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# SURFACE EXCHANGE OF WATER VAPOUR BETWEEN AN OPEN SPHAGNUM FEN AND THE ATMOSPHERE

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**Abstract.** Water loss by evapotranspiration (ET) is a principal component of the hydrologic cycle in wetlands. Using micrometeorological techniques, we measured ET from a *Sphagnum*-dominated open fen in northcentral Minnesota (U.S.A.) from May to October in 1991 and 1992. The daily ET rate ranged from 0.2–4.8 mm d<sup>-1</sup> with a growing season average of 3.0 mm d<sup>-1</sup>. The evapotranspiration rate of the fen was near the potential rate of open water evaporation when the vascular plants were actively growing and the water table level was within or above the rooting zone. Using a dual-source modification of the Penman–Monteith equation (Massman, 1992), we partitioned the measured ET into evaporation from the non-vascular *Sphagnum* surfaces and transpiration from vascular plants. The analysis indicated that about two thirds of the water vapour flux to the atmosphere was from evaporation when the *Sphagnum* surface was wet. Such an evaporative flux was expected because of vertical distribution of vascular plant leaves which had a small leaf area index (0.4–0.7) and intercepted only about 30% of net radiation ( $R_n$ ) during the day. The remainder of  $R_n$  was thus available for evaporation from *Sphagnum*. Evaporation significantly decreased as the *Sphagnum* surface dried out. When the water table was within the rooting zone (0–0.4 m), the vascular plants absorbed *Sphagnum*-generated sensible heat, which amounted up to one third of their transpiration energy flux. Under these conditions, the total water vapour flux remained near its potential rate owing to the enhanced transpiration from vascular plants. A drop in water table of 0.15–0.2 m below the hollow bottom during vascular plant senescence resulted in ET rates lower than the potential rates by 5–65%.

## 1. Introduction

The hydrology of wetlands significantly affects the exchange of trace gases such as methane and carbon dioxide in these systems (e.g., Moore and Knowles, 1989; Gorham, 1991; Shurpali *et al.*, 1995). Excluding human activities such as drainage, water loss by evapotranspiration (ET) and input through precipitation are the principal controls of water table level. In many northern wetlands, *Sphagnum* mosses are the major ground cover. However, coexistence of a sparse vascular plant canopy is also common. Vascular and non-vascular plants have different physical and physiological controls on ET. Therefore, separating the contributions of non-vascular *Sphagnum* and vascular plants has been suggested (Lafleur, 1990). The Penman–Monteith combination model (Monteith, 1965) provides a useful framework for such analysis. In particular, the dual-source modification (e.g., Shuttleworth and Wallace, 1985) of this model allows us to investigate the interrelationships between

evaporation/transpiration, surface properties, and meteorological conditions. This approach has been successfully applied to sparsely vegetated canopies (e.g., Lafleur and Rouse, 1990; Nichols, 1992; Massman, 1992; Stannard, 1993; Sene, 1994; Massman and Ham, 1994). Lafleur and Rouse (1990) applied this dual-source approach to their data collected in a subarctic wetland where the surface was dominated by sedge hummocks. In their study, however, the surface resistance was assumed zero because the surface was saturated due to high water table. As yet, no attempt has been made to incorporate the resistance presented by a non-vascular *Sphagnum* surface into a dual-source Penman–Monteith model of ET.

The objective of our study is to document seasonal variations in daily ET from a *Sphagnum*-dominated fen through two growing seasons and examine the processes governing water vapour exchange in this important ecosystem. We considered three fundamental issues here: (1) does the *Sphagnum*-dominated wetland evaporate at the potential rate? (2) do changes in the water table elevation affect ET rates? and (3) what are the relative roles of vascular and non-vascular plant covers on ET rates? In order to address these questions, we made micrometeorological measurements of the components of the surface energy balance in a *Sphagnum*-dominated fen in northcentral Minnesota from May to October in 1991 and 1992. The dual-source approach of Massman (1992) was used to partition the measured ET into evaporation from the *Sphagnum* moss and transpiration from vascular plants. The major advantage of this method is that no *a priori* assumptions on canopy resistance or canopy temperature are needed (Massman and Ham, 1994).

## 2. Materials and Methods

### 2.1. SITE DESCRIPTION

The study was conducted in an open *Sphagnum* fen, referred to as the Bog Lake Peatland, situated in the Chippewa National Forest, adjacent to the Marcell Experimental Forest (47°32' N, 93°28' W, 416 m above m.s.l.) in northcentral Minnesota during six-month periods in 1991 and 1992. The pH level (4.0–5.2) and the occurrence of plants adapted to nutrient-poor conditions suggest that the study site is transitional between poor-fen (poorly minerotrophic) and bog (oligotrophic) (Verry, 1988). The region is underlain by slightly calcareous glacial debris which is thinly overlain with primarily upland soils. The remaining low lying areas are covered by lowland peat soils and open water (Verry, 1975). The area receives an average annual precipitation of 770 mm and mean annual temperature is approximately 3 °C. It is estimated that approximately 65% of annual precipitation is lost through ET and the remaining precipitation is lost to groundwater or stream outflow (Verry, 1988). The lack of a surface water outlet keeps the water table relatively high in this wet fen. These conditions support the development of *Sphagnum papillosum* and *Sphagnum majus*, which form a nearly continuous carpet. Vascular plants such as

*Scheuchzeria palustris*, *Rhynchospora alba*, *Carex* spp., *Chamaedaphne calyculata*, and *Saracenia purpurea* are also present. The leaf area index of these vascular plants varied from 0.4 to 0.7 during May–September and the canopy height reached up to approximately 0.4 m. The microtopography at the site consists of a pattern of hollows (micro-valleys) and hummocks (micro-hills of 0.15–0.55 m).

## 2.2. FIELD MEASUREMENTS

We measured the fluxes of latent heat ( $\lambda E$ )—where  $E$  is the water vapour flux and  $\lambda$  is the latent heat of vaporization) and sensible heat ( $H$ ) using the Bowen ratio-energy balance approach during May through October in 1991 and 1992. In a concurrent study, these fluxes were also measured independently using the eddy correlation sensors described in Shurpali *et al.* (1995). Mean air temperature and humidity were measured using aspirated ceramic wick psychrometers that exchanged between the heights of 1.0 and 2.0 every 5 minutes (Hartman and Gay, 1981). In 1992, we used these “exchanging” psychrometers equipped with Vaisala capacitive relative humidity sensors (Campbell Scientific, Inc., model HMP35C) which eliminated the use of wicks and water reservoirs. Net radiation ( $R_n$ ) above and below the canopy was measured with net radiometers (Radiation Energy Balance Systems, model Q\*6) positioned at 1.5 m and 0.2 m above the peat surface at two locations. We measured the peat heat flux ( $G$ ) with four heat transducers (Radiation Energy Balance Systems, model HFT-1) installed 50 mm below the peat surface under hollows and hummocks at four locations, and the average peat temperature above these heat transducers with platinum resistance thermometers. The surface peat heat flux (referenced to an average hollow bottom) was then estimated using the combination method (e.g., Kimball *et al.*, 1976). The heat storage ( $W$ ) in the *Sphagnum* hummocks and the standing water column above the peat surface was estimated from the surface energy balance equation, by calculating the difference between ( $R_n - G$ ) measured with the net radiometers and soil heat transducers and ( $\lambda E + H$ ) measured independently using the eddy correlation technique. (The best estimates of accuracy for the measurements of  $R_n$ ,  $G$ , and  $\lambda E$  and  $H$  for typical midday conditions are  $\pm 30 \text{ W m}^{-2}$ ,  $\pm 5 \text{ W m}^{-2}$ , and  $\pm 15\text{--}30 \text{ W m}^{-3}$ , respectively. Hence, any errors in  $R_n$ ,  $G$ ,  $\lambda E$  and  $H$  will be implicit in the estimated values of  $W$ .)

Incoming and outgoing solar radiation ( $R_s$ ) and photosynthetically active radiation ( $Q_p$ ) were measured with pyranometers (Eppley Laboratories, model PSP) and quantum sensors (LI-COR Inc., model LI-190SA), respectively. The profile of horizontal mean wind speed was measured with sensitive cup anemometers (Cayuga Development). Leaf area index ( $L$ ) was measured with LAI-2000 area meter (LI-COR Inc.). Stomatal resistance of *Scheuchzeria palustris* (the most dominant vascular species) was measured with a steady-state porometer (LI-COR Inc., model LI-1600-07). Water table elevation was monitored using a recording well installed near the measurement area. Surface temperature ( $T_s$ ) was measured with an infrared

thermometer positioned about 1 m above peat surface with a viewing angle of  $45^\circ$ .  $T_s$  was assumed to be the temperature of the *Sphagnum* moss surface (as discussed by Massman (1992), the dual-source approach is not extremely sensitive to  $T_s$ ).

### 3. Theoretical Considerations

For the open fen studied here, ignoring the photosynthetic and metabolic terms and storage within vegetation, the energy budget of the *Sphagnum* and vascular foliage can be written as

$$\mathbf{R}_{n(s)} - \mathbf{G} - \mathbf{W} - \lambda \mathbf{E}_s - \mathbf{H}_s \approx 0 \quad (1a)$$

and

$$\mathbf{R}_n - \mathbf{R}_{n(s)} - \lambda \mathbf{E}_v - \mathbf{H}_v \approx 0, \quad (1b)$$

where  $\mathbf{R}_{n(s)}$  is the net radiation reaching the *Sphagnum* surface. The subscript  $s$  refers to the *Sphagnum* component and the subscript  $v$  refers to the vascular component.  $\mathbf{R}_{n(s)}$  can be approximated from net radiation at the canopy top,  $\mathbf{R}_n$ , by  $\mathbf{R}_{n(s)} = \mathbf{R}_n \exp(-\kappa L)$  where  $\kappa$  is the attenuation coefficient for vegetation and  $L$  is the leaf area index. The measured  $\lambda \mathbf{E}$  and  $\mathbf{H}$  above the canopy represent the sum of the two components (*Sphagnum* and vascular), i.e.,

$$\lambda \mathbf{E} = \lambda \mathbf{E}_s + \lambda \mathbf{E}_v \quad (2a)$$

and

$$\mathbf{H} = \mathbf{H}_s + \mathbf{H}_v. \quad (2b)$$

In terms of the *Sphagnum* surface Bowen ratio  $\beta_s (= \mathbf{H}_s / \lambda \mathbf{E}_s)$ , we can express the *Sphagnum* component of latent and sensible heat fluxes as

$$\lambda \mathbf{E}_s = (\mathbf{R}_{n(s)} - \mathbf{G} - \mathbf{W}) / (1 + \beta_s) \quad (3a)$$

and

$$\mathbf{H}_s = \beta_s (\mathbf{R}_{n(s)} - \mathbf{G} - \mathbf{W}) / (1 + \beta_s). \quad (3b)$$

If  $\beta_s$  were known, then all the individual flux components can be obtained from Equations (1a)–(3b) (Massman, 1992). Figure 1 shows a resistance formulation of the dual-source model based on energy balance and aerodynamic considerations. The term  $r_a$  is the aerodynamic resistance;  $r_v$  and  $r_s$  are the canopy stomatal resistance and the *Sphagnum* resistance to water vapor transfer, respectively;  $r_b$  is the canopy boundary-layer resistance;  $r_u$  is the subcanopy resistance;  $e_o$  is the

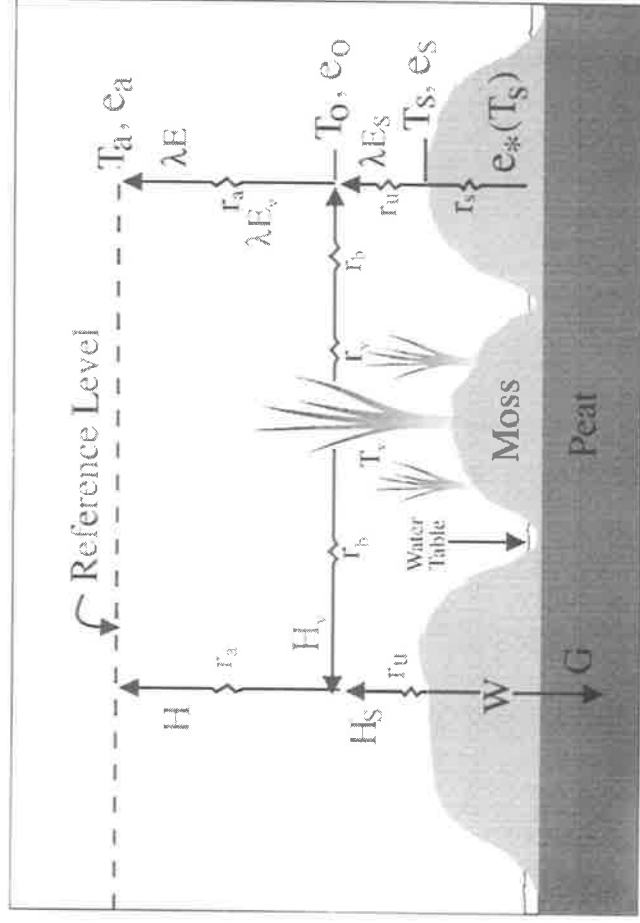


Figure 1. Schematic diagram of the dual-source combination model for a *Sphagnum* fen with sparse vascular plants.

vapor pressure within the canopy and  $e_a$  is the above-canopy vapor pressure;  $e_*$  is the saturated vapour pressure;  $c_p$  is the specific heat of air;  $T_0$  is the air temperature within the canopy and  $T_a$  is the above-canopy temperature; and  $T_v$  and  $T_s$  are the temperatures of the vascular foliage and the *Sphagnum*. Following Massman (1992), we obtain Equation (4) with two unknowns,  $r_s$  and  $\beta_s$ :

$$\begin{aligned} r_s(R_{n(s)} - G - W)/(1 + \beta_s) + [\rho_a c_p(T_s - T_a) - H r_a]/\beta_s \\ = (\lambda \epsilon \rho_a / P)[e_*(T_s) - e_a] - \lambda E r_a, \end{aligned} \quad (4)$$

where  $\epsilon$  is a constant ( $= 0.622$ );  $\rho_a$  is the ambient air density;  $P$  is the atmospheric pressure (in Massman (1992),  $\beta_s$  is further parameterized in terms of a soil parameter ( $c_w$ ) and the equilibrium Bowen ratio ( $\beta_e$ ): i.e.,  $\beta_s = c_w \beta_e$ ).

Alternatively, Massman and Ham (1994) suggest that a surface humidity formulation may be computationally simpler in describing surface evaporation than is an intrinsic surface resistance. We can express  $\lambda E_s$  in terms of  $r_s$  alone as:

$$\begin{aligned} \lambda E_s &= (\lambda \epsilon \rho_a / P)[e_*(T_s) - e_s]/r_s \\ &= (\lambda \epsilon \rho_a / P)(1 - h)e_*(T_s)/r_s \end{aligned} \quad (5)$$

where  $h$  ( $= e_s/e_*(T_s)$ ) is the surface humidity. Using Equations (3a) and (5), we rewrite the first term in Equation (4) and obtain the surface humidity analog (i.e., Equation (1) in Massman and Ham, 1994):

$$\begin{aligned} \lambda\epsilon\rho_a(1-h)e_*(T_s)/P + [\rho_a c_p(T_s - T_a) - \mathbf{H}\mathbf{r}_a]/\beta_s \\ = (\lambda\epsilon\rho_a/P)[e_*(T_s) - e_a] - \lambda\mathbf{E}\mathbf{r}_a. \end{aligned} \quad (6)$$

The aerodynamic resistance  $\mathbf{r}_a$  is estimated as

$$\mathbf{r}_a \approx \bar{U}/u_*^2 \quad (7)$$

where  $\bar{U}$  is the mean horizontal wind speed at height  $z$  and  $u_*$  is the friction velocity. The values of  $u_*$  were computed employing a low-level drag coefficient approach outlined by Deacon and Swinbank (1958) and Bradley (1972). The vascular plants ( $L \approx 0.6$  and canopy height  $< 0.4$  m) grew in a pattern of hummocks and hollows. These micro-hills and valleys were shaped with fibrous, permeable *Sphagnum* moss which formed a nearly continuous carpet over the surface. As a first approximation, the canopy boundary-layer resistance,  $\mathbf{r}_b$ , was expressed as (e.g., Wesely and Hicks, 1977):

$$\mathbf{r}_b \approx (2/ku_*)(D_h/D_v)^{2/3} \quad (8)$$

where  $k$  is von Karman's constant,  $D_h$  is the thermal diffusivity, and  $D_v$  is the molecular diffusivity of water vapor.

Massman (1992) considered  $r_s$  and  $\beta_s$  in Equation (4) as model parameters, whereas Massman and Ham (1994) considered  $h$  and  $\beta_s$  in Equation (6). They assumed these parameters to be constant throughout a given day. Then, using the measured surface energy balance data, they solved Equation (4) for  $r_s$  and  $\beta_s$  (and Equation (6) for  $h$  and  $\beta_s$ ) by a non-linear least squares regression technique. The assumption that  $r_s$  (or  $h$ ) and  $\beta_s$  do not vary much throughout a given day, however, may not be valid for *Sphagnum* fens unless the surface is fully waterlogged or the sky condition is overcast. Due to a lack of water-conducting tissues and a limited capillarity of large pores in the upper layer of *Sphagnum*, rapid drying of surface moss occurs as the atmospheric evaporative demand increases later in the day. We, therefore, grouped the observed energy balance data on a given day into morning and afternoon periods and solved Equation (4) (and Equation (6)) for each period. Once  $r_s$  (or  $h$ ) and  $\beta_s$  are determined, we calculated  $\lambda\mathbf{E}_s$  and  $\mathbf{H}_s$  using Equation (3a) and (3b), and then  $\lambda\mathbf{E}_v$  and  $\mathbf{H}_v$  using Equations (2a) and (2b). Once  $h$  and  $\lambda\mathbf{E}_s$  are determined from Equation (6),  $r_s$  was calculated from Equation (5) for comparison. It is worthwhile to note that the dual-source approach is based on the  $K$ -theory and the associated simplifying assumptions related to within-canopy transfer. For the open fen site studied here, however, the errors should be small.

Table I

Monthly averages of air temperature ( $^{\circ}\text{C}$ ) for 1991, 1992 and for the long-term period (1961–1992). Precipitation (mm) is also given in parenthesis

Month	May	June	July	Aug.	Sep.	Oct.
1991	15.1 (76.2)	18.4 (104.9)	19.2 (74.7)	19.9 (65.3)	11.4 (85.6)	3.5 (45.0)
1992	13.0 (85.3)	14.3 (199.6)	15.1 (114.3)	15.5 (143.0)	11.3 (93.7)	4.5 (5.8)
1961–	11.3	15.9	18.8	17.3	11.8	5.7
1992	(84.3)	(107.4)	(110.0)	(98.6)	(87.6)	(64.5)

#### 4. Results and Discussion

##### 4.1. ENVIRONMENTAL VARIABLES

##### 4.1.1. *Temperature, Precipitation and Estimated Water Budget*

As compared to the long-term averages (Table I), the mean air temperature in 1991 was higher (by  $\sim 2^{\circ}\text{C}$ ) during the summer but lower (by  $\sim 1^{\circ}\text{C}$ ) in autumn. In 1992, however, the summer was cooler (by  $\sim 2^{\circ}\text{C}$ ) and the autumn was near normal. Precipitation during the summer (June, July, August) of 1991 (245 mm) was below normal (76% of the long-term mean value) and the water table was always at or below the hollow peat surface (typically within 80–230 mm below the surface). In contrast, summer rainfall in 1992 (457 mm) exceeded the long-term mean by 42%, resulting in an elevated water table and hollow bottoms that were usually waterlogged (Figure 2).

A complete water budget at the study site (Bog Lake Peatland) is not feasible because the runoff from the watershed and seepage out of the peatland edges were not directly measured. However, measurements of runoff and mineral soil available-water at watershed S-2 (actually a small sub-basin of the Bog Lake watershed to the northeast of the study site) allow reasonable water budget estimates for the Bog Lake Peatland study site proper in 1991 and the total Bog Lake Peatland watershed in 1992, as discussed below.

In 1990 the basin received the second lowest precipitation in a 35-year record at the Marcell Experimental Forest. Annual precipitation in 1990 was 580 mm compared with an average of 770 mm (summer rainfall was only 199 mm). An average snowpack over the 1990–91 winter season (190 mm) was used to satisfy a deficit in available upland soil moisture of 170 mm, and contributed only a minor amount of runoff (E. S. Verry, personal communication). Thus, the 1991 water budget can be reasonably estimated (Precipitation – Seepage – ET = Storage Change) on the basis of the Bog Lake Peatland study area only, with virtually no contribution from the surrounding uplands. Storage changes within the peatland



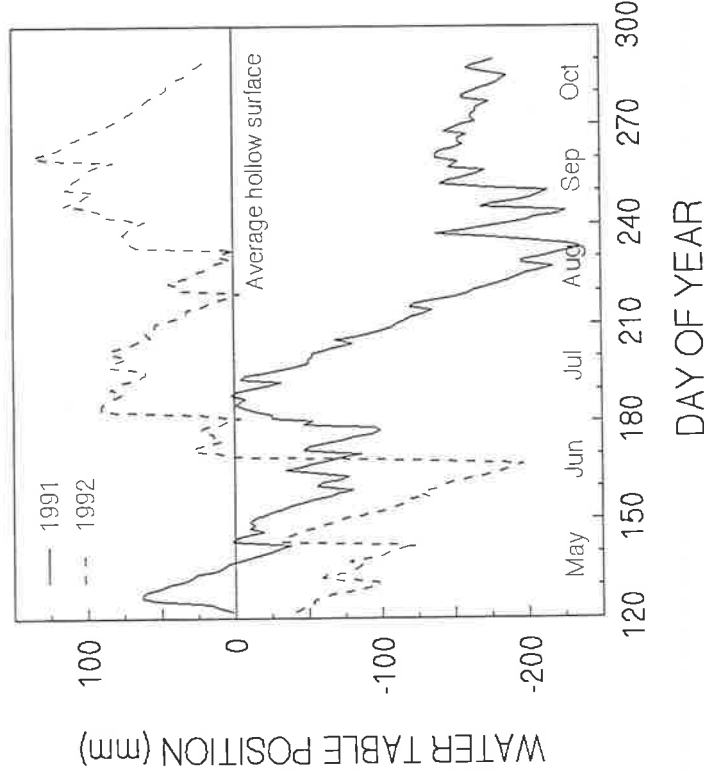


Figure 2. Seasonal distributions of water table position (referenced to the bottom of hollows).

were estimated by the difference in water table elevations (during that measurement period) times a specific yield of 0.33 (Verry and Timmons, 1982). In 1991, the ET (381 mm) during the period from days 120 to 290 was almost the same as the rainfall (385 mm), while the decline in water level was 189 mm. A simple water budget for the study site suggests a seepage rate of 66 mm for the measurement period.

In 1992, the annual precipitation was 830 mm or 60 mm above the average. With the exception of 3 weeks in this year, the upland areas contributed subsurface flow to down-slope peatlands (based on actual runoff measurements from watershed S-2). In 1992, therefore, consideration needs to be given to the subsurface flow water entering the Bog Lake Peatland study area from the mineral soil uplands. From days 171 to 286, the ET and rainfall were 274 mm and 405 mm, respectively. The water table rose by 10 mm. The precipitation, storage change and ET data would suggest a seepage rate of 128 mm for the 116 day measurement period. This amount of seepage resulted due to the subsurface flow water entering the Bog Lake Peatland study site from most of the mineral soils uplands, and percolation from the peatland into the sandy soils surrounding the lower portion of the site. Therefore, the seepage amount in 1992 should be expressed on the area of the total watershed. Considering that the upland to peatland study site area ratio is about

1.7:1, the seepage rate for the measurement period calculated on a per unit of the total watershed area basis would be about 47 mm. Annual seepage rates, per unit of area with actual seepage (as explained above), in 1991 and 1992 are estimated to be 141 mm and 148 mm, respectively.

#### 4.1.2. *Solar and Net Radiation*

The midday values of incident solar radiation ( $\mathbf{R}_s$ ) peaked near 960 W m<sup>-2</sup> during the summer months, and averaged 670 W m<sup>-2</sup> in 1991. In the summer of 1992  $\mathbf{R}_s$  averaged about 560 W m<sup>-2</sup> due to more frequent cloudiness. In autumn, midday  $\mathbf{R}_s$  averaged about 460 W m<sup>-2</sup> in both years. During the measurement periods in 1991 and 1992, the following relationships were found between  $\mathbf{R}_n$  and  $\mathbf{R}_s$ :

$$\mathbf{R}_n = (0.71 \pm 0.01)\mathbf{R}_s - (19 \pm 3), \quad r^2 = 0.99 \quad (1991) \quad (9)$$

$$\mathbf{R}_n = (0.73 \pm 0.01)\mathbf{R}_s - (20 \pm 3), \quad r^2 = 0.99 \quad (1992). \quad (10)$$

The albedo ( $\alpha$ ), the fraction of shortwave radiation which is reflected by the surface, varied from 0.11 to 0.17 with a seasonal midday average of 0.14 in 1991 and 0.13 in 1992 (Figure 3). In general, when the surface was wetter due to a higher water table (e.g., May–June in 1991 and July–August in 1992),  $\alpha$  was low (0.11–0.14) because wet surfaces generally exhibit a lower reflection than dry surfaces (e.g., Jacobs and Van Pul, 1990). During August–October in 1991 and June in 1992,  $\alpha$  was higher (0.13–0.17) because of alteration in the color of the surface mosses as they dried out. These midday  $\alpha$  values agree well with those for *Sphagnum*-sedge bogs (0.12–0.16; Berglund and Mace, 1972) and lie in between those for coniferous forest (0.05–0.15) and those for field crops (0.18–0.26) (e.g., McNaughton and Jarvis, 1983). In the wavelength band of  $\mathbf{Q}_p$  (0.4–0.7  $\mu\text{m}$ ), the measured  $\alpha$  showed a monotonic decrease from about 0.07 in May to 0.05 in June and then remained relatively constant (0.04–0.05) until October.

The loss of net longwave radiation ( $\mathbf{L}_n = (1 - \alpha)\mathbf{R}_s - \mathbf{R}_n$ ) was related to  $\mathbf{R}_s$  with the following linear functions.

$$\mathbf{L}_n = (0.15 \pm 0.01)\mathbf{R}_s + (18 \pm 3), \quad r^2 = 0.83 \quad (1991) \quad (11)$$

$$\mathbf{L}_n = (0.13 \pm 0.01)\mathbf{R}_s + (20 \pm 3), \quad r^2 = 0.80 \quad (1992). \quad (12)$$

The slight decrease in  $\mathbf{L}_n$  in 1992 was associated with more frequent occurrence of high clouds and reduced surface temperature.

## 4.2. EVAPOTRANSPIRATION

### 4.2.1. *Daily Rates*

In both 1991 and 1992 daily ET gradually declined through the season and had high variability (Figure 4). During the period mid May–mid October in both years,

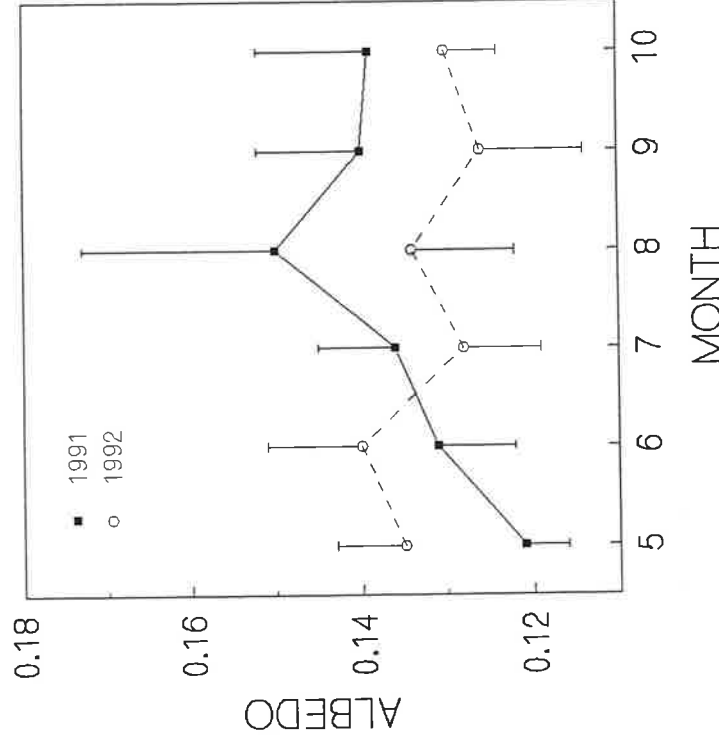


Figure 3. Seasonal trends in monthly means of albedo.

the daily ET ranged from 0.2–4.8 mm d<sup>-1</sup> with a growing season average of about 3.0 mm d<sup>-1</sup>. Boelter and Verry (1977) reported ET rates of about 3.3 mm d<sup>-1</sup> for summer periods for wetlands in the northern Lake States. Our values are also similar to the average summertime ET reported for wetlands in other areas such as a sedge dominated *Sphagnum* bog in Wyoming (3.4 mm d<sup>-1</sup>; Sturges, 1968), a British *Sphagnum* bog (3.3 mm d<sup>-1</sup>; Chapman, 1965), Canadian *Sphagnum* fens (1–4 mm d<sup>-1</sup>; Lafleur and Roulet, 1992, and 2.8 mm d<sup>-1</sup>; Moore *et al.*, 1994), a Dutch quaking fen (2.5 mm d<sup>-1</sup>; Koerselman and Beltman, 1988) and Russian bogs (3.0 mm d<sup>-1</sup>; Bavina, 1967, quoted in Ingram, 1983).

In Figure 5, the measured ET rates are compared with the potential ET of an open water surface as given by Penman (1948).

$$ET_{\text{potential}} = [s(\mathbf{R}_n - \mathbf{G} - \mathbf{W}) + \gamma \mathbf{E}_a] / \lambda(s + \gamma) \quad (13)$$

where  $s$  is the slope of the saturated vapour pressure-temperature curve;  $\gamma$  is the psychrometric constant;  $\mathbf{E}_a = 2.7(1 + u/100)D_a$ ;  $u$  is the wind run (in kilometers per day); and  $D_a$  is equal to the daily averaged vapour pressure deficit (in kPa) measured above the canopy. On average, the fen ET was at or near potential rates (within  $\pm 15\%$ ) through the season. The measured ET was 5–65% lower than the potential rates when the vascular plants became senescent and the water table level

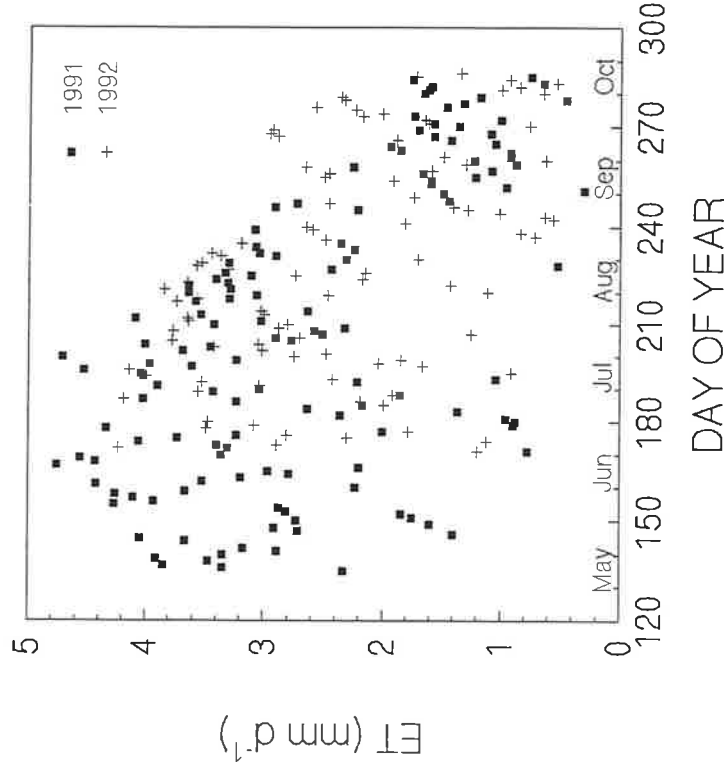


Figure 4. Seasonal distributions of measured ET.

was low (below the bottom of hollows). When the water table was high (above the hollow bottom), however, ET was near the potential rate even during the senescence stage.

As indicated above, the water table position affects the total amount of water evaporated from the *Sphagnum* surface. Figure 6 shows measured  $ET/ET_{\text{potential}}$  in relation to the water table position (which becomes negative when the water table is below the hollow bottom). The ratio of measured ET to  $ET_{\text{potential}}$  ranged from 0.35 to 1.28 and tended to increase with rising water table (from  $-250$  mm to  $140$  mm). Excluding the data during senescence, regression analysis yielded  $r^2 = 0.42$  (significant at  $p = 0.05$ ). Values of  $ET/ET_{\text{potential}} > 1$  may result from advective enhancement of evaporation and possibly due to the surface geometry of *Sphagnum*. Nichols and Brown (1980) argue that *Sphagnum* presents an effective evaporating surface area much greater than the unit ground area of a wetland. Using peat cores collected from a *Sphagnum* bog in northern Minnesota, they found that evaporation from the moss surface was greater than that from a free-water surface. For an open *Sphagnum* bog with vascular plant cover, Boelter and Verry (1977) reported the highest ET at a water table position  $0.1$  m below the surface because the evaporative surface of *Sphagnum* moss is greatest at that level and roots of vascular plants are well aerated. The maximum ET rate in our study

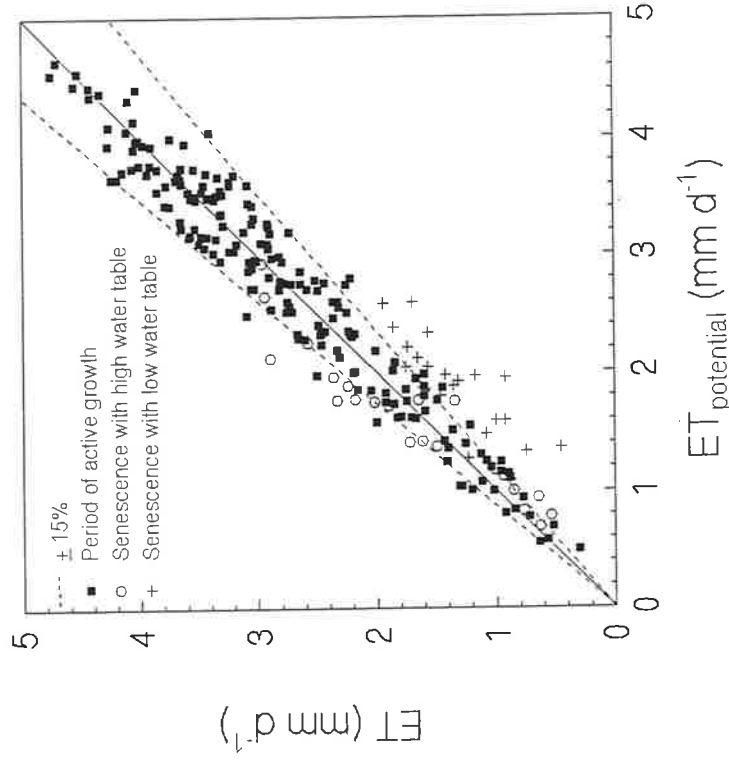


Figure 5. The relationship between the measured daily ET and the potential ET.

was not observed at a water table position of  $-0.1$  m. It appears that the effective evaporative surface area of *Sphagnum* would be somewhat site-specific and would depend on the microtopographic distribution of hummocks and hollows and their position relative to the water table.

*Sphagnum* lacks cuticles and leaf stomata. The tissue water content depends primarily on the quantity of water available for capillary uptake, precipitation, and the ambient conditions. Due to a lack of water-conducting tissues and large pore sizes in the upper layer of *Sphagnum* (Romanov, 1968), capillary rise is insufficient to supply water to the surface when evaporative demand is high. A review by Ingram (1983) indicates that even a few centimeters drop in the water table from the *Sphagnum* surface substantially decreases evaporation. In fact, Lafleur and Roulet (1992) suggest that the rate of capillary draw by *Sphagnum* over a distance of 3 cm is insufficient to keep up with the evaporative demand. Thus, we can expect some physical resistance to water vapour transfer exerted by the drying *Sphagnum* surface. A declining water table does not necessarily cause a noticeable decrease in total ET when transpiring vascular vegetation coexists. Verry (1988) stated that a drop in the water table of 0.2–0.3 m below the hollow bottom has little effect on total ET. Through their extended root systems, vascular plants are directly linked to the water below and can contribute to the total ET through transpiration (Ingram,

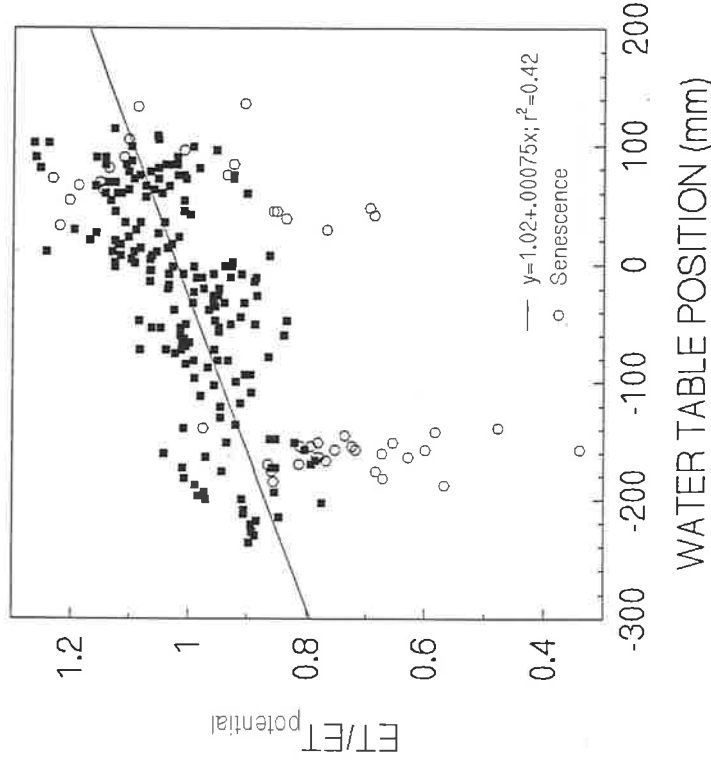


Figure 6. The measured daily ET as a fraction of potential ET in relation to water table position.

1983). Romanov (1968) suggests that ET rates decline significantly only when the water table drops far enough so that the root zone loses contact with the capillary fringe. During our study, the water table position always fluctuated within the rooting zone (0–0.4 m) of vascular plants and ET rates were indeed near potential rates ( $\pm 15\%$ ) except when the vascular plants were senescing (Figure 5).

We conclude this section by examining the “coupling concept” of McNaughton and Jarvis (1983, 1986). They expressed the ET of a well watered vegetated surface in the form:

$$ET = \Omega(ET_{eq}) + (1 - \Omega)(ET_{imp}) \quad (14)$$

where  $\Omega$  ( $= (s/\gamma + 1)/(s/\gamma + 1 + \mathbf{R}_S/r_a)$ ) is a “decoupling factor” and  $\mathbf{R}_S$  is the bulk or “big-leaf” surface resistance for the transfer of water vapor. The term,  $ET_{eq}$  ( $= s(\mathbf{R}_n - \mathbf{G} - \mathbf{W})/[\lambda(s + \gamma)]$ ), is the equilibrium ET which would be achieved if the surface were decoupled from the regional conditions above. The term,  $ET_{imp}$  ( $= \rho_a c_p D/\gamma \mathbf{R}_S$ , where  $D$  is the vapour pressure deficit at a reference height) is the imposed ET which would occur if regional vapour pressure deficit were imposed on the vegetation by efficient turbulent transport. When the water table was within or above the rooting zone, the fen ET generally exceeded  $ET_{eq}$ , with the daily value of the Priestley–Taylor coefficient ( $=$  measured  $ET/ET_{eq}$ ; Priestley and Taylor, 1972)

ranging from 0.93 to 1.53. The value of  $\Omega$  ranged from 0.55 to 0.89, indicating that the fen ET is weakly coupled to the atmospheric driving potential (i.e.,  $D$ ) and biological control (i.e.,  $\mathbf{R}_S$ ).

As the *Sphagnum* surface dries out, however, the effect of increasing  $\mathbf{R}_S$  is no longer negligible. Lafleur (1990) reported that physiological response (e.g., stomatal closure) in vascular plants can also reduce ET when  $D$  becomes large. Unfortunately, the term  $\mathbf{R}_S$  in this single-source model includes both the physical resistance exerted by a drying *Sphagnum* surface and the physiological resistance of the stomata of vascular plants. Later, we come back to this single-source model and discuss its usefulness for comparative purposes. To further examine the influence of vascular and non-vascular vegetation on ET, we now partition the measured ET into evaporation from the *Sphagnum* moss and transpiration from the vascular plants.

#### 4.2.2. Partitioning ET into Evaporation and Transpiration

In order to partition the measured above-canopy ET into *Sphagnum* evaporation and vascular plant transpiration, the two unknowns in the dual-source model (i.e.,  $r_s$  and  $\beta_s$  in Equation (4);  $h$  and  $\beta_s$  in Equation (6)) must be estimated. From the measured surface energy balance and other micrometeorological data, we solved Equation (4) for  $r_s$  and  $\beta_s$  and Equation (6) for  $h$  and  $\beta_s$  by a nonlinear least squares regression technique. As mentioned earlier, using the estimated  $h$  from Equation (6),  $r_s$  was calculated from Equation (5) for comparison. The optimum values for  $r_s$  and  $\beta_s$  from the two methods are given in Table II for 8 days in 1991 and 8 days in 1992 with corresponding  $R^2$  values. (Values corresponding to the two-parameter fit of Equation (4) are given in parentheses.) Data taken between 0700 and 1200 hours and between 1200 and 1800 hours were used for the morning and afternoon periods, respectively. Nighttime data were not used due to the small magnitudes of energy fluxes. As Massman and Ham (1994) have suggested, Equation (6) is linear with regression coefficients,  $(1 - h)$  and  $1/\beta_s$ . Hence, the associated regression calculations were simpler (as compared to Equation (4)), resulting in significantly higher  $R^2$  values. Furthermore, it gave estimates of surface humidity ( $h$ ) that are not only reasonable but also qualitatively and quantitatively consistent with our observations. With Equation (4), we found that non-linear regression converged but produced  $R^2$  of zero for a few mornings and many afternoons. Except for those periods, Equation (4) explained on the average  $\sim 70\%$  of the variance. Overall, Equation (4) provided estimates of  $\beta_s$  and  $r_s$  similar to those given by Equation (6) (see the mean values in Table II).

It is worth noting that even in a wetland the *Sphagnum* surface resistance,  $r_s$ , is not only non-zero but also sizable, ranging from 66–424 s m<sup>-1</sup>. These values are, in general, within the range reported for bare or vegetation-covered soil under dry to wet conditions (e.g., Camillo and Gurney, 1986; Philip, 1987; Raupach and Finnigan, 1988; Massman, 1992; Kelliher *et al.*, 1995). Except for mostly cloudy or overcast days,  $r_s$  values in the afternoon were significantly larger than in the

Table II

Values of the fitting parameters  $r_s$  and  $\beta_s$ , the goodness of fit,  $R^2$ , achieved with Equation (6) and with Equation (4) in parenthesis), and the water table position on selected days (a) in 1991 and (b) in 1992. ( $R^2$  is defined as  $1.0 - \text{rssq/cssq}$ , where rssq is the residual sum of squares and cssq is the sum of squares of the data set about its mean.)

(a)	A.M.			P.M.		
	$r_s$ ( $\text{s m}^{-1}$ )	$\beta_s$	$R^2$	$r_s$ ( $\text{s m}^{-1}$ )	$\beta_s$	$R^2$
1991						
6/27 (partly cloudy to clear)	139 (181)	0.29 0.58	0.99 0.88)	334 (416)	1.09 1.80	0.80 0.37)
7/02 (overcast)	186 (161)	0.47 0.36	0.90 0.51)		no data no data	-13 -10
7/09 (mostly cloudy with breaks)	221 (152)	1.01 0.34	0.58 0)	184 (170)	0.45 0.40	0.71 0)
7610 (partly cloudy)	112 ( $>10^6$ )	0.31 0.00	0.57 0)	241 ( $>10^6$ )	0.60 0.00	0.76 0)
7/19 (partly cloudy to clear)	157 (155)	0.20 0.55	0.85 0.13)	240 ( $>10^{15}$ )	0.59 $>10^{13}$	0.60 0)
7/23 (clear to partly cloudy)	133 (139)	0.50 0.67	0.91 0.59)	424 (349)	3.14 2.96	0.78 0)
8/18 (mostly cloudy)	142 (136)	0.26 0.34	0.81 0.56)	151 ( $>10^{14}$ )	0.37 $>10^{13}$	0.68 0)
8/19 (partly cloudy)	135 (159)	0.35 0.23	0.90 0.94)	216 (193)	0.70 0.24	0.91 0)
Mean	$r_s = 153 \pm 34$ (= 155 $\pm$ 15)			$r_s = 256 \pm 94$ (= 282 $\pm$ 120)		
	$\beta_s = 0.42 \pm 0.25$ (= 0.44 $\pm$ 0.16)			$\beta_s = 1.00 \pm 0.97$ (= 1.35 $\pm$ 1.28)		

morning. This is consistent with our visual observation of a drying *Sphagnum* surface due to the strong evaporative conditions in the afternoon. Typically, the *Sphagnum* surface became wet overnight and the  $r_s$  values were smaller in the morning. Titus and Wagner (1984) also observed marked decline in moss water content measured during daytime and full or partial restoration of water content overnight. On average, as compared to 1992,  $r_s$  in 1991 was generally larger because of a low water table.

Similarly, in 1991 when the water table was below the peat surface,  $\beta_s$  in the afternoon period (0.24–3.14) was significantly greater than in the morning (0.29–1.01). In 1992, the water table remained above the peat surface most of the time and the difference in average  $\beta_s$  values (morning and afternoon) was smaller. On mostly cloudy or overcast days, the morning and afternoon values of  $r_s$  and  $\beta_s$



Table II  
Continued

(b) 1992	A.M.		P.M.		Water table (mm)
	$r_s$ ( $\text{s m}^{-1}$ )	$\beta_s$	$r_s$ ( $\text{s m}^{-1}$ )	$\beta_s$ ( $\text{s m}^{-1}$ )	
		$R^2$		$R^2$	
7/09 (partly cloudy to overcast)	150 (153)	0.39 0.39	0.90 0.74)	173 (164)	0.22 0.31
7/10 (partly cloudy)	80 (66)	0.35 0.18	0.96 0.91)	201 (155)	1.11 0.77
8/03 (mostly cloudy)	83 (83)	0.31 0.37	0.83 0.95)	123 (108)	0.30 0.40
8/10 (partly cloudy to clear)	107 (77)	0.30 0.23	1.00 0.96)	246 (267)	1.17 1.56
8/11 (overcast)	114 (111)	0.25 0.28	0.79 0.92)	no data no data	no data no data
8/18 (clear to partly cloudy)	127 (131)	0.28 0.27	0.89 0.89)	303 (228)	0.63 1.08
8/19 (clear to partly cloudy)	157 (156)	0.30 0.33	0.81 0)	213 (230)	0.42 0.77
8/31 (overcast)	no data no data			175 (238)	0.36 0.40
					0.77 0.68)
	$r_s = 117 \pm 30$ ( $= 111 \pm 37$ )			$r_s = 204 \pm 58$ ( $= 198 \pm 57$ )	
	$\beta_s = 0.31 \pm 0.05$ ( $= 0.29 \pm 0.08$ )			$\beta_s = 0.60 \pm 0.39$ ( $= 0.76 \pm 0.44$ )	

showed no significant differences. Although the focus of this analysis is on  $r_s$  and  $\beta_s$ , it is appropriate to briefly discuss the surface humidity,  $h$ , in Equation 14. The modeled estimates of  $h$  ranged from 0.51 to 0.80 in the morning. In the afternoon the model typically showed a 10–25% decrease in  $h$ , except under overcast or mostly cloudy conditions. These values are well within the range of near-surface humidity concurrently measured with a portable soil  $\text{CO}_2$  chamber at the site (Kim and Verma, 1992).

Using Equations (1–3), the mean values of the sub-canopy energy balance components (i.e.,  $R_{n(s)}$ ,  $R_{n(v)}$ ,  $H_s$ ,  $H_v$ ,  $\lambda E_s$  and  $\lambda E_v$ ) and the Bowen ratios ( $\beta_s$ ,  $\beta_v$ ) were calculated for the vascular plants and the *Sphagnum* surface on a fairly clear day (June 27, 1991) (Table III). The value of  $R_{n(v)}/R_n$  was 0.29 implying that only about 30% of  $R_n$  was intercepted by the vascular plant canopy owing to the small leaf area. On average,  $R_{n(s)}$  was about  $320 \text{ W m}^{-2}$ . The *Sphagnum* surface was wet in the morning and about 50% of  $R_{n(s)}$  was used for evaporation. In the morning the *Sphagnum* evaporation ( $\lambda E_s$ ) amounted to about

Table III

Mean values of measured components of above-canopy energy balance ( $R_n$ ,  $H$  and  $\lambda E$ ) and modelled components of sub-canopy energy balance ( $R_{n(s)}$ ,  $R_{n(v)}$ ,  $H_s$ ,  $H_v$ ,  $\lambda E_s$  and  $\lambda E_v$ ) and the Bowen ratios ( $\beta$ ,  $\beta_s$ ,  $\beta_v$ ) on June 27, 1991

June 27, 1991	$R_n$	$H$	$\lambda E$	$\beta$
	----- $W m^{-2}$ -----			
Whole canopy (measured)	A.M.	449	103	230
	P.M.	447	89	251
				0.36
<i>Sphagnum</i> surface (modeled)	A.M.	318	45	156
	P.M.	319	111	102
				0.29
				1.09
Vascular plants (modeled)	A.M.	131	58	73
	P.M.	128	-22	149
				-0.15

68% of the total  $\lambda E$  measured above the canopy and the vascular transpiration ( $\lambda E_v$ ) contributed the remaining 32%. Although values of  $\beta$  for the whole canopy remained at about 0.4 through the day, the partitioning of flux in the sub-canopy in the afternoon was markedly different from that in the morning. More energy was partitioned into  $H_s$  in the afternoon as the *Sphagnum* surface dried out. As indicated in Table III,  $H_v$  was positive in the morning but negative in the afternoon. (The sign convention employed here is such that the flux directed away from the surface is positive.) The vascular plant canopy absorbed *Sphagnum*-generated sensible heat which accounted for approximately 15% of  $\lambda E_v$  in the afternoon. On some occasions (e.g., July 23, 1991), this additional energy source amounted to one third of the transpiration energy flux. On average, the *Sphagnum* evaporation decreased from about  $0.7\lambda E$  in the morning to about  $0.4\lambda E$  in the afternoon, while the vascular transpiration increased from about  $0.3\lambda E$  in the morning to  $0.6\lambda E$  in the afternoon. Overall, on clear to partly cloudy days during the active growth stage of the vascular plants, enhanced transpiration (due to additional sources of energy generated from the *Sphagnum*) counterbalanced the suppressed evaporation (due to limited water supply to the *Sphagnum* surface), resulting in near potential rates of open water evaporation.

#### 4.3. CANOPY STOMATAL AND AERODYNAMIC RESISTANCES

The dual-source approach used here requires no *a priori* estimate of canopy stomatal resistance,  $r_v$ . However, once the heat and water vapour fluxes of the *Sphagnum*

and vascular plant components have been estimated,  $r_v$  can be computed. Before we consider  $r_u$ , it is worth discussing the subcanopy aerodynamic resistance,  $r_u$ , calculated from the model. Our results indicated that  $r_u$  typically ranged from 3 to 50 s m<sup>-1</sup> during daylight hours. Also,  $r_u$  was not particularly sensitive to the mean wind speed except near sunrise or sunset periods. These results are consistent with those of Ham and Heilman (1991) and Massman (1992). It should be noted that the external capillary movement of water along *Sphagnum* surfaces may be somewhat dependent on the laminar boundary-layer resistance and may not be negligible. The current dual-source model does not include a laminar boundary layer at the *Sphagnum* surface and, therefore, may underestimate  $r_u$ .

For all days used in Table II,  $r_v$  values were of the order of 150 to 250 (±100) s m<sup>-1</sup>. The reasonableness of the magnitudes of  $r_v$  can be inferred from a comparison with the leaf stomatal data. For example, our porometer measurements of *Scheuchzeria palustris* (the most dominant vascular species) yielded resistance values ranging from 49 s m<sup>-1</sup> to 394 s m<sup>-1</sup>, with a midday mean of 110 s m<sup>-1</sup>. Scaling from the leaf stomatal data to the canopy level may be accomplished roughly by dividing the stomatal resistance by the leaf area index. The average leaf area index of 0.6 (measured during June–August) would then produce midday  $r_v$  of about 180 s m<sup>-1</sup>, an estimate in general agreement with the model result given above.

In a single-source approach, the stomatal control of E:T is inferred by rearranging Equation (14) as:

$$r_S = [(s/\gamma)\beta - 1]r_a + \rho_a c_p D / (r \lambda E). \quad (15)$$

Obviously, the “big-leaf” surface resistance  $r_S$  in Equation (15) is different from  $r_v$ . The latter is the bulk equivalent of the plant stomatal resistance and does not include contributions from *Sphagnum* evaporation. Analytical expression relating  $r_S$  and  $r_v$  is a function of  $r_i/r_a$  and  $r_v/r_a$  (e.g., Finnigan and Raupach, 1988; Kelliher *et al.*, 1995), where  $r_i = \rho_a \lambda D / (R_n - G - W)$  is the isothermal resistance (Monteith and Unsworth, 1990). It suggests that the ratio of  $r_S$  and  $r_v$  approaches unity when leaf area index,  $L$ , becomes infinite because the canopy transmission and the soil evaporation both tend to zero. At smaller  $L$ ,  $r_v$  exceeds  $r_S$  because of the effect of *Sphagnum* evaporation. Equation (15) has been used widely for diagnostic purposes and has provided useful information for efforts such as large-scale climate modelling. Equation (15) has also been applied to various wetlands (e.g., a blanket bog – Price, 1991; subarctic marsh – Lafleur and Rouse, 1988; a *Sphagnum* fen – Lafleur and Roulet, 1992) even though evaporation from the surface of these wetlands would be significant. As discussed above, the process of water vapour transfer among *Sphagnum* stems and leaves is not the same as the transpiration through stomata of vascular plants. However, lumping these two processes using Eq. 15 allows intercomparison with other studies, as has been pointed out by Price (1991). With this in mind, we calculated  $r_S$  and  $r_a$  on all the days used in Table II. Their average diurnal variations are shown in Figure 7. The averaged values of  $r_S$  ranged from 80 to 250 s m<sup>-1</sup> with a midday average of 100 s m<sup>-1</sup>. The minimum

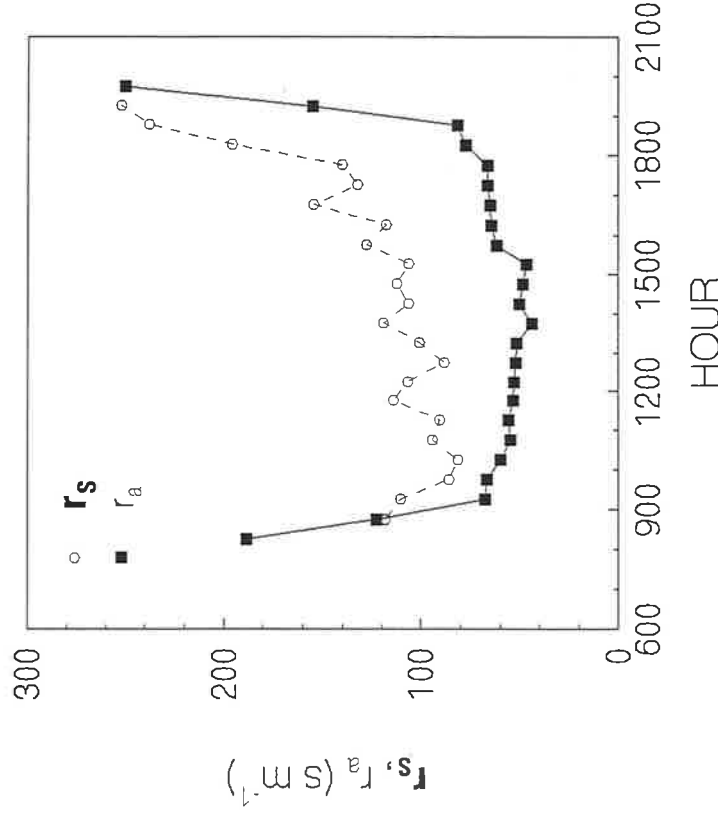


Figure 7. Diurnal variations in the bulk or "big-leaf" surface resistance ( $r_s$ ) and aerodynamic resistance ( $r_a$ ) averaged for the days presented in Table II.

$r_s$  occurred during the period between mid morning and noon hours and the value gradually increased later in the day. The diurnal pattern of  $r_a$  followed that of the inverse of the mean horizontal wind speed. During the day,  $r_a$  averaged about  $50\ s\ m^{-1}$ . Values of  $r_a$  observed in this study are within the range of those for agricultural crops or grassland ( $15\text{--}150\ s\ m^{-1}$ ); whereas  $r_s$  values are somewhat greater than those for well-watered agricultural crops or grassland ( $20\text{--}100\ s\ m^{-1}$ ) and within the range of those for forests ( $50\text{--}200\ s\ m^{-1}$ ) (e.g., Jones, 1983; Kim and Verma, 1990; Kelliher *et al.*, 1993 and 1995).

## 5. Conclusions

The fen ET rate was near the potential rate of open water evaporation when vascular plants were actively growing and the water table was within or above the rooting zone. As the *Sphagnum* surface dried out, sensible heat generated at the *Sphagnum* surface became an additional energy source for transpiration of vascular plants which counterbalanced the reduced surface evaporation. This study demonstrates the usefulness of a dual-source approach of the Penman-Monteith model as a diagnostic tool to examine the partitioning of wetland ET into vascular and non-

vascular components. The results presented here should encourage future efforts to describe quantitatively the interaction of *Sphagnum* surface, vascular plants and the relative position of the water table on the control of the wetland surface energy balance. The model produced reasonable estimates of *Sphagnum* and vascular canopy resistances, subcanopy aerodynamic resistance and surface humidity that are in general agreement with other observations. Our results showed that surface resistance to water vapour exerted by the *Sphagnum* moss was not necessarily zero in spite of the high water table. We suggest that the variation of water table position and the phenology and functional rooting depth of major vascular species should be considered in modelling of wetland ET.

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