

The Effects of Infrared Loading and Water Table on Soil Energy Fluxes in Northern Peatlands

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ABSTRACT

Increased radiative forcing is an inevitable part of global climate change, yet little is known of its potential effects on the energy fluxes in natural ecosystems. To simulate the conditions of global warming, we exposed peat monoliths (depth, 0.6 m; surface area, 2.1 m²) from a bog and fen in northern Minnesota, USA, to three infrared (IR) loading (ambient, +45, and +90 W m⁻²) and three water table (–16, –20, and –29 cm in bog and –1, –10 and –18 cm in fen) treatments, each replicated in three mesocosm plots. Net radiation (R_n) and soil energy fluxes at the top, bottom, and sides of the mesocosms were measured in 1999, 5 years after the treatments had begun. Soil heat flux (G) increased proportionately with IR loading, comprising about 3%–8% of R_n. In the fen, the effect of IR loading on G was modulated by water table depth, whereas in the bog it was not. Energy dissipation from the mesocosms occurred mainly via vertical exchange with air, as well as with deeper soil layers through the bottom of the mesocosms, whereas

lateral fluxes were 10–20-fold smaller and independent of IR loading and water table depth. The exchange with deeper soil layers was sensitive to water table depth, in contrast to G, which responded primarily to IR loading. The qualitative responses in the bog and fen were similar, but the fen displayed wider seasonal variation and greater extremes in soil energy fluxes. The differences of G in the bog and fen are attributed to differences in the reflectance in the long waveband as a function of vegetation type, whereas the differences in soil heat storage may also depend on different soil properties and different water table depth at comparable treatments. These data suggest that the ecosystem-dependent controls over soil energy fluxes may provide an important constraint on biotic response to climate change.

Key words: heat flux; infrared loading; mesocosm; net radiation; soil energy balance; wetland.

INTRODUCTION

Wetlands play a central role in the global carbon budget as well as in global warming. They cover about 4% of global land area (Matthews and Fung 1987; Aselmann and Crutzen 1989), but contribute

about one-fourth of total global methane (CH₄) flux (Bartlett and Harriss 1993). Boreal peatlands comprise about one-half of global wetlands (Matthews and Fung 1987) and contribute 10%–15% of their methane emissions (Bartlett and Harriss 1993; Nisbet and Ingham 1995). Because methane emissions from peatlands are positively correlated with soil temperature (Hargreaves and others 2001; Updegraff and others 2001), the production of this potent greenhouse gas may have a positive feedback

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with climate warming (Bridgham and others 1995). Furthermore, the carbon budgets of peatlands, including methane emissions, are strongly affected by water table elevation (Gorham 1991; Shurpali and Verma 1998), which will likely change along with soil temperatures in future climates (Roulet and others 1992; Rouse 1998). With an estimated $25 \pm 2\%$ of all terrestrial carbon stored in boreal wetlands as peat (Gorham 1991; Sampson and others 1993), it is of utmost importance to understand the processes that govern the exchange of energy and matter in these ecosystems.

An increase in mean temperature is likely to have profound effects on boreal peatlands, because biological processes in boreal ecosystems are largely restricted by low temperature and limited frost-free periods (Van Cleve and others 1991). However, experimental approaches simulating expected future radiation loading have been few, and it is unknown how these changes might affect soil energy balance and energy partitioning between various component fluxes. The available literature suggests that there may be feedbacks between vegetation structure and ecosystem energy fluxes (Harte and others 1995; McFadden and others 1998; Bridgham and others 1999), which further underscores the importance of the issue.

In this study, we investigated the effect of increased IR loading and altered water table depth on the soil energy fluxes in two dominant boreal peatland types—bogs and fens, which differ from one another in their nutrient dynamics, alkalinity, soil carbon quality, hydrology, and plant community composition (Moore and Bellamy 1974; Bridgham and others 1996, 1998, 2001a, 2001b; Weltzin and others 2000), all of which affect the way these ecosystems react to climatic change. Bogs are ombrotrophic (that is, they receive all their water and mineral inputs from precipitation) and consequently have acidic soils, low basic cation content, less humidified peat, and are dominated by *Sphagnum* mosses, ericaceous shrubs, and black spruce. In contrast, fens are minerotrophic (that is, they receive inputs of water and minerals from groundwater and/or overland runoff), which causes more alkaline, higher pH soils, more humidified peat, and dominance by graminoids and nonericaceous shrubs and trees, such as northern white cedar (*Thuja occidentalis* L.) and tamarack (*Larix laricina* (Du Roi) K. Koch).

The experiment was designed to provide quantitative information on the soil energy fluxes in a bog and fen when exposed to increased radiative forcing and different water table depth. The objective of the study was to provide answers to the following ques-

tions: (a) What determines the partitioning of radiative energy to soil heat flux? (b) How will the energy be used when transferred to soil? (c) How does water table depth alter the effects of increased IR loading on the partitioning of energy between different fluxes? and (d) How does the partitioning of radiative energy differ between bog and fen? This experiment was carried out in a larger experimental framework, which is designed to elucidate the interactions and feedback mechanisms between plant communities, energy fluxes, carbon and nutrient cycles and trace gas emissions in response to several potential scenarios of climate change (Bridgham and others 1995; 1999; Weltzin and others 2000, Weltzin and others 2001, Weltzin and others 2003; Updegraff and others 2001; Pastor and others 2003).

METHODS

Study Site

The study site is located about 70 km north of Duluth, Minnesota, USA, and was established in 1994. The research facility consists of 54 mesocosms housing intact peat monoliths extracted from a fen (Alborn, MN, USA) and a bog (Toivola, MN, USA), both located at 47°N, 92°W. The monoliths were removed in the winter when frozen, and the surface vegetation and soil structure were minimally disturbed. The circular peat monoliths (with a surface area of 2.1 m² and depth of 60 cm) were placed in plastic tanks that had been sunk in an open field and insulated from the surrounding soil with 8 cm of sprayed foam to reduce heat transfer between the soil and the peat monoliths. The depths of peat in the donor sites were 3.5 and 4.4 m for the bog and fen, respectively; the basal ages for the two sites were $10,040 \pm 70$ and $9,730 \pm 70$ years, respectively. The upper 60-cm layer of the bog is mostly derived from *Sphagnum* moss and has a pH of 4.1 (Bridgham and others 1998). The vegetation in the bog is dominated by the bryophytes (mosses) *Sphagnum fuscum* (Schimp.) Klinggr., *S. capillifolium* (Ehrh.) Hedw., *S. magellanicum* Brid., and *Polytrichum strictum* Brid., the short (less than 10 cm tall) ericaceous shrubs *Chamaedaphne calyculata* (L.) Moench., *Andromeda glaucophylla* Link., *Kalmia polifolia* Wang., *Vaccinium oxycoccos* L., and *Ledum groenlandicum* Oeder., and short (less than 10 cm tall) black spruce (*Picea mariana* (Mill.) BSP). The surface pH of the peat in the fen is 4.9, and the vegetation is dominated by the graminoids *Rhynchospora alba* (L.) Vahl, *R. fusca* (L.) Ait. f., *Carex limosa* L., *C. lasiocarpa* Ehrh., and *C. livida* (Wahl.) Willd., with

Table 1. Net Radiation (Rn, MJ m⁻² d⁻¹) at Different Infrared (IR) Loading Treatments in Bog and Fen at Different Times during 1999

	Winter* DOY 22–40	Spring* DOY 80–95	Summer DOY 195–215	Fall* DOY 309–323
Fen				
Ambient, H0	0.94±0.50	7.83±0.43	11.65±0.30	1.63±0.16
H1	4.79±0.25	11.20±0.21	16.15±0.30	7.73±0.16
H2	10.00±0.27	14.59±0.23	20.46±0.30	12.28±0.16
Bog				
Ambient, H0	-0.95±0.41	6.47±0.35	12.77±0.30	1.94±0.16
H1	4.01±0.27	9.91±0.23	14.76±0.30	5.87±0.16
H2	7.87±0.27	12.95±0.23	19.66±0.30	10.19±0.16

DOY, day of year

Data are weighted means (±SE) from general linear models procedure (SAS) across all water level treatments. All water table treatments are pooled because water table depth did not affect Rn (see Methods). All IR treatments were significantly different from each other at all periods ($P < 0.001$). The P values for the effect of peatland type and infrared loading treatment on Rn were as follows: Winter— $P_{type} < 0.001$, $P_{heat} < 0.001$, $P_{tch} = 0.033$; Spring— $P_{type} \leq 0.001$, $P_{heat} < 0.001$, $P_{tch} = 0.731$; Summer— $P_{type} = 0.148$, $P_{heat} < 0.001$, $P_{tch} \leq 0.001$; Fall— $P_{type} < 0.001$, $P_{heat} < 0.001$, $P_{tch} < 0.001$. (Asterisks [*] in the table heading indicate significant difference ($P < 0.05$) between fen and bog.)

only minor moss cover. The peat monoliths were extracted from the lower wetter areas (flarks) in the fen and from a large treeless area in the bog to maximize the vegetation contrast inherent to these two types of peatlands.

Experimental Design

This experiment was a fully crossed factorial design with three IR loading treatments (ambient [H0], half heat [H1], and full heat [H2]), three water table treatments (wet [W0], intermediate [W1], and dry [W2]), and two ecosystem types (bog and fen), with three replicates of each treatment combination. The IR loading was augmented continuously (24 h per day) by IR heat lamps (model MRM-1215; Kalglo Electronics, Bethlehem, PA, USA). The lamps were 1.2 m long; factory-rated to 750 and 1,500 W m⁻² at half and full power, respectively; and were mounted 1.3 m above the surface of each plot. The measured net radiation (Rn) above the plots, however, increased only 32–56 W m⁻² for the H1 treatment and 76–104 W m⁻² for the H2 treatment (calculated as the average difference between daily sums) (Table 1).

The water table was maintained with a polyvinyl chloride pipe manostat leading to an adjacent sump tank. Water tables were initially set at -2, -15, and -22 cm in the bog and +3, -10, and -18 cm in the fen relative to the lowest topographic point in the plot. For comparison, water tables at the natural sites are on average about -21 and +2 cm during the growing season in the bog and fen, respectively (Chapin 1988). However, water table heights have been kept constant relative to the *initial* peat sur-

faces but not to the *dynamic* peat surfaces as they change through time due to the gain or loss of soil carbon (we consider this to be a response variable). Due to net soil carbon gain in the bog mesocosms and net carbon loss in the fen mesocosms (S. D. Bridgham unpublished), water tables averaged -16, -20, and -29 cm in the bog mesocosms and -1, -10, and -18 cm in the fen mesocosms (representing W0, W1, and W2 for each ecosystem) as of 1999, the year for which energy data are reported in this paper. The water tables were replenished from natural rainfall and, as necessary, by weekly additions of water transported from a ditch draining the bog. The chemistry of the ditchwater is similar to bog pore water (Bridgham and others 1995, Bridgham and others 1999; Weltzin and others 2000, 2001; Updegraff and others 2001). Active control of the water table was maintained only during the growing season. For more details on the experimental design and setup, refer to Bridgham and others (1999).

Measurements

The energy budget between vegetation and the atmosphere can be expressed as: 1

$$Rn = H + L + G + M \quad (1)$$

where Rn is the net radiation over the mesocosm, H is sensible heat flux, L is the latent heat of evapotranspiration, G is soil heat flux, and M is the energy saved in chemical bonds in the process of photosynthesis. We measured Rn and G to address energy transfer to soil and its partitioning between

different components. For the purposes of this study, R_n can be expressed as the sum of five indistinguishable component fluxes: 2

$$R_n = R_{il} + R_{is} + R_{IR} - R_{ol} - R_{os} \quad (2)$$

where R_{il} and R_{is} are incident incoming long- and short-wave radiation, respectively; R_{ol} and R_{os} are reflected long- and short-wave radiation, respectively; and R_{IR} is the supplemental long-wave component, added as an experimental treatment. The experiment is based on the assumption that R_{il} and R_{is} are equal for all the plots and any observed differences in the measured R_n are due to R_{IR} , R_{ol} or R_{os} . Because the reflectance varies less in the short (R_{os}) than in the long waveband (R_{ol}) (Madeira and others 2001) and the maximum absorbance of water occurs in mid-infrared range, differences in R_n within the same IR loading treatment are caused primarily by variations in R_{ol} . Net radiation (R_n) was measured with Q7.1 Net Radiometers (Radiation and Energy Balance Systems [REBS], Seattle, WA, USA). The sensors were mounted 15–20 cm above the vegetation, which resulted in about 92% of the radiative surface influence originating from the mesocosm (Schmid 1994).

The total energy flux to the soil is distributed between different transfer processes and can be expressed as: 3

$$G = G_s + G_b + S \quad (3)$$

where G_s is the lateral heat flux, G_b is the heat flux through the bottom of the mesocosm, and S is the amount of heat stored in the soil. The fluxes were monitored with HFT3.1 soil heat flux plates (REBS) at the soil surface (G), bottom (G_b) and sides (G_{s1} , G_{s2} , and G_{s3} at 5-, 25-, and 45-cm depth, respectively) of the peat monolith. The surface heat flux plate was 1–2 cm below the peat surface in the center of the plot, whereas the side and bottom heat flux plates were just outside the tank (Figure 1) at depths mentioned above.

For the calculations of total energy gain and loss to and from the monolith, the uppermost side-mounted heat flux plate represented the average flux through the side of the monolith from the surface to the depth of 15 cm, the middle heat flux plate represented the average flux between 15 and 35 cm, and the lowermost heat flux plate represented the average flux between 35 and 60 cm. Thus, soil energy storage was calculated as follows:

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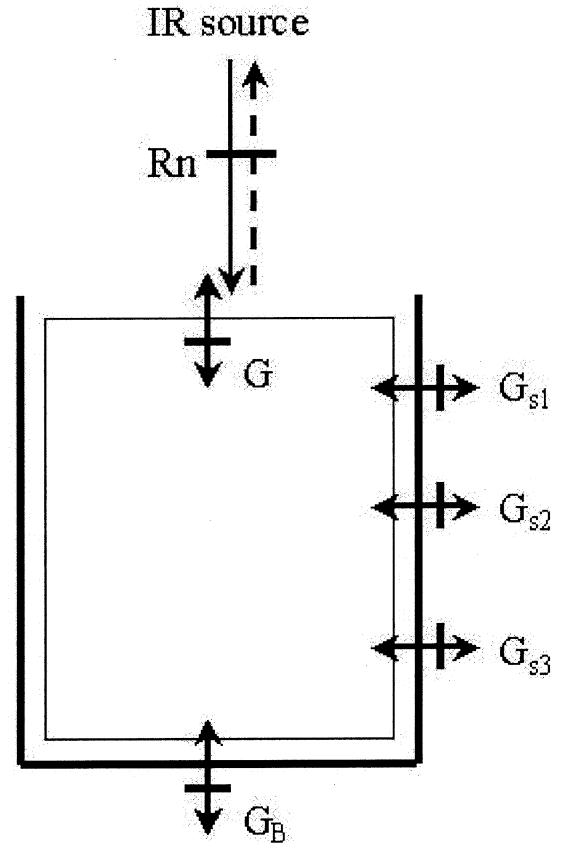


Figure 1. Schematic diagram of a soil mesocosm with the measured fluxes and the sensor locations indicated. R_n , net radiation; G , soil surface heat flux; G_{s1} , G_{s2} , G_{s3} , lateral soil heat fluxes at depths of 5, 25, and 45 cm; G_b , soil heat flux through the bottom of the mesocosm. The mesocosms are cylindrical, 0.6 m deep, and have a surface area of 2.1 m².

$$S = (\pi r_G^2 \times G - \pi r_B^2 \times G_b - \sum_{i=1}^3 G_{si} \times 2\pi r_i l_i) \div \sum_{i=1}^3 \pi r_i^2 l_i \quad (4)$$

where S is heat storage (MJ m⁻³ d⁻¹), G and G_b are soil heat fluxes on the top and bottom of the peat monolith (positive value indicates downward flux—that is, if G is positive the plot gains heat, whereas when G_b is positive the plot loses heat); r_G and r_B are the radii of the mesocosms on the top and bottom (85 and 75 cm, respectively); and G_{s1} , G_{s2} , and G_{s3} are the heat fluxes along the side of the mesocosms from top down, each weighted for the area they represent with radii of 84, 81, and 78 cm,

respectively. The sensors along the side of the mesocosms (G_{S1} , G_{S2} , and G_{S3}) represented sections of 15, 20, and 25 cm, referred to as l_1 , l_2 , and l_3 . The mesocosms gained heat when S was positive and lost heat when S was negative. Measurements of Rn and soil heat fluxes were taken every 20 s, and 30-min averages were recorded with CR10X data loggers (Campbell Scientific, Logan, UT, USA) via MD9 coaxial multidrop interface (Campbell Scientific) and coaxial cables. All data loggers were connected to a central computer, which retrieved data every 12 h.

Data Analysis

The 30-min averages of the parameters were pooled to calculate daily sums for 1999, the 5th year after initiation of the treatments. The heat fluxes in deeper soil layers responded with a time lag of up to 70 days to energy input from the soil surface, whereas individual daily sums varied significantly from day to day. Because energy fluxes in the deeper layers of soil depend on the buffered average input over a period of several days, the statistical analyses were performed on 10-day running averages of data. Data were further pooled to analyze treatment effects during different times of the year. The data were assessed visually and periods with stable parameter values were chosen for further analysis. We chose four 2-week periods to characterize the treatment effects during winter (day of year [DOY] 22–40), spring [DOY 80–95], summer [DOY 195–215], and fall [DOY 309–323]. The transition periods between seasons were deliberately avoided to minimize within-treatment variability while maximizing that among treatments and wetland types.

The variation in plot-level Rn was analyzed as a function of peatland type, time, IR loading, and water table depth. Because water table did not affect Rn, we pooled all water table treatments for further analysis, and because of significant interactions of peatland type with IR loading and time, we separated the two peatland types for all further analyses. The effects of IR loading and water table on soil heat fluxes were estimated by repeated measures analysis of variance (rmANOVA) in SAS (SAS Institute, Cary, NC, USA) using the methods outlined in Cody and Smith (1991). For estimating the effects of the water (W) and heat (H) treatments individually, as well as their interaction term on soil heat fluxes, plot nested by water and heat was used as the error term. For estimating the effect of time of year and its interaction effects with water and heat, the compound of time and plot nested by water and heat was used as an error term. The

effects were considered as statistically significant up to $P = 0.05$ level, but we note if only marginally significant effects were observed. The data are presented as least squares means \pm SE.

RESULTS AND DISCUSSION

Net Radiation (Rn)

The H1 treatment increased Rn by 3.4–6.1 and 2.0–5.0 MJ m⁻² d⁻¹ (or, on average, 55 and 40 W m⁻²) in fen and bog, respectively, whereas the increase in the H2 treatment was 6.8–10.7 and 6.5–8.8 MJ m⁻² d⁻¹ (on average, 101 and 89 W m⁻²) for fen and bog, respectively (Table 1). The water table manipulations did not affect Rn ($P = 0.358$) and therefore; these values were averaged across all water table treatments. These increased heat loads are considerably greater than those projected to occur by the end of 21st century due to anthropogenic increases in atmospheric greenhouse gas concentrations (Kattenberg and others 1996; IPCC 2001), but they were necessary to achieve the predicted degree of soil warming. Our experimental treatments resulted in a mean growing season temperature increase of 1.6–4.1°C at 15-cm depth in the soil (Bridgham and others 1999), which is well within the range of predictions of general climate change models for the next 100 years (Kattenberg and others 1996; IPCC 2001).

The relative enhancement of Rn over ambient was greatest in the winter (bog) or in the fall (fen) and smallest in the spring and summer (Table 1). This pattern is at least partially caused by the constant IR load supplementing seasonally changing solar radiation. However, there was a significant interaction ($P < 0.05$) between IR loading and ecosystem type on Rn in all but the spring period ($P = 0.731$), suggesting an important ecosystem effect on the seasonal signal of Rn. The absolute value of Rn tended to be greater in the fen at any IR loading, which we attribute to lower reflectivity in the long waveband (R_{ol} in Eq. [2]), because the radiation inputs were the same for all plots. However, the individual component fluxes described in Eq. (2) were not actually measured, and the conclusions are based on our current theoretical understanding of the dynamics of the system. We suggest that the higher Rn in the fen can be attributed to higher absorption of radiation in the more complex sedge canopy compared to that of the *Sphagnum* moss in the bog. Clear differences in surface albedo have been described for wetland canopies with different vertical complexity (Spanglet and others 1998; Moore 2002). The canopies of the two wetlands

Table 2. The *P* Values for the Main and Interactive Effects of Water Table (W), Infrared Loading (H), and Time of Year (T) with Respective Degrees of Freedom (df) on Soil Surface Heat Flux (G), Energy Flux at the Bottom of the Mesocosms (G_B) and Soil Heat Storage Flux (S)

Source (df)	<i>P</i> values		
	G	G_B	S
Fen			
W (2)	0.307	0.062	0.637
H (2)	0.006	0.640	0.031
W × H (4)	0.303	0.363	0.647
T (3)	<0.001	<0.001	<0.001
W × T (6)	0.491	0.432	0.362
H × T (6)	0.019	0.239	0.060
W × H × T (12)	0.077	0.005	0.261
Bog			
W (2)	0.295	0.004	0.603
H (2)	0.006	0.707	0.067
W × H (4)	0.102	0.418	0.401
T (3)	<0.001	<0.001	<0.001
W × T (6)	0.942	0.957	0.681
H × T (6)	0.979	0.949	0.678
W × H × T (12)	0.412	0.903	0.810

Effects shown in bold were considered statistically significant.

also have very different water-holding capacities, particularly due to the specialized hyaline cells in *Sphagnum* (Clymo and Hayward 1982). Water table depth had no effect on Rn in either wetland; However, given that it is an attribute of vegetation type, it is possible that water table depth also contributed to the differences in Rn between the fen and bog, although the primary effect, clearly, is through the structural properties of the canopy.

Heat Input and Partitioning (G)

The treatment differences in G were similar to those observed for Rn, being significantly affected by IR load, but not by water table depth (Table 2). In the fen, however, there was a significant IR loading × time interaction (Table 2) and a marginally significant IR loading × time × water table interaction, with a tendency for the effect of IR loading on G to be greater in wetter plots during the spring and fall periods (Figure 2). The net effect of these results was that G values were relatively similar in fen and bog plots during summer and winter months, but the fen plots showed greater heat gains in the spring and greater heat losses in the fall, especially in the

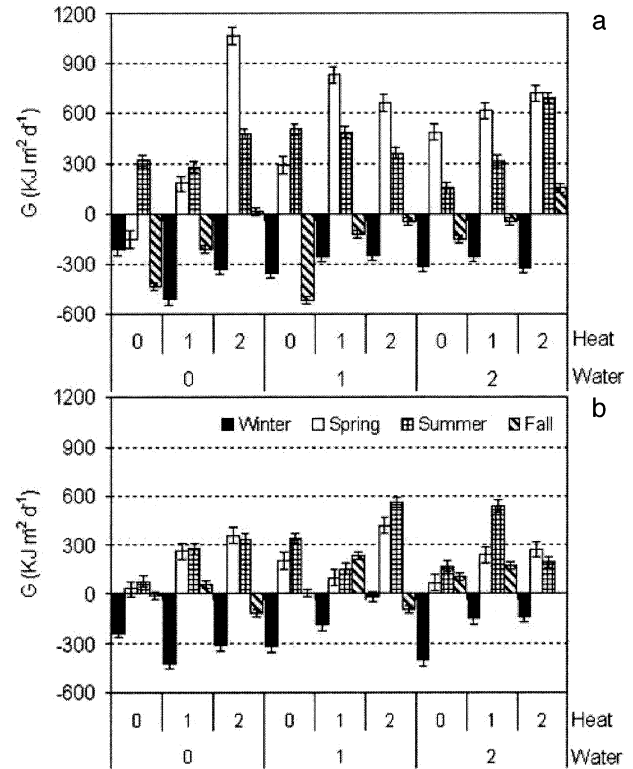


Figure 2. Soil surface heat flux (G) under different IR loading and water table manipulations at different times of year in fen (a) and bog (b). The *P* values and associated degrees of freedom (df) for the main and interactive effects of water table and IR loading are shown in Table 2.

high water table treatment. Although the effect of IR loading on G in the fen plots was greatest in spring and smallest in summer, the coupling between G and Rn was relatively low ($R^2 = 0.035, 0.208, 0.223, \text{ and } 0.287$ in winter, spring, summer, and fall, respectively). The respective R^2 values for the bog were 0.075, 0.145, 0.301, and 0.325. The low coupling in winter can be attributed to snow cover on the plots. It is obvious that the sum of daily average heat fluxes from four seasons (Figure 1) at a given treatment does not add to zero. This is because the seasons are of different duration and the data are not weighed for the length of the seasons.

The lack of a water table effect (Table 2) suggests that the greater G in fen plots compared to bog plots during spring and fall was due to different vegetation dynamics in the two ecosystems. The canopy of the bog plots, dominated by *Sphagnum* mosses and secondarily by evergreen shrubs, remains intact throughout the winter and spring, whereas in fen plots the graminoid-dominated vegetation senesces and dies in fall and does not become fully grown

until July (Bridgham and others 1999; Weltzin and others 2000). Lower live plant cover (Weltzin and others 2000) in fens during these periods might explain the observed differences in G between bog and fen. Similarly, Harte and others (1995) also found that soil temperature (and G) in a montane meadow warming experiment was greater in areas with lower plant cover.

The relative partitioning of energy to G (as percent of R_n) was independent of IR loading and water table depth, whereas it was, like G , dependent on the time of year (data not shown). The partitioning was slightly, yet significantly ($P < 0.05$), greater in the fen than in the bog (5.4% and 4.5% for fen and bog, respectively). The observed values of 3% to 8% of R_n are similar to those reported in the literature for a number of mid- to high-latitude wetlands—generally ranging from 5% to 15% (Burba and others 1999b). Due to the uniform fractional partitioning of energy to G , the available energy ($R_n - G$) also reflected the general pattern observed in R_n (data not shown). The available energy, of which 80%–90% can be used for evapotranspiration (Burba and others 1999b), ranged from 7.9 to 13.3 $\text{MJ m}^{-2} \text{d}^{-1}$ in fens and from 11.9 to 13.7 $\text{MJ m}^{-2} \text{d}^{-1}$ in bogs under ambient IR load, and reached up to 21.7 $\text{MJ m}^{-2} \text{d}^{-1}$ in fen plots at high IR loading treatment. Although latent and sensible heat fluxes were not measured, the estimates of evapotranspiration (Bridgham and others 1999) based on water budget data for the mesocosms suggest that most of the available energy was used as latent heat.

Energy dissipation from the peatland mesocosms to the surrounding soil was dominated by the vertical exchange through the bottom of the mesocosms (G_B) (Figure 3), whereas lateral fluxes (G_{S1} , G_{S2} , G_{S3}) were 10- to 20-fold smaller than G_B and independent of IR loading and water table treatments (data not shown). The deeper layers responded to energy input with a substantial delay (for example, G_B remained high until DOY 280, whereas G reached low winter values around DOY 240). For all treatments, heat loss through the bottom of the mesocosms (G_B) was positive during summer but negative during spring, fall, and winter, indicating that mesocosms received energy from the deeper soil layers during the cooler seasons of the year. G_B was significantly affected by the water table depth (although only marginally so in the fen plots) ($P = 0.0617$) (Table 2) but not by IR loading, despite the significant effects of IR loading on G . In the fen plots, there was also a significant water \times heat \times time interaction reflective of lower

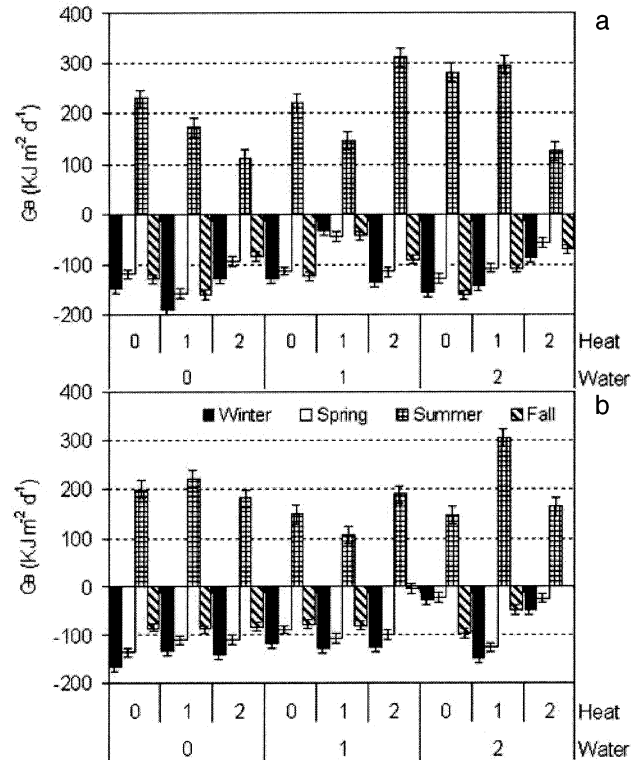


Figure 3. Soil heat flux through the bottom of the mesocosms (G_B) under different IR loading and water table manipulations at different times of year in fen (a) and bog (b). The P values and associated degrees of freedom (df) for the main and interactive effects of water table and IR loading are shown in Table 2.

water table treatments losing more energy as G_B during summer and gaining less during spring, fall, and winter than high water table treatments (Figure 3 and Table 2). In the bog, G_B was less negative at lower water table during winter and spring, with no significant interaction between the water table effect and season.

Heat Storage (S)

Energy, once transferred to soil ($+G$), can be (a) emitted back to atmosphere ($-G$), (b) transferred to other soil layers (G_{S1} , G_{S2} , G_{S3} , G_B), or (c) stored (S), (Eq. [4]). Cumulative heat storage (S) over a period of a year is close to zero, but in the short term it reflects changes in soil temperature. In our study, S was strongly correlated with G ($R^2 = 0.95$ and $R^2 = 0.42$ for fen and bog, respectively) during individual seasons. Although S responded to IR loading in both fen and bog plots, the two ecosystems displayed significant differences in the magnitude and seasonality of soil heat storage (Figure 4).

The sensitivity of S to IR loading was greater in

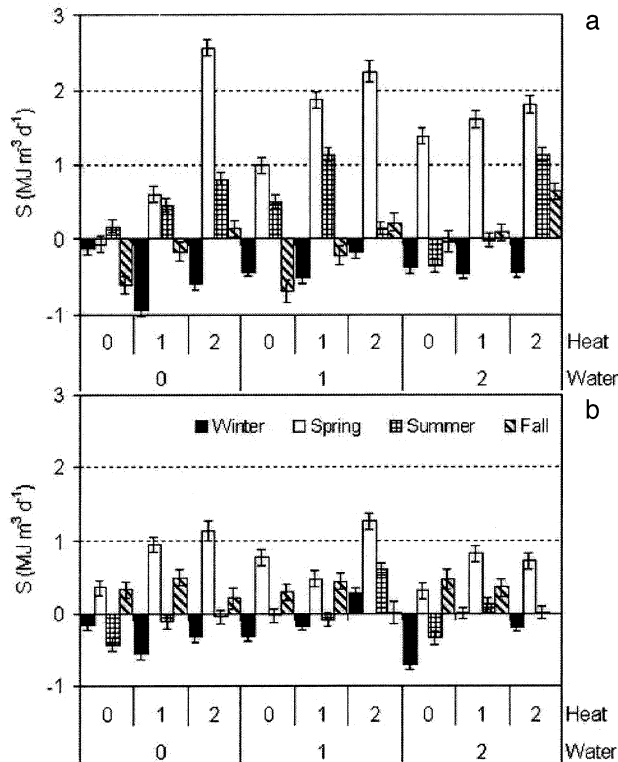


Figure 4. Soil heat storage flux (S) under different IR loading and water table manipulations at different times of year in fen (a) and bog (b). The P values and associated degrees of freedom (df) for the main and interactive effects of water table and IR loading are shown in Table 2

fen than in bog plots (Table 2). The bog plots had positive S in spring and fall, lost energy in winter, and showed either energy loss or near-zero balance in summer. Fen plots had positive S during spring and summer and lost energy in winter in most treatments, with mixed results in fall. The fen plots had generally higher R_n than bog plots ($P < 0.001$, except in summer), as well as greater S in spring and summer ($P < 0.001$), which was also reflected in higher soil temperatures in fen plots throughout the growing period (Bridgham and others 1999). The fen plots showed greater extremes in S than bog plots, especially in spring during the highest G .

This implies that the ability of fen to buffer extremes in radiative loading may be less than that of bog because of the seasonality of their plant cover. The differences between these two wetland types could be attributed to either the structural properties of the plant canopy or to the heat capacity of the soil, which can also be viewed as an attribute of the vegetation type. The average water table depth in the fen plots was 10–15 cm higher than in the bog plots at similar water table treatment. This, and

differences in soil root-free bulk density—0.087 and 0.022 g cm⁻³ in the fen and bog, respectively (data not shown)—may have contributed to the observed effects in S . However, further evidence that distinguishes between the effects of water table depth, soil properties, and vegetation properties above ground is required to validate this hypothesis.

Although environmental processes in wetlands have been well researched, the majority of the studies in the boreal region have been carried out during the snow-free growing season. As a result of logistical and technical difficulties related to equipment maintenance in winter, most of our knowledge of environmental control of wetland energy fluxes is based on growing-season data. Burba and others (1999a) compared surface energy fluxes during summer months in three types of prairie wetlands in Nebraska and observed greater diurnal extremes of G in open-water areas of the wetlands than in vegetated areas. They also found that despite large positive daytime G values in a water-covered *Phragmites australis*-dominated wetland in Nebraska, the S over a period of weeks was relatively small due to comparable energy dissipation back to the atmosphere during the night (Burba and others 1999b).

In the current experiment, where the water table was below the soil surface in all experimental treatments, significant daily S was observed in fen plots throughout the growing season, although the maximum S occurred during spring months (Figure 4). The magnitude of S was smaller for bog plots, where the water table was 10–15 cm deeper than in respective fen plots. However, for fen and bog plots individually, S was predominantly determined by IR loading, with no effect of water table depth. Therefore, we cannot conclusively distinguish between the effect of vegetation type and the absolute effect of water table depth. The higher water table in fen compared to bog plots, combined with minimal live vegetation (Weltzin and others 2000), may have contributed to higher spring-time storage compared to respective bog plots. The marginally significant interaction of IR loading and time of year on S (Table 2) in fen plots but not in bog plots can be attributed to the seasonality of fen vegetation. The current study shows that in both wetland types, significant energy storage occurs at time scales longer than a day throughout the year and that the magnitude of the fluxes strongly depends on the wetland type and IR loading. Water table depth had a surprisingly small effect on S within a wetland type, but it may have been important in determining differences in S between the two wetland types.

CONCLUSIONS

The results from the present study, with its manipulative treatments, offer valuable insights into how changing IR loading and water table levels will affect the energy budget of northern peatlands in a way that is not possible with observational studies of natural sites. In both peatland types, R_n , G , and S were predominantly determined by IR loading. Water table depth did not affect G and S in the bog plots, but in the fen the higher water table amplified the stimulatory effects of IR loading on G during lowest live canopy coverage in spring and fall. In contrast, G_B in both fen and bog plots was primarily driven by water table depth, with no IR loading effect. Higher average water tables in the fen than in the bog may also explain the higher S in the fen, even though water table depth was not significant in explaining the variation of S among the treatments of each individual ecosystem. Despite having similar qualitative main treatment effects, the fen displayed wider seasonal variation and greater extremes in G than did the bog. These differences between the bog and the fen can be attributed to more complex and seasonally changing plant cover in the fen. Although the effects of plant cover type and water table depth between the two wetland types are difficult to distinguish conclusively based on the data collected in this experiment, our results nevertheless suggest that the observed ecosystem-specific control over soil energy fluxes provides an important constraint on biotic response to climate change.

An extrapolation of these results to natural settings suggests that the magnitude and seasonal variation of soil energy fluxes, and hence of soil temperature, due to projected increases in radiative forcing and associated changes in the water regime may be greater in fens than in bogs. These changes in soil energy balance will in turn affect the biotic processes in each ecosystem, such as the gain or release of carbon. Results like those reported in this study are much needed to validate comprehensive mechanistic-empirical wetland models (Zhang and others 2002). Because it has been suggested that the moderating effect of vegetation on increased IR loading may equal the direct effect of radiative forcing (Sellers and others 1997), we have begun further studies inquiring into the feedback interactions between vegetation properties and the ecosystems' energy fluxes. With boreal wetlands playing such a key role in the global carbon budget, it is essential that information gained from the mechanistic feedback studies be incorporated in global circulation models (GCMs) that currently treat wetlands as

"outliers" in their projections (see Zheng and others 2003).

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