

# Effect of drainage on CO<sub>2</sub> exchange patterns in an intensively managed peat pasture

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**ABSTRACT:** Eddy correlation measurements of CO<sub>2</sub> exchange ( $F$ ) were made in intensively managed peat pastures at 2 different groundwater tables during most of a growing season.  $F$  was separated into a respiratory ( $F_r$ ) and an assimilatory ( $F_a$ ) CO<sub>2</sub> flux. The fit of the Arrhenius temperature response to  $F_r$  showed that  $F_r$  was generally higher at low groundwater tables. The fit of a hyperbolic irradiance response to  $F_a$  showed that  $F_a$  was also generally higher at low groundwater tables, more than compensating for higher  $F_r$ . The daily CO<sub>2</sub> balance suggested that the low groundwater pasture was a larger CO<sub>2</sub> sink or a smaller CO<sub>2</sub> source than the high groundwater pasture during the measurement period. The difference in  $F_r$  between the groundwater tables was substantially less than the factor 2 difference in level of soil subsidence. This suggests that oxidization of soil organic matter was a relatively minor factor in soil subsidence.

**KEY WORDS:** Eddy correlation · CO<sub>2</sub> exchange · Assimilatory flux · Respiratory flux · Pasture · Grassland · Peat · Drainage

## 1. INTRODUCTION

In assessing the global C balance, a major C sink has been noted for the northern hemisphere (Ciais et al. 1995). A combination of ecosystem processes, land use changes and spatially explicit biomes has shown that this global C sink is constituted by a complex of smaller C sinks and sources (Box 1988, Klein Goldewijk et al. 1994, King et al. 1995, Schimel 1995).

Land use has been seen as a major factor in the terrestrial C balance, in view of the different typical biome C contents (Wolf & Janssen 1991, King et al. 1995, Batjes & Sombroek 1997). Over the last centuries a world-wide conversion of natural and semi-natural grasslands and forests to arable land has constituted an important C source (Ojima et al. 1993, Schimel 1995). Management practices equally affect the C balance of agro-ecosystems. Parton et al. (1987) showed that increased grazing reduced the C content of grasslands;

Fisher et al. (1994) suggested that the introduction of deeply rooting grasses increased the C content of savannas.

Peatland constitutes an important biome because of its high soil C content. Like many ecosystems, peatland accumulates C under undisturbed (undrained) conditions and emits C (CO<sub>2</sub> by oxidization) under disturbed (drained) conditions (Oades 1988, Glenn et al. 1993, Francez & Vasander 1995, Nykänen et al. 1995, Laiho et al. 1996, Silvola et al. 1996). Peat soil subsidence after drainage is often seen as a rough measure for CO<sub>2</sub> emission, though little agreement exists on the fraction of the subsidence that can be attributed to oxidization (Schothorst 1982, Glenn et al. 1993). In the course of time, many peatlands have been partially drained and converted into forests (Laiho et al. 1996).

Of the total land area in The Netherlands, 10% consists of peat soils, whereas 30% of the pastures in The Netherlands are situated on peat soils that are drained to varying extents (Langeveld et al. 1997). Most of these pastures are centuries old, but only a few

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decades ago the drainage was intensified to improve management practices (Schothorst 1982); improved drainage also increased soil subsidence. This paper compares micrometeorological CO<sub>2</sub> flux measurements done in 1994 in these pastures at 2 different levels of drainage. It evaluates the instantaneous CO<sub>2</sub> flux characteristics and the CO<sub>2</sub> balance during several months in the growing season.

## 2. MATERIALS AND METHODS

**2.1. Experimental site.** Measurements were done at the experimental farm ROC Zegveld near Zegveld in The Netherlands (52° 7' N, 4° 52' E). The land use is characterised by pastures, predominantly consisting of *Lolium perenne* and used for intensive dairy farming (1.5 head of cattle ha<sup>-1</sup>), with mixed grazing and mowing. The soil is a peat soil (terric histosol) with a massive peat layer (wood sedge peat) up to a depth of 7 m; the top 0.2 m has a relatively high clay content of 30% (Velthof & Oenema 1995). The land has been cultivated since about the year 1000 AD.

The pastures were situated in long strips alternated by small waterways of 2 m width (every 50 m, approximately 5% of the total surface). Two different levels of drainage have been imposed since 1969; the characteristics are given in Table 1. The high groundwater table (waterway -0.3 m) was located into wind directions 7 to 74° and 187 to 272°; the low groundwater table (waterway -0.6 m) into wind directions 74 to 187° and 272 to 334°.

**2.2. Flux measurements.** Eddy correlation measurements of CO<sub>2</sub> exchange were done by The Netherlands Energy Research Foundation (ECN) in 1994, from April to June and from August to October.

The measurements were made on an open frame tower at a height of 4 m. The sonic anemometer (Applied Technologies, Inc., Boulder, CO; model SWS-211/3K) and the CO<sub>2</sub> sampling inlet were located at the south side. The tower was also equipped with temperature sensors and cup anemometers at 1, 2 and 5 m height. CO<sub>2</sub> and H<sub>2</sub>O concentrations were measured with a NDIR (Li-Cor, Inc., Lincoln, NE; model LI-6262), using fast solid state detectors. The CO<sub>2</sub> concentration was corrected for the density fluctuations due to H<sub>2</sub>O and temperature (Webb correction; Hensen et al. 1995). The air flow was 7.5 l min<sup>-1</sup>; the reference N<sub>2</sub> flow was 50 ml min<sup>-1</sup>. The 5 m long and 0.25 inch (0.635 cm) wide polyethylene tube was isolated with a 1 cm thick layer of foam to prevent condensation. The air sample and reference flows

were regulated by mass flow controllers. Air pressure was measured and used for instantaneous pressure correction of the CO<sub>2</sub> and H<sub>2</sub>O measurements.

Calibration of the NDIR was done every day at 10:00 h CET using N<sub>2</sub> as zero gas; the standards were calibrated against NOAA station standards. The zero drift of the monitor was generally less than 1 μmol mol<sup>-1</sup> d<sup>-1</sup>. The span drift was less than 0.5 μmol mol<sup>-1</sup> d<sup>-1</sup> (0.1%) and therefore negligible. The short-time reproducibility of the monitor at 360 μmol mol<sup>-1</sup> was 0.1 μmol mol<sup>-1</sup>.

The 10 Hz analog output of the NDIR was connected to the analog input of the sonic anemometer. Since the CO<sub>2</sub> concentration was monitored with a closed path sensor, a delay occurred between the fluctuating component of the vertical wind velocity ( $w'$ ) and the corresponding CO<sub>2</sub> signal ( $c'$ ). This delay was determined by recalculating the CO<sub>2</sub> flux with several time delays, optimising the correlation between  $w'$  and  $c'$ .

All measurements (8%) with a drag coefficient ( $C_{\text{drag}} = u_*^2/u^2$ ) higher than 0.02 were discarded to avoid non-homogeneous flow. Measurements made between wind angles 350° and 30° (15%) were omitted because of disturbance by the tower. Between 30° and 350° an undisturbed fetch of more than 1 km was available, whereas the technique required approximately 0.5 km (at a measurement height of 4 m).

**2.3. Additional meteorological measurements.** Short-wave irradiance (0.3 to 3 μm) was measured using a Kipp CM11 pyranometer, ventilated to prevent condensation on the dome; the pyranometer was equipped with a shadow band to measure diffuse irradiance.

**2.4. CO<sub>2</sub> fluxes.** Ecosystem CO<sub>2</sub> fluxes were separated into respiratory and assimilatory fluxes. To account for this, a distinction was made between measured night-time ( $F_n$ ) and day-time ( $F_d$ ) CO<sub>2</sub> fluxes.  $F_n$  represented the (upward) respiratory CO<sub>2</sub> flux ( $F_r$ ).  $F_d$  represented the sum of  $F_r$  and the (downward) assimilatory CO<sub>2</sub> flux ( $F_a$ ).  $F_a$  was derived from  $F_d$  and  $F_r$  (Ruimy et al. 1995).

**2.5. Respiratory CO<sub>2</sub> fluxes.** An Arrhenius temperature dependence for the  $F_r$  was assumed:

Table 1. Characteristics of the pastures in Zegveld at 2 different levels of drainage. Source: Velthof & Oenema (1995), ROC Zegveld (pers. comm.)

Ground-water table	Wind directions	Distance waterway-land (cm)	Soil subsidence (cm yr <sup>-1</sup> )	C content of top 0.2 m (kg kg <sup>-1</sup> )	C/N ratio of top 0.2 m
High	7-74°/187-272°	30	0.5	0.156	9.6
Low	74-187°/272-334°	60	1.1	0.223	12.0

Table 2. Explained variances ( $r^2$ ) and regression coefficients ( $p < 0.0001$ ) for respiratory CO<sub>2</sub> flux (Eq. 1) and assimilatory CO<sub>2</sub> flux (Eq. 2) and 5 and 95 percentiles of day-time temperature are given for high (H) and low (L) groundwater tables. \* $p < 0.005$

	n		Respiratory CO <sub>2</sub> flux				$T_{a(p5)} - T_{a(p95)}$		n		Assimilatory CO <sub>2</sub> flux					
			$r^2$		$F_{r(20)}$ (mg m <sup>-2</sup> s <sup>-1</sup> )		(°C)				$r^2$		$\epsilon$ (µg J <sup>-1</sup> )		$F_{a,mx}$ (mg m <sup>-2</sup> s <sup>-1</sup> )	
	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L
Apr	63	95	0.10	0.12	0.328	0.360	8.6–19.7	2.3–19.9	120	167	0.87	0.84	2.5	2.1	4.07	3.07
May	119	116	0.20	0.47	0.484	0.585	9.1–17.6	8.7–21.9	268	294	0.79	0.67	2.4	3.2	1.64	1.83
Jun	103	74	0.18	0.34	0.409	0.441	11.3–18.5	11.0–20.7	351	196	0.81	0.78	2.8	2.3	1.01	1.16
Aug	52	65	0.22	0.18	0.284	0.399	13.5–23.9	12.8–23.7	85	135	0.77	0.72	1.8	2.0	1.22	1.80
Sep	273	168	0.17	0.12	0.452	0.502	11.3–20.1	11.7–20.0	289	208	0.80	0.89	3.8	3.3	1.31	2.06
Oct	58	41	0.43	0.14	0.484	0.602	10.4–19.6	8.5–20.9	44	32	0.91	0.84	3.9	2.9	1.88	1.53*

$$F_r = F_{r(20)} \times e^{[1/293 - 1/(273 + T_a)] \times E/R} \quad (1)$$

where  $F_{r(20)}$  is the (upward) reference respiratory CO<sub>2</sub> flux at 20°C (mg m<sup>-2</sup> s<sup>-1</sup>),  $T_a$  the air temperature at 1 m height (°C),  $E$  the activation energy (J mol<sup>-1</sup>) and  $R$  the universal gas constant (J mol<sup>-1</sup> K<sup>-1</sup>).

Eq. (1) was fitted to  $F_n$  as a function of  $T_a$  on a monthly basis. To account for temporal differences in biomass,  $F_{r(20)}$  varied, but  $E$  was assumed to be constant. The fitting was done separately for each level of drainage. To avoid anomalous effects due to twilight,  $F_n$  values within 30 min from sunset and sunrise were excluded from regression.

**2.6. Assimilatory CO<sub>2</sub> fluxes.** The relationship between  $T_a$  and  $F_n$  was assumed to represent the relationship between  $T_a$  and  $F_r$ . Calculated  $F_r$  was subtracted from  $F_d$  to obtain  $F_a$ .

$F_a$  was related to the short-wave irradiance ( $R_s$ ) using a conventional rectangular hyperbola:

$$F_a = -\epsilon \times F_{a,mx} \times R_s / (\epsilon \times R_s + F_{a,mx}) \quad (2)$$

where  $F_{a,mx}$  is the asymptotic value of the (downward) assimilatory CO<sub>2</sub> flux (mg m<sup>-2</sup> s<sup>-1</sup>), and  $\epsilon$  the slope of the hyperbola (mg J<sup>-1</sup>) at  $R_s = 0$  W m<sup>-2</sup>. Eq. (2) was fitted to the derived  $F_a$  as a function of  $R_s$ .

**2.7. CO<sub>2</sub> exchange and CO<sub>2</sub> balance.** Non-linear regression analysis followed the iterative Marquardt-Levenberg algorithm (Fox et al. 1994). The response of the CO<sub>2</sub> exchange components ( $F_r$  and  $F_a$ ) to environmental factors was investigated on a monthly basis.

To assess the monthly CO<sub>2</sub> balance at the 2 groundwater levels, the monthly average diurnal patterns of CO<sub>2</sub> exchange were considered. Each month was compressed into one single diurnal pattern consisting of 48 half-hourly values. These patterns were directly composed from the flux measurements: 48 monthly averages (at  $n \geq 3$ ) of the original half-hourly averages. The monthly average daily CO<sub>2</sub> balance was calculated as their numerical integral. Since the weather conditions associated with the measurements at the 2 groundwa-

ter levels were not the same, the CO<sub>2</sub> balances may not readily compare. Therefore, these diurnal patterns were also calculated from the monthly fitted responses of  $F_a$  to  $R_s$  and of  $F_r$  to  $T_a$ —for a single diurnal weather pattern. The monthly average daily CO<sub>2</sub> balance was now calculated as the sum of the numerical integrals of diurnal  $F_a$  and  $F_r$ .

### 3. RESULTS

#### 3.1. Respiratory CO<sub>2</sub> fluxes

The fitted  $E$  for Eq. (1) amounted to 66.7 kJ mol<sup>-1</sup> for the high groundwater table ( $r^2 = 0.25$ ,  $n = 668$ ;  $p < 0.0001$ ) and 78.3 kJ mol<sup>-1</sup> for the low groundwater table ( $r^2 = 0.30$ ,  $n = 559$ ;  $p < 0.0001$ ). Corresponding  $Q_{10}$  values would be 2.6 and 3.1, respectively. Table 2 shows the fitted values for  $F_{r(20)}$ .

Fig. 1 shows the fitted responses of  $F_r$  to temperature for the 2 groundwater tables for all measurements.  $F_r$  was higher at the low groundwater table: approxi-

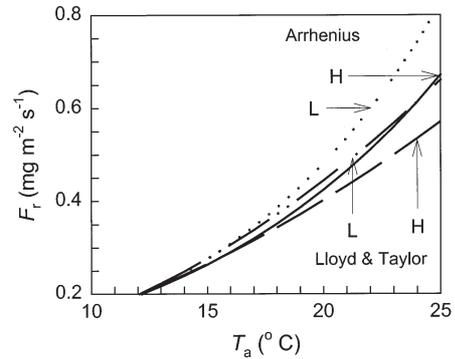


Fig. 1. Fitted response of respiratory CO<sub>2</sub> flux ( $F_r$ ) to air temperature ( $T_a$ ) at the high (H) and low (L) groundwater tables for the Arrhenius and Lloyd & Taylor equations in which  $E$  decreases with temperature

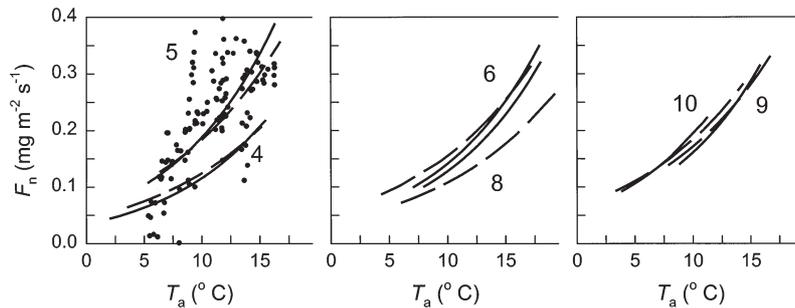


Fig. 2. Fitted monthly response of night-time CO<sub>2</sub> flux ( $F_n$ ) to air temperature ( $T_a$ ) at the high (dashed lines) and low (solid lines) groundwater tables. Measurements at the low groundwater table in May 1994 are shown as dots. Months are referred to by number

mately  $0.5 \text{ mg m}^{-2} \text{ s}^{-1}$  at  $20^\circ\text{C}$ . Table 2 and Fig. 2 compare the 2 groundwater tables on a monthly basis.  $F_r$  was higher at the low than at the high groundwater table in May, August and October; the difference was greatest in August. Differences were not evident in April, June and September.

### 3.3. Assimilatory CO<sub>2</sub> fluxes

Although  $F_{a,\text{max}}$  reached  $2 \text{ mg m}^{-2} \text{ s}^{-1}$ ,  $F_a$  rarely exceeded  $1 \text{ mg m}^{-2} \text{ s}^{-1}$ . The initial radiation use efficiency ( $\epsilon$ ) varied from 2.0 to  $3.5 \mu\text{g J}^{-1}$ .

Table 2 and Fig. 3 show the response of  $F_a$  to  $R_s$  at both groundwater tables.  $F_a$  was generally higher at low groundwater tables than at high groundwater tables.

The situation was reversed in April and October. Table 2 also indicates that the prevailing air temperatures were lower at the low than at the high groundwater table in April and October, because of the correlation between weather type and wind direction. This may have resulted in less optimal temperatures for CO<sub>2</sub> assimilation at the low groundwater table.

### 3.4. Diurnal patterns and balance of CO<sub>2</sub> fluxes

Fig. 4 shows monthly average diurnal patterns of total ecosystem CO<sub>2</sub> flux ( $F$ ),  $R_s$  and  $T_a$ . Table 3 lists the monthly average daily CO<sub>2</sub> balance derived from Fig. 4 by numerical integration ( $\Sigma F$ ) of the diurnal averages ('measured'). A shifting balance between night-time and day-time CO<sub>2</sub> flux (Fig. 4) and a change from a net uptake to a net release of CO<sub>2</sub> (Table 3) indicate that the relative contribution of the

$F_r$  increased as the season progressed. The low groundwater pasture was a stronger CO<sub>2</sub> sink than the high groundwater pasture in April, May and June. In September, the low groundwater pasture was a stronger CO<sub>2</sub> source than the high groundwater pasture.

Since irradiance and temperature differed among the measurements for the different groundwater levels, these estimates of the CO<sub>2</sub> balance may not readily compare. The diurnal CO<sub>2</sub> exchange pattern was alternatively calculated from the fitted response curves (Table 2) for  $F_r$  and  $F_a$  for the diurnal patterns of  $R_s$  and  $T_a$  in Fig. 4. The 48

calculated diurnal values of  $F_r$  and  $F_a$  were added to obtain the monthly average daily CO<sub>2</sub> balance.

Table 3 ('fitted') shows the daily respiratory ( $\Sigma F_r$ ), assimilatory ( $\Sigma F_a$ ) and total ( $\Sigma F_r + \Sigma F_a$ ) CO<sub>2</sub> balance. The pasture's CO<sub>2</sub> sink activity decreased between spring and autumn, firstly by increasing  $F_r$ , later by decreasing  $F_a$ . The calculations also suggest that the low groundwater pasture was a stronger CO<sub>2</sub> sink than the high groundwater pasture. The low groundwater pasture was a stronger CO<sub>2</sub> sink in May and a smaller CO<sub>2</sub> source in September. There was little difference in June, whereas the low groundwater pasture was a smaller CO<sub>2</sub> sink in April.

## 4. DISCUSSION

### 4.1. Respiratory CO<sub>2</sub> fluxes

$E$  in the Arrhenius equation generally decreases at increasing temperatures (Criddle et al. 1994, Lloyd & Taylor 1994). Application of an equation that allows for a decreasing  $E$  at increasing temperature (Lloyd &

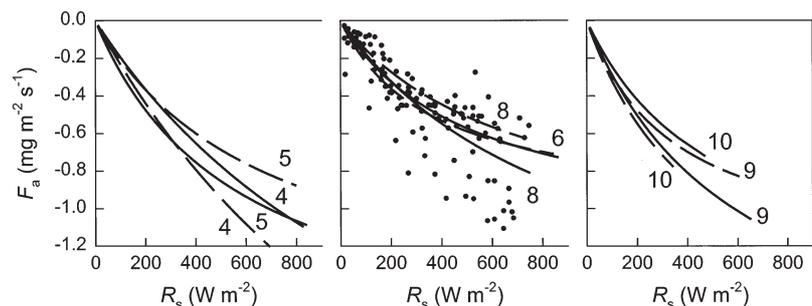


Fig. 3. Fitted monthly response of assimilatory CO<sub>2</sub> flux ( $F_a$ ) to short-wave irradiance ( $R_s$ ) at the high (dashed lines) and low (solid lines) groundwater tables. Measurements at the low groundwater table in August 1994 are shown as dots. Months are referred to by number

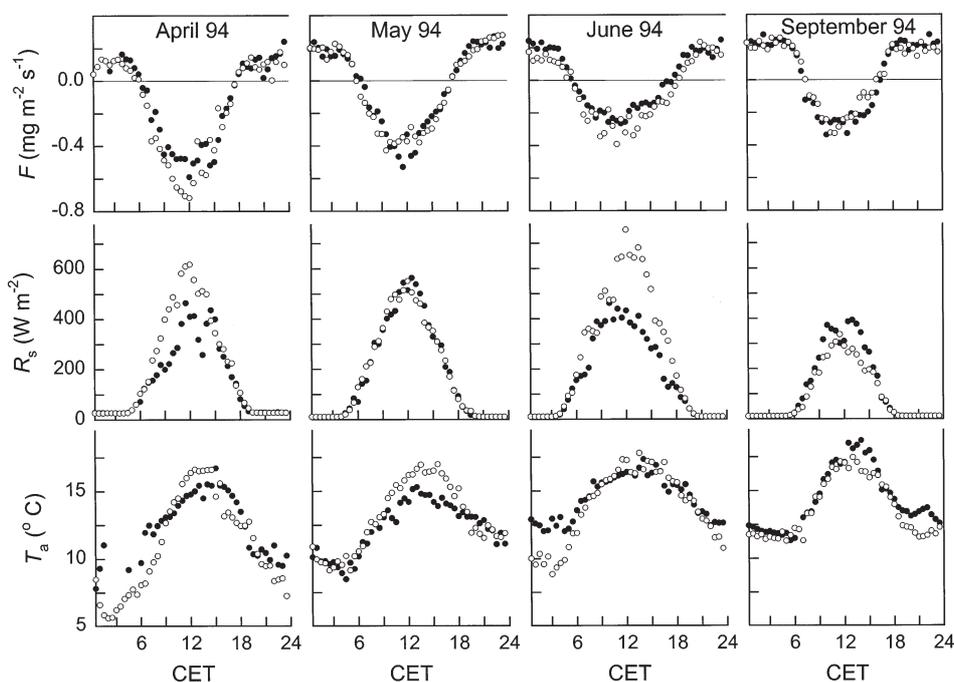


Fig. 4. Monthly average diurnal patterns of measured ecosystem CO<sub>2</sub> flux ( $F$ ), short-wave irradiance ( $R_s$ ) and temperature ( $T_a$ ) at the high (●) and low (○) groundwater tables. For each 30 min average  $n \geq 3$

Taylor 1994) increased the explained variance by a single percent. However, this equation is elusive and difficult to apply. The Arrhenius equation was retained for reasons of simplicity.

Fitted  $E$  indicates that the temperature response of  $F_n$  was stronger at the low than at the high groundwater table (78 vs 67 kJ mol<sup>-1</sup>). This difference may stem from differences in the physiological status of the grass or in the soil microbial populations. High groundwater levels may be associated with a lower nitrogen status. Silvola et al. (1996) found different temperature responses of the CO<sub>2</sub> emission from boreal mires at different groundwater tables, albeit in the opposite direction.  $E$  fell within the ranges reported in literature: 81 to 124 kJ mol<sup>-1</sup> ( $\equiv Q_{10} = 5$ ) for Scottish peat soils (Chap-

man & Thurlow 1996) and 53 kJ mol<sup>-1</sup> ( $\equiv Q_{10} = 2$ ) for a variety of ecosystem soils (Lloyd & Taylor 1994).

$F_r$  was higher at the low than at the high groundwater level (Fig. 2), but less than the factor of 2 difference in soil subsidence (Table 1). The maximum difference at 15°C was 0.05 mg m<sup>-2</sup> s<sup>-1</sup> at an  $F_r$  of 0.2 to 0.3 mg m<sup>-2</sup> s<sup>-1</sup>. The agreement between subsidence (0.5 and 1.1 cm yr<sup>-1</sup>) and drainage (-0.3 and -0.6 m) suggests differences in  $F_r$  due to oxidization of peat, though waterway levels do not directly translate into aerated depths due to a limited horizontal permeability in these soils (Schothorst 1982). This phenomenon may equally explain part of the temperature effect, since a correlation between aerated depth and air temperature can be expected. Glenn et al. (1993) found an increase in

Table 3. Monthly average daily CO<sub>2</sub> balance: total ( $F$ ), respiratory ( $F_r$ ) and assimilatory ( $F_a$ ) CO<sub>2</sub> flux values calculated from measurements shown in Fig. 4 ('measured') or fitted curves given in Table 2 ('fitted'). ● and ○:  $R_s$  and  $T_a$ , as in Fig. 4. H and L: groundwater levels. Observed differences thus originate from parameter values (H, L) and weather conditions (●, ○)

	$R_s, T_a$	Measured $F$ (g m <sup>-2</sup> d <sup>-1</sup> )		Fitted $F$ (g m <sup>-2</sup> d <sup>-1</sup> )		Fitted $F_r$ (g m <sup>-2</sup> d <sup>-1</sup> )		Fitted $F_a$ (g m <sup>-2</sup> d <sup>-1</sup> )	
		H	L	H	L	H	L	H	L
Apr	●	-8.5		-11.0	-7.1	+13.6	+13.3	-24.6	-20.4
	○		-13.0	-20.1	-14.8	+12.6	+12.2	-32.7	-26.9
May	●	-2.2		-3.6	-8.5	+20.3	+21.7	-23.8	-30.2
	○		-2.7	-2.1	-6.6	+22.0	+24.0	-24.1	-30.6
Jun	●	+0.8		-0.9	+0.5	+21.1	+20.8	-21.9	-20.3
	○		-4.2	-6.7	-5.9	+20.1	+19.7	-26.8	-25.6
Sep	●	+3.9		+2.2	+0.7	+23.2	+23.6	-21.0	-22.9
	○		+4.6	+3.4	+2.4	+21.7	+21.9	-18.3	-19.4

peatland CO<sub>2</sub> emission at increased drainage from 0.04 (–0.1 m) to 0.10 mg m<sup>–2</sup> s<sup>–1</sup> (–0.5 m). Silvola et al. (1996) measured the CO<sub>2</sub> emission from boreal mires to rise by 0.002 mg m<sup>–2</sup> s<sup>–1</sup> for every additional cm of drainage.

$F_r$  relates to a whole ecosystem rather than a soil component alone, much of  $F_r$  as such and part of the difference in  $F_r$  between the groundwater levels originated from sources other than oxidization. When assuming a proportionality between soil subsidence and CO<sub>2</sub> emission, most of  $F_r$  would be related to the vegetation. The higher  $F_a$  at low groundwater (Fig. 3) indeed suggests a higher biomass and respiration. The patterns of  $F_r$  in April and June were proportional to those of  $F_a$ .

The relatively small differences in  $F_r$  between the groundwater levels and the uncertainty about its constituents made it difficult to determine a proportionality factor between soil subsidence and CO<sub>2</sub> emission. The highest difference in  $F_r$  (0.05 mg m<sup>–2</sup> s<sup>–1</sup>) between the groundwater levels was similar to differences in  $F_r$  between drainage levels after removal of the vegetation mentioned by Glenn et al. (1993) and Silvola et al. (1996). In boreal mires subject to various levels of drainage, Silvola et al. (1996) found that lowering the groundwater table increased the CO<sub>2</sub> emission, but only up to a depth of 0.3 to 0.4 m. For Canadian drained peat soils, Glenn et al. (1993) calculated that only 10% of the subsidence could be attributed to oxidization; shrinkage is a major source of soil subsidence (Schothorst 1982).

#### 4.2. Assimilatory CO<sub>2</sub> fluxes

$F_a$  showed no light saturation. Ruimy et al. (1995) noted a lower initial slope of the response of the CO<sub>2</sub> flux to irradiance ( $\epsilon$ ) in grasslands as compared to forests and crops. The relatively erectophile structure of grass canopies was suggested as one of the reasons. Ruimy et al. (1995) listed an  $\epsilon$  value (total ecosystem CO<sub>2</sub> flux and  $R_s$ ) of 0.9  $\mu\text{g J}^{-1}$  for C<sub>3</sub> grasslands and 1.3  $\mu\text{g J}^{-1}$  for grasslands in general. Correction for the yet hypothetical day-time  $F_r$  would yield higher values, but well below the 2 to 3  $\mu\text{g J}^{-1}$  in our calculations (Table 2).

The correlation between wind direction and weather type resulted in anomalies in the comparison of the response of  $F_a$  to  $R_s$ .  $F_a$  was often higher at the low groundwater tables, but not in April and October. In those months, the day-time temperature was lower for the low groundwater measurements (Table 2).  $F_a$  was therefore limited by temperature (low  $\epsilon$ ) and not comparable to the high groundwater table measurements.

In May, August and September,  $F_a$  was highest at the low groundwater table. The higher productivity of well-drained pastures is associated with better conditions for growth (aeration), different management practices (cutting and grazing regime, fertilisation) and a higher nitrogen availability (Schothorst 1982). However, the groundwater level was not the only factor that differed in our measurements. The 2 pasture types represent different albeit realistic agro-ecosystems. Differences in CO<sub>2</sub> flux components stem from differences in the compound agro-ecosystems based on the implementation of the level of drainage, rather than from differences in the level of drainage only.

#### 4.3. Diurnal patterns and balance of CO<sub>2</sub> fluxes

The pastures are components of 2 intensive dairy farming systems, whose boundaries are not precise. Some C flows reach beyond the flux measurements. Supplementary cattle fodder constitutes an additional C input. Most of the manure is returned to the pasture and its decomposition therefore included in the measurements, but only part of the CO<sub>2</sub> respired by the cattle (Langeveld et al. 1997) is measured. Dairy produce accounts for additional C flows.

The monthly average daily CO<sub>2</sub> balances in Table 3 ('measured') suggest that the low groundwater pastures were a larger CO<sub>2</sub> sink than the high groundwater pastures. But Fig. 4 shows that the effect of groundwater tables cannot be immediately observed due to differing weather conditions during the measurements. Instead of adding the measured  $F$  in Fig. 4, we used the equations and coefficients from Table 2 to calculate  $F_r$  and  $F_a$  from the irradiance and temperature patterns in Fig. 4. This corrects for minor environmental differences, but it leaves larger differences (April) unaccounted for, because the response of  $F_a$  to  $R_s$  changes in the periphery of the temperature range. In fact, an additional error is introduced into the balance estimate, illustrated by comparison of measured and calculated  $F$  (Table 3). The suggestion is nevertheless retained that the low groundwater pasture was a larger CO<sub>2</sub> sink in May and a smaller CO<sub>2</sub> source in September. Groundwater tables had little effect in June, as shown in the CO<sub>2</sub> flux components (Figs. 2 & 3). The absence of real differences in June has no immediately obvious reason.

The data suggest that in May and September the increased (upward)  $F_r$  at low groundwater tables was more than compensated for by an increased (downward)  $F_a$ . Lower groundwater tables in these peat pastures generally lead to higher levels of peat oxidization and a higher grassland productivity (Schothorst 1982); part of the assimilated dry matter accumulates as soil

C (Jenkinson & Rayner 1977, Wolf & Janssen 1991). Accumulation and oxidization of C do not occur independently, since oxidization results in mineralisation (Schothorst 1982) and thus adds to the N availability to the vegetation. The pastures probably constituted a CO<sub>2</sub> sink in spring only. Representing disturbed ecosystems, either pasture type may well have been a yearly CO<sub>2</sub> source. The oxidization of peat proceeds year-round and the ratio of respiration to assimilation increases throughout the season. Though the analysis suggests that the high groundwater table pasture acted as the largest year-round CO<sub>2</sub> source, this cannot be concluded from the data in view of the limited range of measurements.

A minor ecosystem in terms of surface cover, peat pastures bear conceptual resemblance to tundras, having subsoil rich in C at varying levels of drainage and permanent vegetation cover. Tenhunen et al. (1995) measured CO<sub>2</sub> exchange in sloping (and therefore differentially drained) tussock tundra.  $F_a$  was determined by leaf area and irradiance — critically important to the net CO<sub>2</sub> balance. The diurnal pattern of  $F_r$  followed temperature; its seasonal pattern was determined by the aerated soil volume that closely aligned to water table depth. Interaction between  $F_a$  and  $F_r$  components in the ecosystem of Tenhunen et al. (1995) was not apparent.

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