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Soil surface CO_2 flux in a Minnesota peatland[1]

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Abstract. Soil surface CO_2 flux was measured in hollow and hummock microhabitats in a peatland in north central Minnesota from June to October in 1991. We used a closed infrared gas exchange system to measure soil CO_2 flux. The rates of CO_2 evolution from hummocks (9.8 ± 3.5 g m^{-2} d^{-1}, [mean ± SE]) were consistently higher than those from hollows (5.4 ± 2.9 g m^{-2} d^{-1}) (the hummock values included the contribution of moss dark respiration, which may account for 10–20% of the total measured flux). The soil CO_2 flux was strongly temperature-dependent ($Q_{10} \approx 3.7$) and appeared to be linearly related to changes in water table depth. An empirical multiplicative model, using peat temperature and water table depth as independent variables, explained about 81% of the variance in the CO_2 flux data. Using the empirical model with measurements of peat temperature and estimates of hollow/hummock microtopographic distribution (relative to water table elevation), daily rates of "site-averaged" CO_2 evolution were calculated. For the six-month period (May–October), the total soil CO_2 released from this ecosystem was estimated to be about 1340 g CO_2 m^{-2}.

Introduction

Major peatland areas occur in boreal, subarctic, and arctic regions and occupy approximately 25–50% of the earth's land surface in high latitudes (e.g., Moore 1986; Moore & Knowles 1987). Northern peatlands accumulate carbon in peat at an estimated rate of 0.076 Pg y^{-1} and consist of about one-third of the world pool of soil carbon (1395 Pg) (Billings, 1987; Oechel, 1989; Gorham, 1991). It is important to understand how these northern peatlands will respond to predicted changes in climate (e.g., temperature, precipitation). Several studies have demonstrated that the net ecosystem carbon balance in arctic tundra, for example, is sensitive to small changes in temperature and water table depth (Billings et al. 1982, 1983; Peterson et al. 1984; Moore & Knowles, 1989; Gorham, 1991; Oberbauer et al. 1992).

Previous studies have primarily concentrated on subarctic and arctic peatlands (e.g., Peterson & Billings 1975; Svensson 1980; Poole & Miller 1982; Luken & Billings 1985; Moore 1986; Oberbauer et al. 1992). However, relatively little is known about the CO_2 evolution rates from peatlands in other areas. Here, we report on a study conducted in a peatland in north central Minnesota to (a) evaluate the diurnal and seasonal patterns of CO_2 flux from hollow/hummock microhabitats and (b) examine the dependence of the flux on peat temperature and water table depth. We employed a closed infrared gas exchange system (Norman et al. 1990, 1992), which is vented to the atmosphere to maintain pressure equilibrium. This small portable system has proven to provide rapid and reliable measurements of soil surface CO_2 flux.

Methods and materials

Study area

The study site, referred to as the Bog Lake Peatland, is located in the Chippewa National Forest, adjacent to the Marcell Experimental Forest (47°32'N, 93°28'W, 416 m above m.s.l.) in north central Minnesota. These peatlands cover 21% of the land area within the Chippewa National Forest, have deep (up to 12 m) peat deposits, and consist of *Sphagnum* peat at the surface with woody, sedge, and aquatic peats deeper in the solum (Verry 1975). The area receives an average annual precipitation of 770 mm. The mean annual temperature is 3 °C. The vegetation is dominated by *Sphagnum* moss, which forms a nearly continuous carpet throughout all of the peatlands, with some hummock-growing vascular plants such as *Scheuchzeria palustris, Carex* spp., and *Chamaedaphne calyculata*. Surface water pH values in the peatland range from 4.0 to 5.2.

Measurement of soil CO_2 flux

A closed gas exchange system (e.g., Nakayama 1990; Norman et al. 1990) was used to measure CO_2 evolution from the soil *in situ*. The soil CO_2 flux was obtained with a 0.75 L dark chamber (41.3 cm^2 circular cross section) attached to a LI-COR 6200 infrared gas exchange system (LI-COR Inc., Lincoln, NE). This system has been described in detail and evaluated by Norman et al. (1992). In our study, the chamber was used on thin-walled PVC collars (76.2 mm diameter and 50 mm long) that were inserted into the peat to a depth of about 30 mm. The chamber was vented to the atmosphere by a tube to maintain pressure equilibrium.

The thin-walled PVC collars were placed on a hollow and on an adjacent hummock at six locations at the site. The use of collars helped minimize surface disturbance for repeated measurements at a given location. To minimize the contribution of dark respiration of aboveground vegetation, vascular plants growing inside collars on the moss carpeted hummocks were clipped. We did not remove the moss on the hummocks to avoid causing damage to the hummock microtopography. Generally, there was no green vegetation inside collars on the hollows.

Sampling was done generally at 90 min. intervals between 0800 and 2000 hrs. for about 40 days from June to October 1991. Boardwalks were used during the sampling to minimize any disturbance. Each measurement of soil CO_2 flux took 5—10 min. depending on the magnitude of the flux. Although a foam gasket was placed around the flange of the soil chamber to provide a seal between the soil chamber and the collar, small leaks were unavoidable. Thus, an ambient CO_2 concentration near the collar was measured before measurements were started. Then the soil chamber was placed on the collar carefully and the CO_2 concentration inside the chamber was drawn down about 20 ppmv below the ambient value. Following stabilization, the concentration inside the chamber steadily increased, and then we measured the rate of change of concentration with time from 10 ppmv below to 10 ppmv above the ambient value. From these measurements the CO_2 flux was calculated.

Bar platinum resistance thermometers (0.2 m long) were installed horizontally to measure average peat temperatures (T) at a depth of 0.1 m from the peat surface under hollows and hummocks. Also, the peat temperature inside each collar (at 0.1 m depth below the peat surface) was measured with a hand-held platinum resistance thermometer. Mean air temperature (T_a) was measured with aspirated ceramic wick psychrometers (Hartman & Gay 1981). Solar radiation (R_s) was measured with a pyranometer (Eppley Laboratories, Newport, RI). The water table elevation was monitored using a recording well installed near the measurement area.

Modeling soil CO_2 flux

Bunnell et al. (1977) proposed a multiplicative model for the computation of soil respiration as:

$$F_s(\mathrm{T},\mathrm{M}) = [\mathrm{M}/(a_1 + \mathrm{M})]\,[a_2/(a_2 + \mathrm{M})]a_3\,a_4^{[(\mathrm{T}-10)/10]} \qquad (1)$$

where F_s is the respiration rate at temperature T (°C) and moisture level M (percent moisture content on a dry weight basis), a_3 is optimum respiration rate (i.e., at 10 °C), and a_4 is the temperature Q_{10} coefficient. The coefficients a_1 and a_2 are empirical constants related to metabolic water requirements and to oxygen availability, respectively. Equation (1) has been shown to be applicable to various ecosystems (e.g., Bunnell et al. 1977; Heal 1979; Schlentner & Van Cleve 1985; Carlyle & Than 1988).

The first term, $[M/(a_1 + M)]$, on the right side of Eq. (1) indicates that metabolic water requirements of decomposer organisms become less limiting as water content increases [for details, see Bunnell & Tait (1974), Bunnell et al. (1977)]. Peat water content was not measured in our study. However, we monitored the water table depth. Luken and Billings (1985) indicated that water table depth, when it is close to the peat surface, is a better predictor of soil CO_2 flux than is peat moisture content. Verry (1988) also reported that peatlands evapotranspire at potential rates when the water table is within about 0.3—0.4 m of hollow surfaces, and at a fraction of potential rates when the water table is below this level. In our study, water table was within 0.2 m of the hollow surface throughout the season. The moisture content of the surface peat was, therefore, considered to be at field capacity, and the effect of the first term was assumed to be negligible (i.e., $M/(a_1 + M) \approx 1$ when $M \gg a_1$).

The second term, $[a_2/(a_2 + M)]$, on the right side of Eq. (1) describes the effect of water on effective path length available for diffusion of oxygen at high moisture content. Peterson et al. (1984) found that soil CO_2 flux was sensitive to changes in water table depth due to changes in oxygen availability for microbial respiration in the aerated zone between the water table and the hollow/hummock surface. We assumed a linear relationship between F_s and water table depth at high moisture content (i.e., when the water table was within 0.4 m of the hollow surface). Therefore, we rewrite Eq. (1) in terms of peat temperature (T) and water table depth (D) as:

$$F_s(T, D) = [(b_1 + b_2 D)/(b_1 + 0.4\, b_2)]\, a_3\, a_4^{[(T-10)/10]} \text{ for } 0 \leqslant D \leqslant 0.4 \text{ m} \qquad (2)$$

where b_1 is a nondimensional constant, b_2 is a constant with unit of m^{-1}, and D is the distance (in m) from the water table to the average hollow/hummock surface.

Results and discussion

Diurnal trends

The diurnal courses of the soil CO_2 flux and peat temperature (at 0.1 m depth) for three selected days in 1991 are presented in Figs. 1A—C. The CO_2 flux from the hollow/hummock microhabitats seemed to gradually

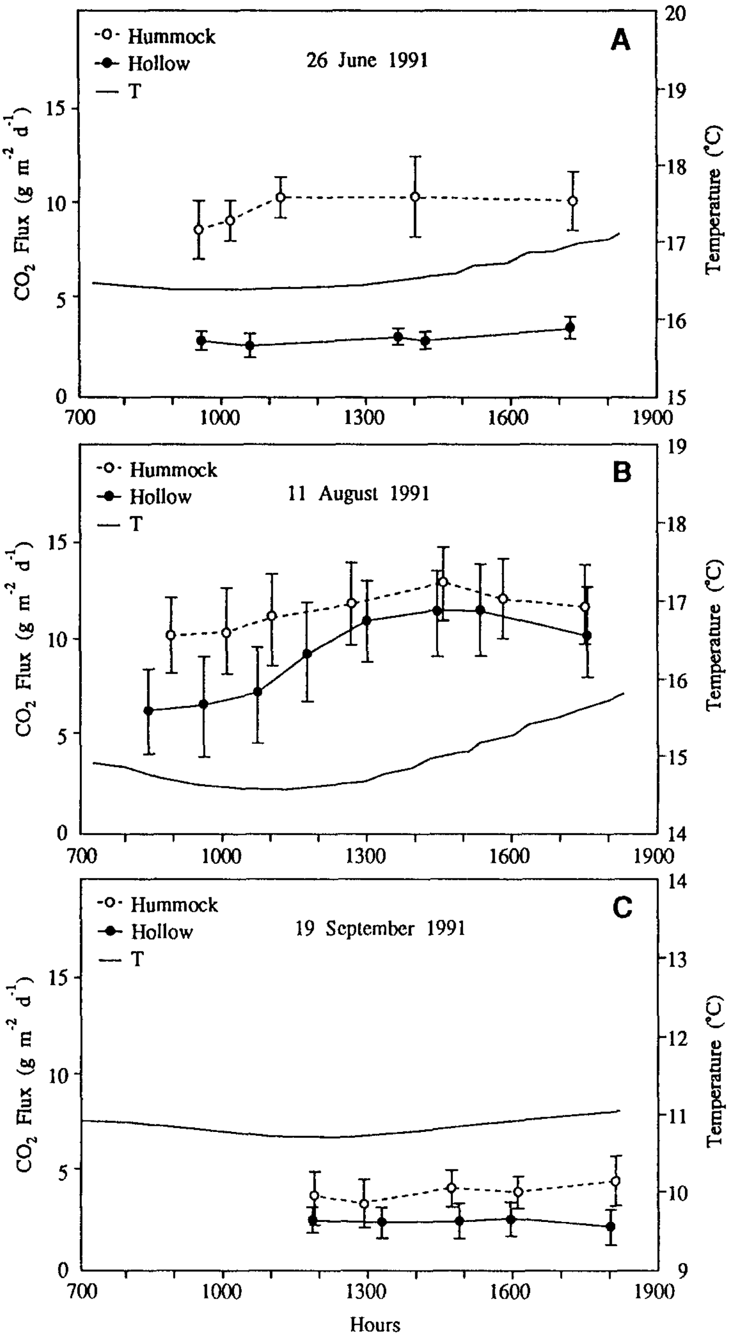

Fig. 1. Diurnal courses of soil CO_2 flux and peat temperature (at 0.1 m depth) on three selected days in a Minnesota peatland: (A) 26 June, (B) 11 August, and (C) 19 September, 1991 ($1\ \text{mg}\ \text{m}^{-2}\ \text{s}^{-1} \approx 22.7\ \mu\text{mol}\ \text{m}^{-2}\ \text{s}^{-1}$).

increase during the day, generally following the diurnal pattern in peat temperature. Such a trend is evident when there was peat temperature variation of more than 1 °C (Fig. 1B) and less obvious when temperature changes were smaller (Fig. 1A and 1C). It was partly cloudy on 26 June and the mean daytime peat temperature was around 17 °C. The CO_2 evolution rate from hummocks (average $\approx$ 11.3 g m^{-2} d^{-1}) was considerably higher (Fig. 1A) than the rates from hollows (average $\approx$ 3.4 g m^{-2} d^{-1}). On this day, the water table was located near the hollow surface ($D < 0.1$ m). The water table depth ($D \approx 0.26$ m) relative to a hummock was greater, which allowed a larger zone for aerobic microbial respiration (The average distance between hollow and hummock surfaces was approximately 0.16 m). The CO_2 flux measured from hummocks includes the contribution of dark respiration of *Sphagnum* moss. Based on a few sets of nocturnal canopy CO_2 flux (soil + plant respiration) measurements from June to August, we estimate that the contribution of moss respiration is about 1 to 3 g m^{-2} d^{-1} (approximately 10—20% of the total CO_2 flux measured in hummocks during this period). Oechel (1976) reported respiration rates of 0.1 to 1.3 mg g^{-1} (dry weight) h^{-1} (roughly equivalent to about 0 to 2 g m^{-2} d^{-1}, based on the dry weight per unit of ground area measured at our study site) from arctic mosses at temperatures ranging from 0 to 20 °C. The observed midday variations in the CO_2 flux in hummocks may have resulted from variations in air temperature (Fig. 1A). Also, warmer temperature during the midday in the unsaturated zone of the hummocks may have enhanced decomposition, thereby contributing to the observed daytime variation in the CO_2 flux from hummocks. The environmental conditions (i.e., peat and air temperature, radiation) on 11 August were similar to those on 26 June. The depth to water table, however, was substantially greater ($D = 0.19$ m for hollows and 0.35 m for hummocks). On this day, mean daytime soil CO_2 flux from hollows was nearly three times the value on 26 June and the CO_2 flux for hummocks was 20% greater than the value on 26 June (Fig. 1B). September 19 was substantially cooler (mean daytime peat temperature $\approx$ 11 °C) and the vegetation was senescing. The elevation of water table rose and the average values of D for hollows and hummocks were 0.14 and 0.30 m, respectively. The mean daytime CO_2 evolution rates from both hollows and hummocks were low (2—5 g m^{-2} d^{-1}) throughout the day (Fig. 1C).

Seasonal trends

Daily averaged soil CO_2 flux during June—October, 1991 is shown in Fig. 2. Also shown are the corresponding values of peat and air temperature, and water table depth. The soil CO_2 flux from hollows and hummocks

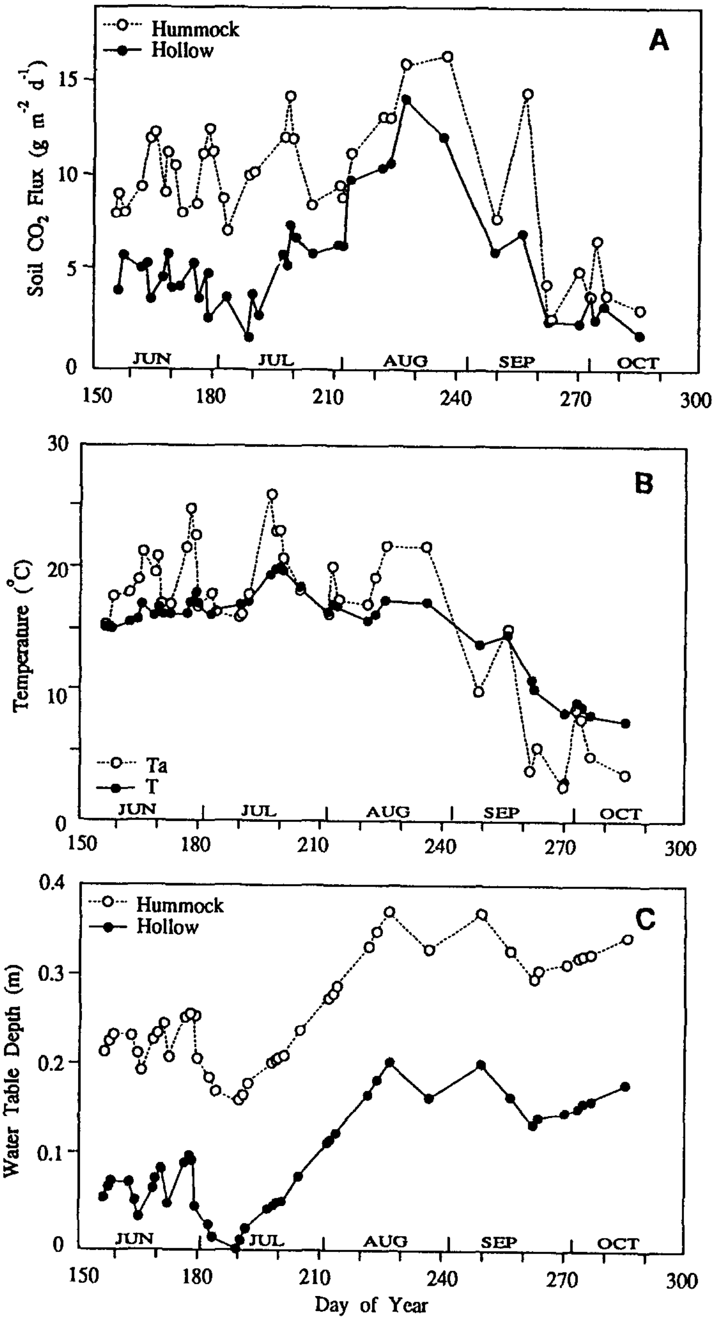

Fig. 2. Seasonal trends in (A) soil CO_2 flux, (B) peat and air temperatures, and (C) average water table depth (D = distance from the water table to the average hollow/hummock surface) during June to October in 1991.

exhibited marked seasonal variations. Maximum CO_2 fluxes (14.5 g m^{-2} d^{-1} for hollows and 16.7 g m^{-2} d^{-1} for hummocks) were observed in mid August when the water table depth was greatest and peat temperature was high. The CO_2 flux declined rapidly with falling temperatures in September. The flux values during October were 2.7 g m^{-2} d^{-1} in hummocks and 1.9 g m^{-2} d^{-1} in hollows.

The overall mean CO_2 flux from hummocks (9.8 ± 3.5 g m^{-2} d^{-1}, [mean ± SE]) was higher than that from hollows (5.4 ± 2.9 g m^{-2} d^{-1}). The variations in the hummock CO_2 flux may at least be partly attributable to changes in air temperature affecting both the moss dark respiration and the decomposition in the larger unsaturated zone of the hummocks (Fig. 2B). The water table was close (within 0.1 m) to the hollow surface in June and July (Fig. 2C), decreasing the availability of oxygen for aerobic microbial respiration in hollows. For example, on day 189 when the water table rose slightly above the hollow surface (Fig. 2C) due to frequent rainfall, CO_2 flux reached a seasonal minimum of 1.5 g m^{-2} d^{-1}. During this period of shallow water table depth (June—mid July), there was a substantial difference (about 8 g m^{-2} d^{-1}) in CO_2 flux between hollows and hummocks. The water table receded rapidly in late July due to low precipitation and the difference in CO_2 flux between hummocks and hollows decreased to about 4 g m^{-2} d^{-2}. For the period from 5 June to 12 October, the cumulative soil CO_2 flux from the hollow and hummock microhabitats was estimated to be about 700 and 1300 g CO_2 m^{-2}, respectively.

Relationships with temperature and water table depth

Soil CO_2 flux in the field is affected by a number of environmental variables (e.g., temperature, moisture content, water table depth). Thus, when only one of the controlling variables is considered, a scatter diagram results (Fig. 3). Daily values of soil CO_2 flux from the entire measurement period are plotted against those of peat temperature (T at 0.1 m depth) in Fig. 3A. To minimize the confounding effect of water table depth (D), data are grouped in different intervals of D. As expected, the rate of CO_2 evolution was temperature-dependent, and this dependence was stronger when D was large. Under similar ranges of D (0.12—0.24 m), the temperature dependence of CO_2 flux from hummocks and hollows was comparable. The relationship between the soil CO_2 flux and water table depth for three intervals of T is shown in Fig. 3B. It is difficult to discern any distinct relationship at low to moderate temperatures ($5 < T < 15$ °C). However, when T exceeded 15 °C, the soil CO_2 flux was nearly linearly related with D. This relationship is consistent with the results of

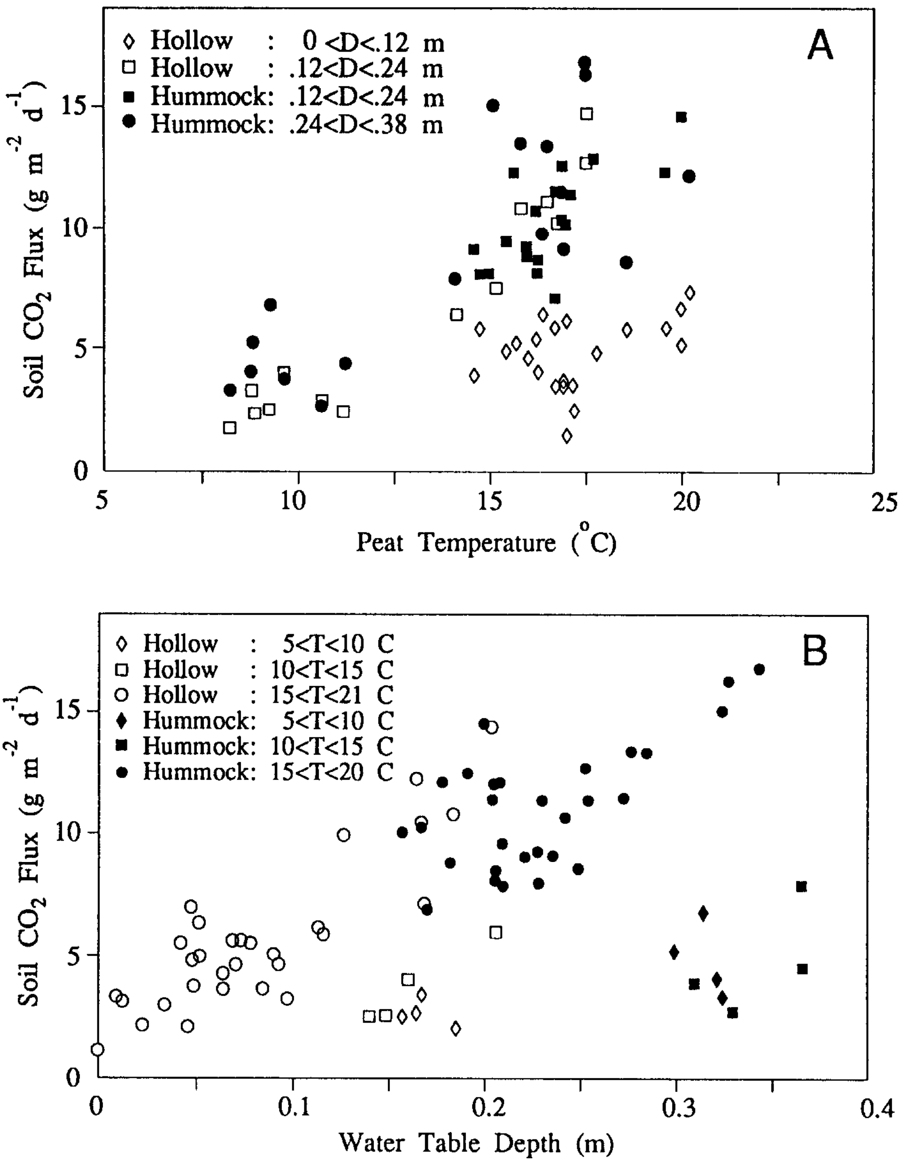

Fig. 3. Relationships between (A) soil CO_2 flux and peat temperature and (B) soil CO_2 flux and water table depth for the hollow and hummock microhabitats.

laboratory studies on field-collected microcosm cores in the arctic tundra (e.g., Billings et al. 1982; Peterson et al. 1984).

Assuming that the temperature dependence is comparable for hollow and hummock microhabitats (as indicated in Fig. 3A), it appears that the difference in water table depth can explain most of the observed contrast in rates of soil CO_2 evolution measured in the two microhabitats (Fig. 3B). We, therefore, fitted (using non-linear least squares) Eq. (2) to the values of soil CO_2 flux from hollows and hummocks (combined data set) and respective peat temperature and water table depths. The resulting equation is

$$F_s(T, D) = [(0.002 + 0.025D)/0.012]\,(6.97)\,(3.7)^{[(T-10)/10]} \qquad (3)$$

The values of the asymptotic standard errors of the parameters (b_1, b_2, a_3 and a_4) and r^2 are listed in Table 1. Equation (3) accounted for about 81% of the variations in data. The Q_{10} value (a_4) of 3.7 is within the range (2—5) reported for various peatland ecosystems (e.g., Flanagan & Veum 1974; Svensson 1980).

Table 1. The values of the parameters in equation (3) with their asymptotic standard errors and r^2.

	Values
Number of data points	76
b_1	0.002 ± 0.000
b_2, m^{-1}	0.025 ± 0.005
a_3, $g\ m^{-2}\ d^{-1}$	6.97 ± 0.53
a_4	3.70 ± 0.40
r^2	0.81

Estimating ecosystem soil CO_2 flux

To estimate "site-averaged" soil CO_2 flux in this ecosystem, we need to consider the distribution of hollow/hummock microtopography relative to the water table elevation. On 18 October 1991, the study site was surveyed along five transects (each approximately 200 m long) using a laser range finder/theodolite (Leitz/Sokkia Company, Overland Park, KS, Set #2 – total station). The elevations of the hollow/hummock surfaces and the water table were measured every 2 m and 10 m, respectively. The frequency of water table depth (distance from the hollow/hummock surfaces to the water table) is presented in Table 2. The "site-averaged" water table depth calculated from the data in Table 2 was about 0.26 m. Using this value, in conjunction with the data on water table elevation[2] measured at a reference station throughout the season, we calculated daily values of "site-averaged" water table depth for the entire season. These estimates, along with measurements of peat temperature, were then used

Table 2. Frequency distribution of water table depth (m) at the study site measured on 18 October 1991.

Water table depth (m)	Frequency (%)
0.00—0.05	1.4
0.05—0.10	5.2
0.10—0.15	8.6
0.15—0.20	10.8
0.20—0.25	19.9
0.25—0.30	25.1
0.30—0.35	13.1
0.35—0.40	7.2
0.40—0.45	4.6
0.45—0.50	1.8
0.50—0.55	1.6
0.55—0.60	0.6

in Eq. (3) to calculate daily rates of “site-averaged” CO_2 evolution. The estimated CO_2 flux ranged from 3 to 18 g m^{-2} d^{-1} (Fig. 4). For the six-month period (May—October), the total soil CO_2 released from this ecosystem was estimated to be about 1340 g CO_2 m^{-2} (note that moss dark respiration was included in measurements in hummocks and may

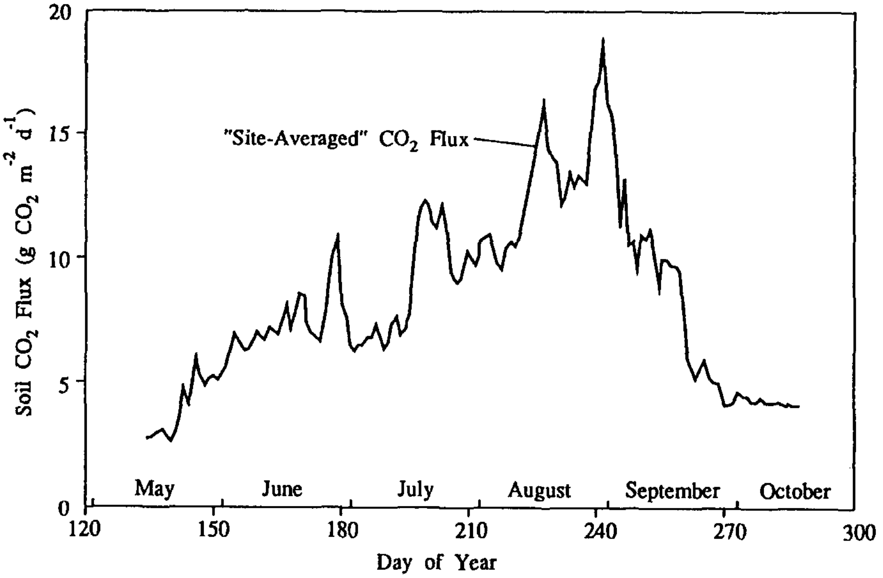

Fig. 4. Estimated “site-averaged” soil CO_2 flux in a Minnesota peatland during May—October 1991.

account for 10—20% of the values from hummocks). The range of soil CO_2 flux encountered in this study is similar to that reported (1 to 16 g m^{-2} d^{-1}) through the year for a marginal fen in Minnesota by Reiners (1968).

Comparison with other ecosystems

The range of soil CO_2 flux observed in this study, 3—18 g m^{-2} d^{-1}, is higher than the reported values from subarctic peatlands. Daily evolution rates for various subarctic peatlands range from 0.1 to 10 g CO_2 M^{-2} (Peterson & Billings 1975; Schlesinger 1977; Billings et al. 1977; Svensson 1980; Poole & Miller 1982; Luken & Billings 1985; Moore 1986). Our values, however, are comparable to those (0—15.8 g m^{-2} d^{-1}) observed in a boreal forest in interior Alaska (e.g., Flanagan & Van Cleve 1977; Schlentner & Van Cleve 1985; Bonan 1991). Higher values have been reported from temperate deciduous and coniferous forests (0—24.5 g m^{-2} d^{-1} — Reiners 1968; Anderson 1973; Edwards 1975; Singh & Gupta 1977; Baldocchi et al. 1986; Carlyle & Than 1988) and from grasslands (1—35 g m^{-2} d^{-1} — Kucera & Kirkham 1971; Singh & Gupta 1977; Grahammer 1989; Norman et al. 1992). The magnitudes of CO_2 from tropical rain forests are even higher, ranging from 3 to 38 g m^{-2} d^{-1} (e.g., Schulze 1967; Wanner 1970; Medina & Zelwer 1972; Keller et al. 1986; Fan et al. 1990).

Some of the variability in CO_2 flux arises from differences in measurement periods and measurement techniques. The results, however, reflect the impact of biological activity on the rates of soil CO_2 evolution in various ecosystem types. Higher rates of CO_2 evolution are associated with higher net primary production such as in wet tropical ecosystems (Singh & Gupta 1977); while lowest rates are observed in ecosystems located in colder regions.

Summary

Peatland soil respiration showed diurnal and seasonal variations that were related to changes in peat temperature and water table elevation. The maximum rate of CO_2 release, which occurred in mid to late August, was associated with the lowest water table elevation and high peat temperature. The CO_2 release decreased rapidly during September and October as the peat temperature fell below 10 °C. The magnitudes of CO_2 flux differed significantly between hollows and hummocks, indicating the importance of the microtopographic heterogeneity. Our data indicate that, under high moisture conditions, soil CO_2 release and water table depth are strongly correlated. These results are similar to the previously observed effects in the laboratory of water table on CO_2 exchange of field-collected microcosm cores. Future studies should include measurements of moss dark respiration and peat moisture content to investigate the effect of water table depth on soil CO_2 exchange under limiting moisture conditions.

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Notes

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[2] Water table elevations measured at approximately 100 locations across the study site indicated the standard deviation value of 0.025 m. We, therefore, assume that the water table elevation is relatively uniform at the site.

References

Anderson JM (1973) Carbon dioxide evolution from two temperate, deciduous woodland soils. J. Appl. Ecology 10: 361—378

Baldocchi DD, Verma SB, Matt DR & Anderson DE (1986) Eddy-correlation measurements of carbon dioxide efflux from the floor of a deciduous forest. J. Appl. Ecology 23: 967—975

Billings WD (1987) Carbon balance of Alaskan tundra and Taiga ecosystems: past, present and future. Quat. Sci. Rev. 6: 165—177

Billings WD, Peterson KM, Shaver GR & Trent AW (1977) Root growth, respiration, and carbon dioxide evolution in an arctic tundra soil. Arct. Alp. Res. 9: 129—137

Billings WD, Luken JO, Mortensen DA & Peterson KM (1982) Arctic tundra: a source or sink for atmospheric carbon dioxide in a changing environment? Oecologia (berl) 53: 7—11

Billings WD, Luken JO, Mortensen DA & Peterson KM (1983) Increasing atmospheric carbon dioxide: possible effects on arctic tundra. Oecologia (berl) 58: 286—289

Bonan GB (1991) Atmosphere-biosphere exchange of carbon dioxide in boreal forests. J. Geophys. Res. 96: 7301—7312

Bunnell FL & Tait DEN (1974) Mathematical simulation models of decomposition processes. In: Holding AJ, Heal OW, MacLean Jr. SF & Flanagan PW (Eds) Soil Organisms and Decomposition in Tundra (pp 207—225). Tundra Biome Steering Committee, Stockholm

Bunnell FL, Tait DEN, Flanagan PW & Van Cleve K (1977) Microbial respiration and substrate weight loss — I. A general model of the influences of abiotic variables. Soil Biol. Biochem. 9: 33—40

Carlyle JC & Than UB (1988) Abiotic controls of soil respiration beneath an eighteen-year-old *Pinus radiata* stand in south-eastern Austr. J. Ecol. 76: 654—662

Edwards NT (1975) Effects of temperature and moisture on carbon dioxide evolution in a mixed deciduous forest floor. Soil Sci. Soc. Am. Proc. 39: 361—365

Fan S-M, Wofsy SC, Bakwin PS & Jacob DJ (1990) Atmosphere-biosphere exchange of CO_2 and O_3 in the central Amazon Forest. J. Geophys. Res. 95: 16851—16864

Flanagan PW & Veum AK (1974) Relationships between respiration, weight loss, temperature and moisture in organic residues on tundra. In: Holding AJ, Heal OW MacLean Jr. SF & Flanagan PW (Eds) Soil Organisms and Decomposition in Tundra (pp 249—277). Tundra Bioms Steering Committee, Stockholm

Flanagan PW & Van Cleve K (1977) Microbial biomass, respiration and nutrient cycling in a black spruce taiga ecosystem, soil organisms as components of ecosystems. Ecol. Bull. 25: 261—273

Gorham E (1991) Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. Ecol. Appl. 1: 182—195

Grahammer K (1989) Respiration of soil and vegetation in grassland. M. S. Thesis, Dept. of Agronomy, Univ. of Nebraska, Lincoln

Hartman RK & Gay LW (1981) Improvements in the design and the calibration of temperature measurement systems. Processings of the 15th Conference on Agricultural and Forest Meteorology, 210 p

Heal OW (1979) Decomposition and nutrient release in even-aged plantations. In: Ford ED, Malcolm DC & Atterson J (Eds) The Ecology of Even-aged Forest Plantations (pp 257—291). Proceedings of the Meeting of Division I., International Union of Forest Research Organizations, Edinburgh 1978. Institute of Terrestrial Ecology, Cambridge

Keller M, Kaplan WA & Wofsy SC (1986) Emission of N_2O, CH_4 and CO_2 from tropical forest soils. J. Geophys. Res. 91: 11791—11802

Kucera CL & Kirkham DR (1971) Soil respiration studies in tallgrass prairie in Missouri. Ecology 52: 912—914

Luken JO & Billings WD (1985) The influence of microtopographic heterogeneity on carbon dioxide efflux from a subarctic bog. Holarc. Ecol. 8: 306—312

Medina E & Zelwer M (1972) Soil respiration in tropical plant communities. In: Golley PM & Golley FB (Eds) Papers from a Symposium on Tropical Ecology with an Emphasis on Organic Productivity (pp 245—269). Univ. Georgia, Athens

Moore TR (1986) Carbon dioxide evolution from subarctic peatlands in eastern Canada. Arct. Alp. Res. 18: 189—193

Moore TR & Knowles R (1987) Methane and carbon dioxide evolution from subarctic fens. Can. J. Soil Sci. 67: 77—81

Moore TR and Knowles R (1989) The influence of water table levels on methane and carbon dioxide emissions from peatland soils. Can. J. Soil Sci. 69: 33—38

Nakayama FS (1990) Soil respiration. Remote Sens. Rev. 5: 311—321

Norman JM, Garcia R & Verma SB (1990) Soil surface CO_2 fluxes on the Konza Prairie. Proceedings of American Meteorological Society, pp 29—31

Norman JM, Garcia R & Verma SB (1992) Soil surface CO_2 fluxes and the carbon budget. J. Geophys. Res. (in press)

Oberbauer SF, Oechel WC & Riechers GH (1986) Soil respiration of Alaskan tundra at elevated atmospheric carbon dioxide concentrations. Plant Soil 96: 145—148

Oberbauer SF, Gillespie CT, Cheng W, Gebauer R, Sala Serra A & Tenhunen JD (1992) Environmental effect on CO_2 efflux from riparian tundra in the northern foothills of the Brooks Range, Alaska, USA (submitted)

Oechel WC (1976) Seasonal patterns of temperature response of CO_2 flux and acclimation in arctic mosses growing *in situ*. Photosynthetica 10: 447—456

Oechel WC (1989) Nutrient and water flux in a small Arctic watershed: an overview. Holarc. Ecol. 12: 229—237

Peterson KM, Billings WD & Reynolds DN (1984) Influence of water table and atmospheric CO_2 concentration on the carbom balance of arctic tundra. Arc. Alp. Res. 16: 331—335

Peterson KM & Billings WD (1975) Carbon dioxide flux from tundra soils and vegetation as related to temperature at Barrow, Alaska. The American Midland Naturalist 94: 88—98, 177

Poole DK & Miller PC (1982) Carbon dioxide flux from three arctic tundra types in north-central Alaska, USA. Arct. Alp. Res. 14: 27—32

Reiners WA (1968) Carbon dioxide evolution from the floor of three Minnesota forests. Ecology 49: 471—483

Schlentner RE & Van Cleve K (1985) Relationships between CO_2 evolution from soil, substrate temperature, and substrate moisture in four mature forest types in interior Alaska. Can. J. For. Res. 15: 97—106

Schlesinger WH (1977) Carbon balance in terrestrial detritus. Annu. Rev. Ecol. Syst. 8: 51—81

Schulze E (1967) Soil respiration of tropical vegetation types. Ecology 48: 652—653

Singh JS & Gupta SR (1977) Plant decomposition and soil respiration in terrestrial ecosystems. The Botanical Review 43: 449—528

Svensson BH (1980) Carbon dioxide and methane fluxes from the ombrotrophic parts of a subarctic mire. In: Sonesson M (Ed) Ecology of a Subarctic Mire. Ecol. Bull. 30: 235—250

Verry ES (1975) Streamflow chemistry and nutrient yields from upland-peatland watersheds in Minnesota. Ecology 56: 1149—1157

Verry ES (1988) Hydrology of wetlands and men's influence on it. In: Symposium on the Hydrology of Wetlands in Temperate and Cold Regions, Vol. 2, 6—8 June, 1988, Joensuu, Finland. Publications of the Academy of Finland (Helsinki) 5: 41—61

Wanner H (1970) Soil respiration, litter fall and productivity of tropical rain forest. J. Ecol. 58: 543—547