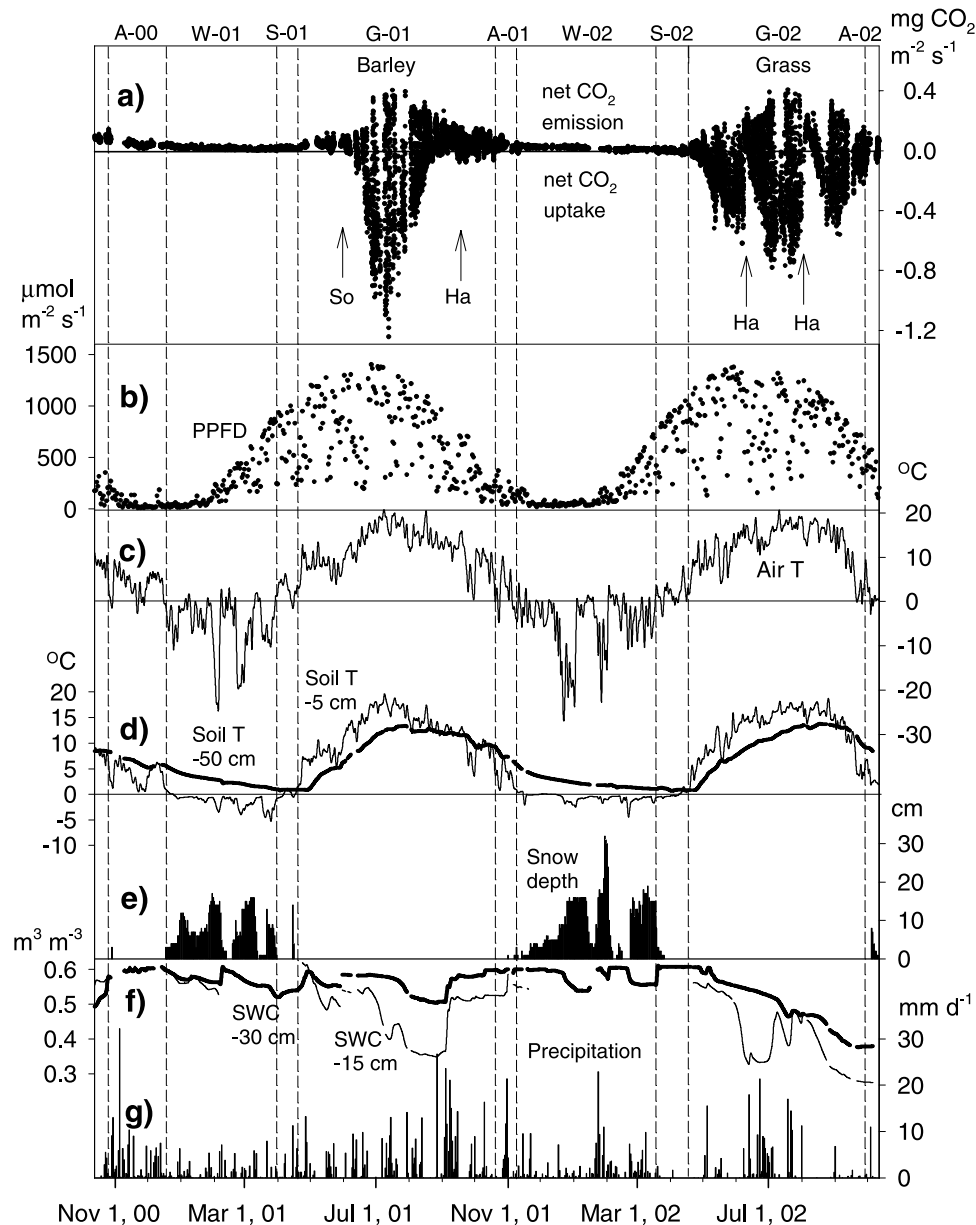


Figure 2. Measured values of (a) the half-hourly NEE, (b) the daily mean of the midday (1000–1600, local time) photosynthetic photon flux density (PPFD), (c) daily mean air temperature at 2 m above the ground, (d) daily mean soil temperatures at depths of 0.05 and 0.50 m e) snow depth, (f) soil volumetric water content at depths of 0.15 and 0.30 m in unfrozen soil, and (g) daily precipitation during the study period from 13 October 2000 to 12 October 2002. The seasonal periods are shown at the top (A, autumn; W, winter; S, spring; G, growing season). Arrows indicate the time of sowing (“So”) and harvest (“Ha”).

[23] In 2002, a small CO₂ uptake by grass already commenced in the middle of March when the first 0.20 m of the soil was still frozen. However, a more notable and strongly increasing assimilation began on 23 April, only three days after the beginning of the thermal growing season. The onset of continuous photosynthesis coincided with the soil’s thorough thawing. Before the first harvest on 7–10 June, the highest observed daytime net CO₂ uptake values were about $-0.45 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. An even greater instantaneous uptake, about $-0.7 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, was observed between the first and second harvests. An explanation for the difference is the sparse vegetation and

relatively low LAI (<3) before the first harvest (Figure 3), resulting from the wet autumn of 2001, when the heavy rains flattened the barley crop. In many places the grass was choked by the laid-down barley, and next spring after the snowmelt there were patches of bare soil on the field. The grass then gradually spread to these spots in the course of the summer, leading to the higher average LAI before the second harvest.

[24] Figure 4 shows the hyperbolic relationship between NEE and PPFD for the peak growing season period for both years. The reason for the higher daily net CO₂ uptake of barley (see Figures 5a and 5b) was predominantly the higher

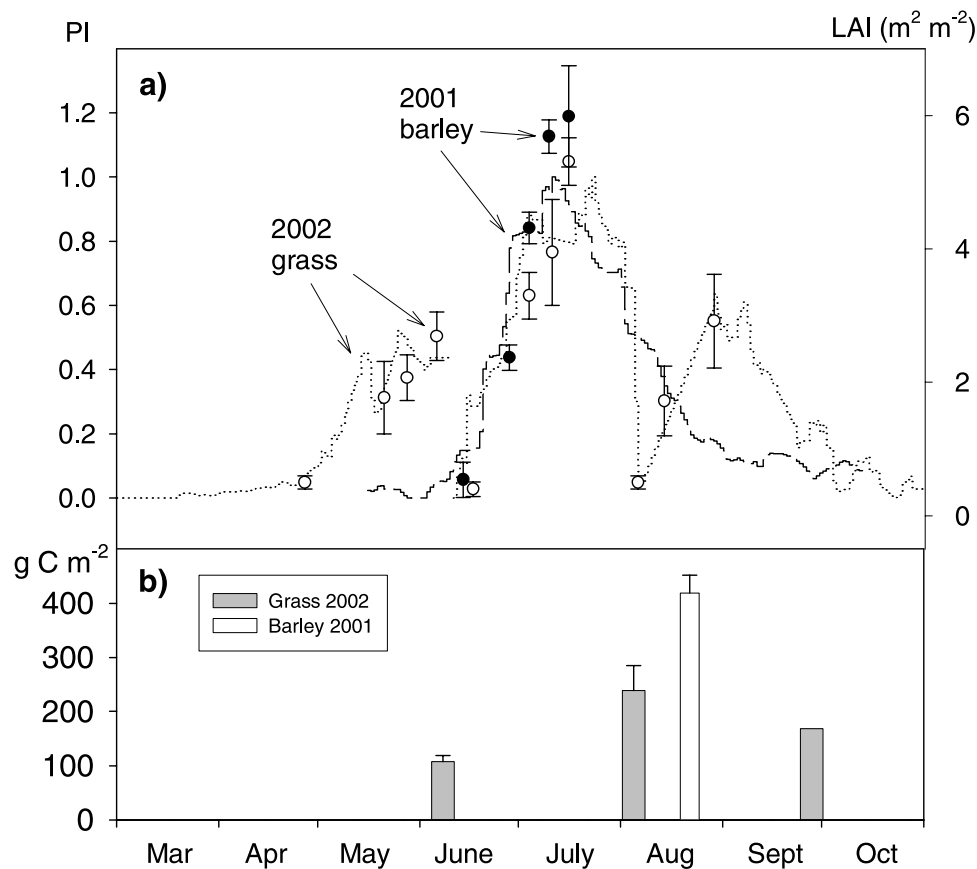


Figure 3. (a) Seasonal variation of PI (phytomass index) and measured LAI (\pm standard error) in 2001 (solid circles and dashed line) and 2002 (open circles and dotted line) and (b) the accumulated aboveground biomass at peak biomass (2001) at each harvest and at the end of the growing season (2002).

GP_{max} of barley, not the higher respiration of grass. On the contrary, the total ecosystem respiration (R_{tot}) (as estimated from the hyperbolic fit with equation (1a)) during the peak period was actually higher for barley ($0.30 \text{ mg m}^{-2} \text{ s}^{-1}$) than for grass ($0.24 \text{ mg m}^{-2} \text{ s}^{-1}$). The greater maximum LAI of barley possibly partly explains the difference in the GP_{max} (Figure 3a), though the influence of VPD may have also been moderate. However, the apparent quantum yield (α) during the peak growing season was similar for both barley and grass.

3.4. Winter CO₂ Efflux

[25] The timing of the winter period according to the abovementioned definition also varied between the two years. In autumn 2000, soil freezing and the onset of the thermal winter took place later than normal, in the middle of December, whereas in the next year the winter began at the beginning of November (Figure 2a). The ending date of the winter varied less between the years, from 29 March to 18 March. Consequently, the duration of the winter period was 103 and 133 days in 2000–2001 and 2001–2002, respectively. In general, during the wintertime the field acted as a small but persistent CO₂ source, despite the freezing of the first 0.40 m of the soil. During the two consecutive winters with different crop types, there were practically no differences in the average wintertime CO₂ efflux (\pm standard deviation), which were 16.5 ± 7.6 and 15.6 ± 9.4 in the first and second winter period, respectively.

The lowest monthly fluxes of the two annual periods were 10.7 ± 5.2 and $8.3 \pm 3.7 \mu\text{g CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, both measured in February. As we are not aware of published data on wintertime NEE on snow-covered agricultural fields measured with the EC method, results achieved with other methods were used in comparison. Fluxes from our site were smaller than those measured with a snow gradient method in a sandy loam soil growing barley in Canada, where the respiration rate from the snow-covered, unfrozen soil ranged from 15 to $78 \mu\text{g CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in February and March 1994–1997 [van Bochove et al., 2000]. Koizumi et al. [1996] reported CO₂ fluxes of a nearly equal magnitude to ours, about $8 \mu\text{g CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, in practically the same peat soil as ours using the snow gradient and closed chamber method. In agricultural sandy and clay soils the CO₂ production rates were smaller, ranging from 3 to $6 \mu\text{g CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ [Koizumi et al., 1996]. In a peat soil grassland in eastern Finland, clearly higher wintertime emissions of $2.9 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, equivalent to $34 \mu\text{g CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, have been measured with the chamber technique [Alm et al., 1999].

3.5. Daily CO₂ Balances

[26] As shown earlier, the first photosynthetic uptake by barley was observed at the beginning of June 2001, about a week after the sowing. However, it was two more weeks before the daily NEE became slightly negative for the first time, i.e., before the net assimilation exceeded the

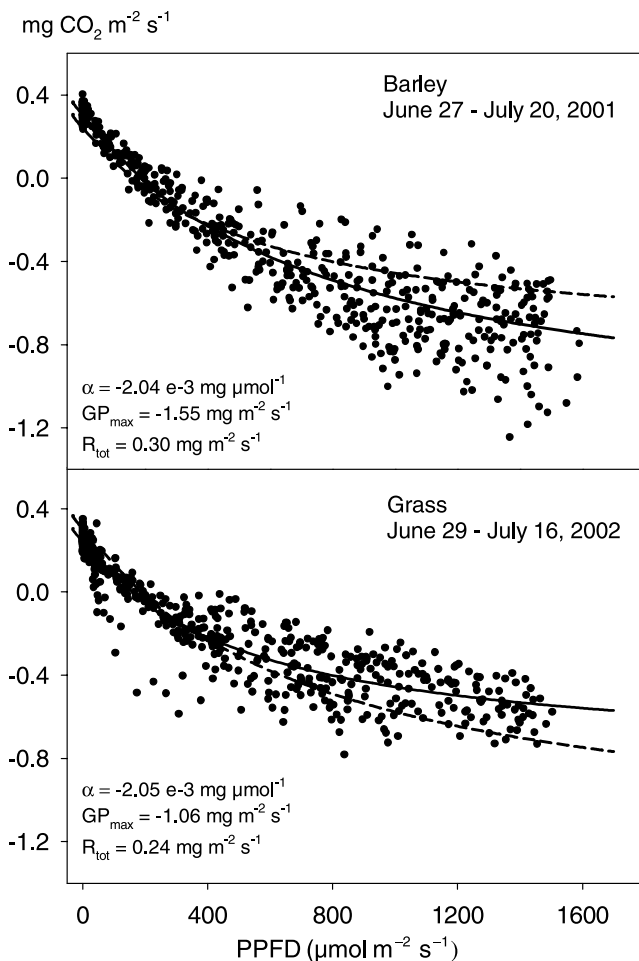


Figure 4. Half-hourly NEE versus PPFD during the peak growing season in (top) 2001 and (bottom) 2002. The full curve shows a fit to the data (equation (1a)). For comparison, the dashed line is the fit of the other year's data.

soil respiration and the ecosystem accumulated carbon on a daily basis (Figure 5a). The barley field acted as a daily sink for CO₂ from the last week of June until the beginning of August, the highest net uptake being about $-20 \text{ g m}^{-2} \text{ d}^{-1}$, except during cloudy or rainy days on which there was a net emission of CO₂ from the barley field to the atmosphere. At the beginning of August the daily NEE turned positive again. Thus the length of the net CO₂ uptake period for barley was less than six weeks. The drop in the photosynthesis, caused by the senescence of the plants and the decreasing radiation level, was more pronounced than that in the respiration, and relatively high mean daily emissions of $10 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, with a maximum of $16 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, were observed until mid-September.

[27] In 2002, the first day with a daily negative NEE was in 6 May (Figure 5b), about 1.5 months earlier than in the preceding year with barley. The daily CO₂ uptake increased to about $-10 \text{ g m}^{-2} \text{ d}^{-1}$ before the first cutting, and was even higher in July before the second cutting. After both cuttings, large CO₂ emissions, more than $10 \text{ g m}^{-2} \text{ d}^{-1}$ was observed. The respiration was higher after the second cutting, which is most likely explained by the higher root

biomass and warmer deep soil temperatures during the late summer. The last day with negative NEE and also the first day with a negative daily air temperature was 21 September.

[28] In general, the season with a net CO₂ uptake was considerably shorter for the barley than for the grass: in 2001 the daily net balance was only negative for 39 days, as against 84 days in 2002. The net CO₂ uptake on a daily basis was, however, higher for barley than for grass, peaking at about -20 and $-15 \text{ g m}^{-2} \text{ d}^{-1}$, respectively (Figures 5a and 5b). These daily NEE values are considerably lower than those reported by *Soegaard et al.* [2003] for spring barley in Denmark (NEE peaking at about $-40 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) and by *Anthoni et al.* [2004] for winter wheat in Germany ($-44 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$). The markedly lower daily NEE from the Jokioinen barley site is not unexpected, since the other studies were conducted on mineral soils. The contribution of soil respiration to the daytime NEE is probably much greater in the peat soil, where the soil respiration may be many-fold as compared to that in the mineral soils [Lohila et al., 2003]. On the other hand, the effect of the climatic conditions, such as the maximum PPFD level or the temperature conditions, cannot be totally excluded.

[29] The daily wintertime fluxes in the Jokioinen peat field varied from 0.5 to $2 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ (Figures 5a and 5b), being higher early in winter and smallest at the end of the winter season as the deeper soil layers gradually cooled down.

3.6. Annual NEE and NEP

[30] Integration of measured and calculated NEE data from two consecutive yearly periods (13 October 2000 to 12 October 2001 and 13 October 2001 to 12 October 2002) resulted in CO₂ balances of 771 and $290 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ (or 210 and $79 \text{ g C m}^{-2} \text{ yr}^{-1}$) for the agricultural peat soil growing barley and grass, respectively. The uncertainties for these balances were 104 and $91 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$, respectively (Appendix A). The large annual CO₂ release was most probably related to the high decomposition rate of the peat material, exceeding the amount of the CO₂ fixed by the crop vegetation.

[31] The difference between the years was mainly related to crop species having a different seasonal behavior. First of all, the onset of photosynthesis in perennial grass already took place in March and the actual growth started in April. This was not the case with the barley field, which was vegetation-free until the early June. As illustrated in Figure 6, the most outstanding difference between the years took place in the May–June period, during which the grass field fixed more than $100 \text{ g CO}_2 \text{ m}^{-2}$, while in the corresponding period the barley field released about $200 \text{ g CO}_2 \text{ m}^{-2}$. Second, in 2002 the growing season was prolonged due to frequent cuttings, keeping the grass in the vegetative stage throughout the growing season, whereas the barley rapidly progressed through its growth stages and was practically mature by the middle of August. Accordingly, the number of days with net CO₂ uptake was far higher in 2002 as compared to 2001, although the thermal growing season was 17 days longer in 2001. This difference can be also seen in the growing season mean daily NEE, which was 2.0 and $-0.4 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2001 and 2002, respectively (Table 2). However, there was

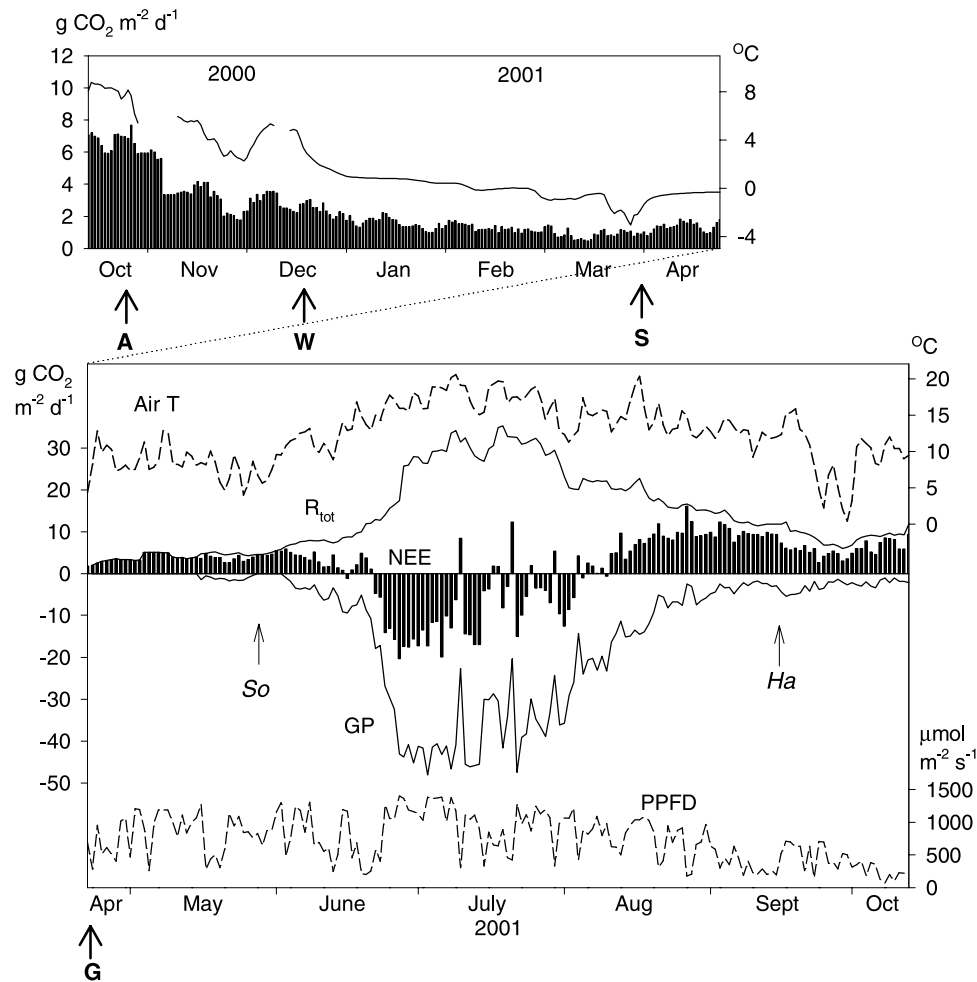


Figure 5a. Daily sums of the net ecosystem CO₂ exchange (NEE, black bars), total respiration (R_{tot} , top line) and gross production (GP, bottom line) between 13 October 2000 and 12 October 2001. Also shown are the daily mean air temperature and the mean of the midday (1000–1600, local time) PPFD. (top) Daily NEE sums from 13 October to the end of the spring season together with the soil $T_{-0.15\text{m}}$. (bottom) Period from the beginning of the growing season to 12 October. The thin arrows indicate the time of sowing (“So”) and harvest (“Ha”). The thick arrows show the beginning of the seasonal period with the same abbreviations as in Figure 1.

practically no difference in the mean daily winter emission between the years.

[32] In addition to the differences in the crops, the meteorological conditions also contributed to the annual balances. The annual periods were practically identical in terms of mean temperature, while the precipitation was considerably higher during the first yearly period. However, even though the mean annual temperatures were similar, the seasonal temperature means were not. For example, during the first annual period, the first and last months (13 October to 31 December 2000 and 1 September to 12 October 2001) were about 3°C warmer than in the corresponding months of the second annual period. This can be also seen in the cumulative NEE during October–November and August–October, the growth rate being higher in 2000–2001 than in 2001–2002 (Figure 6). Nevertheless, with two years of data including two different crops, it is impossible to quantitatively determine the contribution of the meteorology to the annual CO₂ balances.

[33] The amount of maximum accumulated aboveground biomass, estimated from the biomass clipping, was 419 g C m⁻² in barley, measured in late August after the barley ripening (Figure 3b). In grass, the clippings were done during the harvests in June and August, resulting in aboveground biomasses of 107 and 239 g C m⁻², respectively. In September, when the growth had ceased, no clipping was done. Instead, the biomass was estimated based on LAI and grass height measurements, as there seemed to be a linear relationship between these and the biomass (results not shown). By summing the biomasses from June and August with this estimate (168 g C m⁻²) the total amount of accumulated aboveground biomass was found to be 581 (107 + 239 + 168) g C m⁻² (Figure 3b).

[34] However, in agricultural ecosystems the ultimate carbon balance is strongly affected by human disturbance, as typically a considerable proportion of the carbon produced is harvested and transported away from the field. In 2001, 126 g C m⁻² was exported from the site in the form

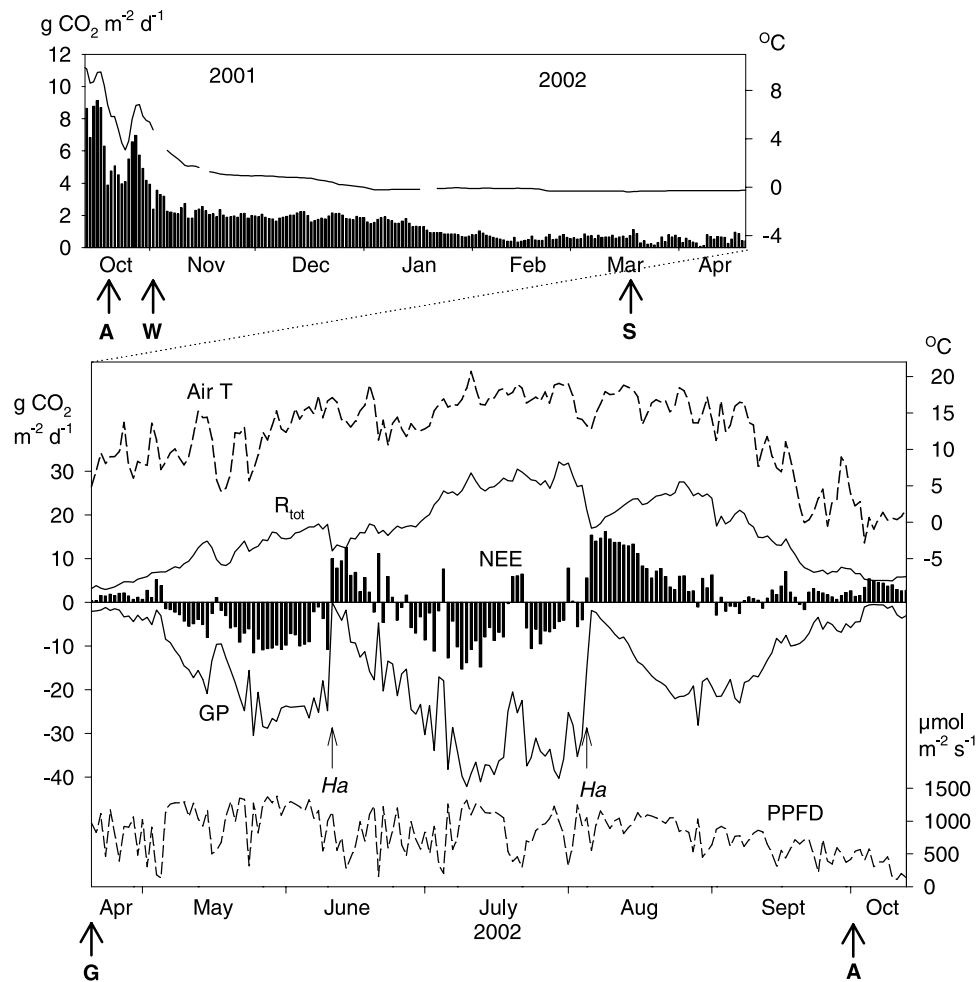


Figure 5b. As in Figure 5a, but between 13 October 2001 and 12 October 2002.

of barley grains, against 373 g C m^{-2} of harvested forage grass in 2002 (Table 3). The net ecosystem production (NEP), denoting the net accumulation or loss of C by an ecosystem is calculated by summing NEE and the exported amount of C. Thus the barley field lost 336 g C m^{-2} ($210 + 126$), whereas the C loss in the grass field was higher, 452 g C m^{-2} ($79 + 373$). This was a bit surprising, since at first glance one might expect that the crop with the longer CO₂ uptake period would have the lower NEP. However, the longer growing period was enabled by keeping the grass in a vegetative stage by means of cutting, and this also enhanced the biomass yield, contributing in turn to the NEP. Nevertheless, it seems probable that changing from an annual to a perennial crop does not necessarily help in turning the agricultural peat soil ecosystem into a carbon dioxide sink, at least during the first year after the switch.

[35] The annual emission estimates from the Jokioinen peat soil are among the highest published net CO₂ balances in any ecosystem, at least when only considering studies conducted with micrometeorological methods. Recently, *Anthoni et al.* [2004] presented the annual NEE sum for winter wheat in Germany. Their NEE estimate ranged between -680 and $-900 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$, but, after taking into account the harvested biomass, the wheat field was a source of C at a rate of $45\text{--}105 \text{ g C m}^{-2} \text{ yr}^{-1}$ (comparable

to our NEP). Most of the forest types investigated in Europe have been shown to be sinks of CO₂, the highest sink term exceeding $-2400 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ in the broadleaf evergreen and deciduous forests of southern Europe [*Valentini et*

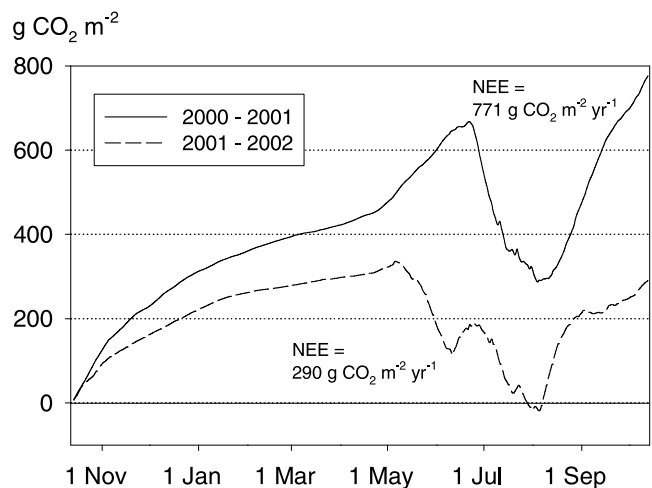


Figure 6. The cumulative sum of the daily NEE between 13 October and 12 October in 2000–2001 and 2001–2002.

Table 2. Seasonal Sums of Net CO₂ Exchange Between 13 October 2000 and 12 October 2002

Period	Description	Time ^a	g (CO ₂) m ⁻²	
			period ⁻¹	day ⁻¹
End of the growing season 2000	bare soil	13–25 Oct. 2000 (13)	88	6.7
Autumn 2000	bare soil	26 Oct. to 16 Dec. 2000 (52)	189	3.6
Winter 2000–2001	bare soil	17 Dec. 2000 to 29 March 2001 (103)	144	1.4
Spring 2001	bare soil	30 March to 21 April 2001 (23)	31	1.3
Growing season 2001	barley and undersown grass	22 April to 19 Oct. 2001 (181)	361	2.0
Autumn 2001	grass (plus remnants of barley)	20 Oct. to 5 Nov. 2001 (17)	65	3.8
Winter 2001–2002	grass	6 Nov. 2001 to 18 March 2002 (133)	182	1.4
Spring 2002	grass	19 March to 19 April 2002 (32)	17	0.5
Growing season 2002	grass	20 April to 30 Sept. 2002 (164)	–59	–0.4
Autumn 2002	grass	1–12 Oct. 2002 (12) ^b	43	3.5

^aLength of the period is given in parentheses (in days).

^bThe autumn period ended 2 days later.

al., 2000]. In a northern temperate grassland, the yearly carbon balance was -77 and 66 g CO₂ m⁻² yr⁻¹ during a normal and a dry year, respectively [Flanagan *et al.*, 2002]. The year-round measurements conducted on pristine wetlands have indicated that these ecosystems fix carbon at small or moderate rates. Lafleur *et al.* [2001] reported an annual uptake of -248 g CO₂ m⁻² for a Canadian bog peatland, whereas a smaller uptake, -68 g CO₂ m⁻² yr⁻¹, was observed in a subarctic fen in Finland [Aurela *et al.*, 2002].

4. Conclusions

[36] The cultivated peat soil was a source of CO₂ on a yearly basis, and the switch from an annual to a perennial species did not succeed in making the NEE of the peat field ecosystem negative (i.e., to the carbon sink), at least during the first year. The annual NEE of the peat soil growing spring barley in 2001 was 771 ± 104 g CO₂ m⁻² yr⁻¹, whereas the CO₂ release from the perennial grass in 2002 was 290 ± 91 g m⁻² yr⁻¹. These are among the highest reported annual CO₂ emissions for any ecosystem. The main reasons for the difference in annual balances were (1) 1 month of potential growing season was lost because of the late sowing of the barley, which is typical for peat soils, and (2) the grass was kept in the vegetative phase from April to September by harvesting, whereas barley progressed through all its growth stages in 2.5 months. Owing to the differences in GP_{max}, the daily CO₂ uptake was slightly higher in barley than in grass during the peak growing season. There was no detectable difference in winter efflux between the crops. Because of the higher accumulated biomass, the net ecosystem production (NEP) was higher for the grass than for the barley.

Appendix A: Uncertainty Analysis

[37] The uncertainty in the annual balance was assessed by examining some of the most important errors associated with the flux measurements and data processing. The error estimation presented here is by no means exhaustive, but tries to examine the magnitude of some of the most important errors. The errors are generally divided into random and systematic errors [e.g., Moncrieff *et al.*, 1996]. Following the approach used by Aurela *et al.* [2002], the random error (E_r) was calculated as the differ-

ence between the measured (F_{meas}) and modeled (F_{mod}) flux values as

$$E_r = \sqrt{\sum_{i=1}^n \frac{(F_{\text{meas}} - F_{\text{mod}})^2}{(n-1) \times n}}.$$

This estimate, however, also includes the uncertainties in the gap-filling model, and hence the random error of the flux measurement is less than E_r , which was 1.7 and 6.0% of the annual balances in 2001 and 2002, respectively. The underestimation of the nighttime fluxes is generally considered as one of the most significant systematic errors [Goulden *et al.*, 1996]. The problem was here addressed by substituting the flux values measured during calm periods with modeled values. However, the scarcity of nighttime CO₂ flux data leads to another possible error source: the uncertainty of the respiration model. This uncertainty was tested for a midsummer period with the least nighttime data in both years. The error was defined as the standard deviation of the normalized (to 10°C using equation (2)) accepted nocturnal flux values divided by the mean of the normalized values. This procedure resulted in relative errors of 11.7 and 14.0% in 2001 and 2002, respectively. A more conservative estimate of the error related to the scarcity of nocturnal data was obtained by allocating the relative error to the nighttime balances of longer time periods (3.5 and 4 months in 2001 and 2002, respectively) and to a wider radiation range (PPFD < 10 μmol m⁻² s⁻¹). By doing so, errors amounting to 10.9 and 29.0% of the annual balances were obtained in 2001 and 2002, respectively. Another error source is the correction for the missing high-frequency components of the measured cospectrum. The correction

Table 3. The Net Ecosystem Exchange (NEE), the Exported Biomass, and the Net Ecosystem Production (NEP) in 2001 and 2002^a

	2001	2002
NEE	210	79
Harvested biomass exported from the field	126 ^b	373 ^c
NEP	336	452

^aAll values have been expressed in g C m⁻². The biomass was converted into carbon by multiplying the dry weight by 0.42.

^bBarley grain yield; sampled on 21 September.

^cForage grass biomass; 118 g C m⁻² in June and 255 g C m⁻² in August.

relating to the high-frequency loss was typically about 15%, and assuming an uncertainty of 30% in the correction procedure as by Aurela *et al.* [2002], a relative uncertainty of about 4.5% will result. Errors in the CO₂/H₂O analyzer span concentration will introduce an additional error into the annual balance. The mean error in the analyzer span concentration was 2.3 ppm, leading to an error of 0.6% in the annual balances. The uncertainty in the yearly CO₂ balance caused by fluxes from the adjacent experimental plot of size 46 m × 30 m was greatest during the growing season and especially when the difference in the vegetation cover between the plot and the surrounding field was greatest. The largest difference in mean LAI (and in transient downward fluxes) between the plot and the studied field was about 100% at the time of a harvest of either one. Assuming that the difference and error during the whole growing season is on average 15% and using the mean frequency of the northwesterly wind direction (15 and 8% in 2001 and 2002, respectively), the relative errors were correspondingly 2.3 and 1.2%. Allocated to the sum of the calculated growing season gross production, uncertainties of about 6.4 and 9.1% are obtained in the annual balances of 2001 and 2002, respectively. Finally, the relative uncertainty was calculated in 2001 as

$$\sqrt{0.017^2 + 0.109^2 + 0.045^2 + 0.006^2 + 0.064^2} \\ = \pm 13.5\% (\pm 104 \text{ g CO}_2 \text{ m}^{-2} \text{ s}^{-1})$$

and in 2002 as

$$\sqrt{0.060^2 + 0.290^2 + 0.045^2 + 0.006^2 + 0.091^2} \\ = \pm 31.3\% (\pm 91 \text{ g CO}_2 \text{ m}^{-2} \text{ s}^{-1}).$$

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References

- Alm, J., S. Saarnio, H. Nykänen, J. Silvola, and P. J. Martikainen (1999), Winter CO₂, CH₄ and N₂O fluxes on some natural and drained boreal peatlands, *Biogeochemistry*, **44**, 163–186.
- Anthoni, P. M., A. Freibauer, O. Kolle, and E.-D. Schulze (2004), Winter wheat carbon exchange in Thuringia, Germany, *Agric. For. Meteorol.*, **121**, 55–67.
- Armentano, T. V., and E. S. Menges (1986), Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone, *J. Ecol.*, **74**, 755–774.
- Aurela, M., J.-P. Tuovinen, and T. Laurila (1998), Carbon dioxide exchange in a subarctic peatland ecosystem in northern Europe measured by eddy covariance technique, *J. Geophys. Res.*, **103**, 11,289–11,301.
- Aurela, M., J.-P. Tuovinen, and T. Laurila (2001a), Net CO₂ exchange of a subarctic mountain birch ecosystem, *Theor. Appl. Climatol.*, **70**, 135–148.
- Aurela, M., T. Laurila, and J.-P. Tuovinen (2001b), Seasonal CO₂ balances of a subarctic mire, *J. Geophys. Res.*, **106**, 1623–1637.
- Aurela, M., T. Laurila, and J.-P. Tuovinen (2002), Annual CO₂ balance of a subarctic fen in northern Europe: Importance of the wintertime efflux, *J. Geophys. Res.*, **107**(D21), 4607, doi:10.1029/2002JD002055.
- Baldocchi, D. (1994), A comparative study of mass and energy exchange rates over a closed C₃ (wheat) and an open C₄ (corn) crop: II. CO₂ exchange and water use efficiency, *Agric. For. Meteorol.*, **67**, 231–291.
- Biscoe, B. V., R. K. Scott, and J. L. Monteith (1975), Barley and its environment III: Carbon budget of the stand, *J. Appl. Ecol.*, **12**, 269–293.
- Finnish Meteorological Institute (1991), *Climatological Statistics in Finland 1961–1990, Supplement to the Meteorological Yearbook of Finland*, Helsinki.
- Flanagan, L. B., L. A. Wever, and P. J. Carlson (2002), Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate grassland, *Global Change Biol.*, **8**, 599–615.
- Gent, M. P. N., and R. N. Kiyomoto (1992), Canopy photosynthesis and respiration in winter wheat adapted and unadapted to Connecticut, *Crop Sci.*, **32**, 425–431.
- Gorham, E. (1991), Northern peatlands: Role in the carbon cycle and probable responses to climate warming, *Ecol. Appl.*, **1**, 182–195.
- Goulden, M. L., J. W. Munger, S.-M. Fan, B. C. Daube, and S. C. Wofsy (1996), Measurements of carbon sequestration by long-term eddy covariance: Methods and a critical evaluation of accuracy, *Global Change Biol.*, **2**, 169–182.
- Goulden, M. L., et al. (1998), Sensitivity of boreal forest carbon balance to soil thaw, *Science*, **279**, 214–217.
- Helminen, V. A. (1988), Temperature conditions, in *Atlas of Finland, Folio 131, Climate*, edited by P. Alalammi, pp. 4–10, Natl. Board of Surv. and Geogr. Soc. of Finl., Helsinki.
- Kim, J., S. B. Verma, and R. J. Clement (1992), Carbon dioxide budget in a temperate grassland ecosystem, *J. Geophys. Res.*, **97**, 6057–6063.
- Koizumi, H., M. Kontturi, S. Mariko, and T. Mela (1996), Carbon dioxide evolution from snow-covered agricultural ecosystems in Finland, *Agric. Food Sci. Finland*, **5**, 421–430.
- Koizumi, H., M. Kontturi, S. Mariko, T. Nakadaï, Y. Bekku, and T. Mela (1999), Soil respiration in three soil types in agricultural ecosystems in Finland, *Acta Agric. Scand., Ser. B*, **49**, 65–74.
- Kolkki, O. (1969), Katsaus Suomen ilmastoon, *Ilmatieteen laitoksen tiedontantaja 18*, Ilmatieteen laitös, Helsinki.
- Kosov, V. I. and V. N. Kreshtapova (1996), The peat resources of Russia and their utilization, in *Global Peat Resources*, edited by E. Lappalainen, pp. 127–131, Int. Peat Soc., Jyväskylä, Finland.
- Laffleur, P. M., N. T. Roulet, and S. W. Admiral (2001), Annual cycle of CO₂ exchange at a bog peatland, *J. Geophys. Res.*, **106**, 3071–3081.
- Lloyd, J., and J. A. Taylor (1994), On the temperature dependence of soil respiration, *Funct. Ecol.*, **8**, 315–323.
- Lohila, A., M. Aurela, K. Regina, and T. Laurila (2003), Soil and total ecosystem respiration in agricultural fields: Effect of soil and crop type, *Plant Soil*, **251**, 303–317.
- Maljanen, M., P. J. Martikainen, J. Walden, and J. Silvola (2001), CO₂ exchange in an organic field growing barley or grass in eastern Finland, *Global Change Biol.*, **7**, 679–692.
- McMillen, R. T. (1988), An eddy correlation technique with extended applicability to non-simple terrain, *Boundary Layer Meteorol.*, **43**, 231–245.
- Moncrieff, J. B., Y. Malhi, and R. Leuning (1996), The propagation of errors in long-term measurements of land-atmosphere fluxes of carbon and water, *Global Change Biol.*, **2**, 231–240.
- Moore, C. J. (1986), Frequency response corrections for eddy correlation systems, *Boundary Layer Meteorol.*, **37**, 17–35.
- Myllys, M. (1996), Agriculture on peatlands, in *Peatlands in Finland*, edited by H. Vasander, pp. 64–71, Finn. Peatland Soc., Helsinki.
- Nykanen, H., J. Alm, K. Lång, J. Silvola, and P. J. Martikainen (1995), Emissions of CH₄, N₂O and CO₂ from a virgin fen and a fen drained for grassland in Finland, *J. Biogeogr.*, **22**, 351–357.
- Paustian, K., C. V. Cole, D. Sauerbeck, and N. Sampson (1998), CO₂ mitigation by agriculture: An overview, *Clim. Change*, **40**, 135–162.
- Rannik, Ü., T. Vesala, and R. Keskinen (1997), On the damping of temperature fluctuations in a circular tube relevant to the eddy covariance measurement technique, *J. Geophys. Res.*, **102**, 12,789–12,794.
- Ruimy, A., P. G. Jarvis, D. D. Baldocchi, and B. Saugier (1995), CO₂ fluxes over plant canopies and solar radiation: A review, *Adv. Ecol. Res.*, **26**, 1–68.
- Soegaard, H., N. O. Jensen, E. Boegh, C. B. Hasager, K. Schelde, and A. Thomsen (2003), Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modelling, *Agric. For. Meteorol.*, **114**, 153–173.
- Solantie, R. (1990), The climate of Finland in relation to its hydrology, ecology and culture, *Contrib. 2*, Finn. Meteorol. Inst., Helsinki.
- Suyker, A. E., and S. B. Verma (2001), Year-round observations of the net ecosystem exchange of carbon dioxide in a native tallgrass prairie, *Global Change Biol.*, **7**, 279–290.
- Suyker, A. E., S. B. Verma, and G. G. Burba (2003), Interannual variability in net CO₂ exchange of a native tallgrass prairie, *Global Change Biol.*, **9**, 255–265.
- Tuovinen, J.-P., M. Aurela, and T. Laurila (1998), Resistances to ozone deposition to a flark fen in the northern aapa mire zone, *J. Geophys. Res.*, **103**, 16,953–16,966.

- Valentini, R., et al. (2000), Respiration as the main determinant of carbon balance in European forest, *Nature*, *404*, 861–865.
- van Bochove, E., H. G. Jones, N. Bertrand, and D. Prévost (2000), Winter fluxes of greenhouse gases from snow-covered agricultural soil: Intra-annual and interannual variations, *Global Biogeochem. Cycles*, *14*, 113–125.
- Webb, E. K., G. I. Pearman, and R. Leuning (1980), Correction of flux measurements for density effects due to heat and water vapour transfer, *Q. J. R. Meteorol. Soc.*, *106*, 85–100.
- Yli-Halla, M., and D. L. Mokma (2001), Soils in an agricultural landscape of Jokioinen, south-western Finland, *Agric. Food Sci. Finl.*, *10*, 33–43.
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