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EVAPORATION FROM A SPHAGNUM MOSS SURFACE*[1]

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ABSTRACT

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Peat cores, 45 cm in diameter, were collected from a sphagnum bog in northern Minnesota, and used to measure the effects of different temperatures and water levels on evaporation from a sphagnum moss surface in a growth chamber. Under all conditions, evaporation from the moss surface was greater than that from a free-water surface. Evaporation from the moss increased 92% as the temperature was raised from 9° to 25°C. The energy used in evaporation from the moss exceeded net radiation except at 9°C. Evaporation from the moss was less when the water level was at the surface of the peat than when it was lowered to 5, 10, or 15 cm below the surface. The presence of an overstory of grasses and sedges protected the moss from desiccation when the water level was 15 cm below the surface, but had no effect on total water vaporization at any water level. When the peat cores were maintained in the greenhouse for a year, changes in either the peat, the moss, or both occurred which resulted in significantly lower evaporation when measured in the growth chamber.

INTRODUCTION

Peatlands cover large areas of northern Europe, Asia, and North America. The northern Lake States of the U.S.A. (Minnesota, Wisconsin, and Michigan) contain more than $6 \cdot 10^4$ km^2 ($15 \cdot 10^6$ acres) of peatlands (Davis and Lucas, 1959). Undisturbed peatlands are typically well vegetated and have high water tables so that actual evapotranspiration from them is nearly equal to potential evapotranspiration calculated from climatic data (Eggelsmann, 1963; Bay, 1966, 1968). Evapotranspiration generally represents the major hydrologic loss from peatlands. Potential annual evapotranspiration in the

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northern Lake States ranges from 432 to 584 mm (17 to 23 in.) compared to an annual average precipitation of 508 mm (20 in.) in northwestern Minnesota to 860 mm (34 in.) in parts of Michigan's upper peninsula. In northern Minnesota, potential evapotranspiration typically exceeds precipitation from June through September. Stream flows from peatlands which lack groundwater input are usually very low during the summer months (Boelter and Verry, 1977).

There is increasing interest in the use of peatlands for sewage effluent disposal, in harvesting peat for industrial–chemical uses and for fuel, and in clearing and draining peatlands for agricultural purposes (Tilton et al., 1976; Pippo, 1977; Farnham, 1978; Fuchsman, 1978). These activities can affect and be affected by the peatland water balance.

Sphagnum mosses are the major ground cover in many northern peatlands, but little is known about evaporation from them. Bay (1966), Williams (1968) and Boelter (1972) have measured water losses from small tanks of sphagnum and other bog vegetation under field conditions. Sphagnum, like all mosses, lacks specialized water absorption and internal water conduction systems. Water is transported and conducted by an external wicking system and adsorption along the stem and leaf surfaces (Bold, 1957). Due to its surface geometry sphagnum may present an effective evaporating surface area much greater than the plane surface area of a peatland. The present study was designed to: (1) compare evaporation rates from a sphagnum moss surface under different, controlled temperatures; and (2) determine the effect of a slight lowering of the water table upon evaporation from a moss surface and evapotranspiration from a surface of moss plus grasses and sedges. All values were compared to evaporation from an open water surface, and an energy budget was estimated for all conditions.

METHODS

Large-diameter peat cores were extracted from a sphagnum bog on the Marcell Experimental Forest near Grand Rapids, Minn. (47°32′N, 93°28′W). The cores were carefully trimmed to avoid damaging the surface vegetation and root structure and were fitted snugly into plastic tubs 45 cm in diameter and 23 cm deep. The cores were brought to the laboratory and maintained in a greenhouse or outside under shade. Vegetation on the peat cores consisted of a continuous mat of mosses, predominantly sphagnum (*Sphagnum recurvum* Beau.) with minor amounts of juniper hair-cap (*Polytrichum juniperinum* Hedw.), with an overstory of sedge (*Carex trisperma* Dew.) and cotton grass (*Eriophorum tenellum* Nutt.).

A tub of peat and a control tub of water were placed in the growth chamber on platforms which were supported by water-filled innertubes. The valve cores were removed from the innertubes and the valve stems connected to manometers. Evaporation was determined by adjusting an index mark to the manometer fluid meniscus at the beginning of each measurement period, then adding sufficient water to the tubs at the end of the measurement period to return the meniscus to the initial mark. The water was added to the bottom of the tubs via a 3-cm diameter well installed in the tub and was carefully measured to determine the amount lost by evaporation. With this system a water loss of less than 0.1 mm could be measured accurately and precisely. The effects of temperature and depth to the water table were examined, with five replicates of each treatment, each with a free-water surface control.

Four growth chamber air temperatures, 9.0°, 14.5°, 20.0° and 25.0°C, were tested with the water table at the surface of the peat. Due to the irregular surface of the peat, the water table was considered to be "at the surface" when ~50% of the peat surface was covered by water. A tub of peat, with the grass-sedge overstory removed and the sphagnum mat intact, and a control tub of water were placed in the growth chamber at 9°C and allowed to equilibrate for 16 hr. Evaporation was then measured for an 8-hr. period, and the water in each tub was returned to its initial level. The air temperature was then raised to 14.5°C, the tubs were allowed to equilibrate for 16 hr., and the evaporation measured for 8 hr. at this temperature. This sequence was repeated at each temperature using five different tubs of peat. Four water table depths — at the surface of the peat, and at 5, 10 and 15 cm below the surface of the peat — were tested at 20°C. After evaporation was measured for 8 hr. at one water level, the water level was lowered 5 cm and the tubs were allowed to equilibrate for 48 hr. before the next 8-hr. measurement period. In this manner, evaporation from each of the five tubs of peat was measured at the four water levels, first with the grass-sedge overstory intact and then with it removed exposing the sphagnum mat.

The light intensity in the growth chamber was 53,800 lm m^{-2} (5000 f.c.) measured at the evaporating surface. Net radiation was measured by miniature net radiometers placed over the surface of each tub; vegetation surface temperature was determined by an infra-red thermometer and continuously recorded; and water surface temperature was measured by a micro-thermocouple suspended at the water surface. Growth chamber wet and dry-bulb temperatures were also continuously recorded.

RESULTS

At all temperatures the rate of evaporation from the moss was about twice that from the water (significant at 0.05 level) (Fig. 1, Table I). There was no statistically significant difference (0.05 level) in the ratio of evaporation from the two surfaces from one temperature to another. Evaporation from the moss and water increased an average of 92 and 75%, respectively, as the temperature was increased from 9° to 25°C. Evaporation rates were quite variable from one tub of peat to the other (as indicated by the con-

TABLE I

Evaporation from water and moss surfaces* and energy relations at four temperatures

Air temperature (°C)	Surface temperature (°C)	Vapor pressure deficit (mm Hg)	Evaporation (mm hr^{-1})	Bowen ratio (E/A)	E/R_n	A/R_n	G/R_n	Ratio of moss to water evaporation
Moss:								
8.9	11.9	2.25	0.291	0.344	0.81	0.28	−0.09	1.97
14.4	14.6	5.21	0.384	0.009	1.17	0.01	−0.18	2.37
20.3	17.6	9.73	0.479	−0.194	1.31	−0.25	−0.06	1.91
25.3	20.8	14.07	0.558	−0.280	1.47	−0.41	−0.06	2.04
Water:								
8.9	13.2	2.25	0.155	0.417	0.50	0.21	0.29	
14.4	17.7	5.21	0.163	0.199	0.49	0.10	0.29	
20.3	21.2	9.73	0.250	0.041	0.68	0.03	0.29	
25.3	25.9	14.07	0.272	0.018	0.71	0.01	0.28	

* Water level at the surface of the peat.

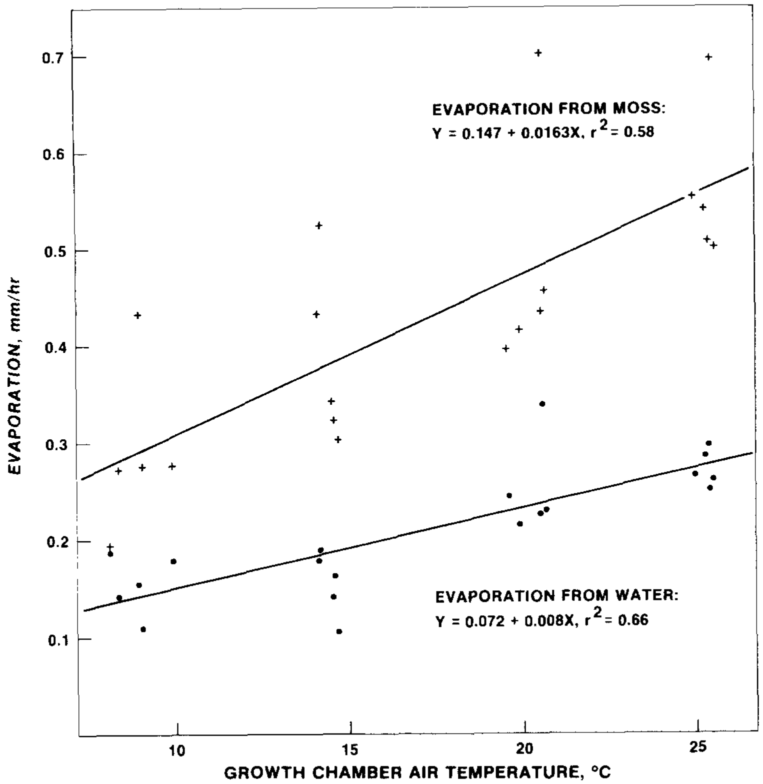

Fig. 1. Evaporation from moss and water surfaces at different temperatures.

siderable scatter in the moss evaporation data shown in Fig. 1); in fact, the differences in evaporation between the different tubs of peat at similar temperatures were statistically significant at the 0.05 level.

Figure 2 shows the average vapor pressure deficit and temperature in the growth chamber for each 8-hr. measurement period. Over the temperature range of this study, the increase in vapor pressure deficit with temperature was almost perfectly linear ($r^2 = 0.97$). Also shown in Fig. 2 are the temperatures and vapor pressure deficits measured at noon, each day from May through October, 1975, in a bog on the Marcell Experimental Forest in north-central Minnesota*. It can be seen that the conditions of temperature and humidity in the growth chamber fell within the range of natural conditions.

Part of the net radiation received at a surface such as a tub of peat or water is absorbed as latent heat in the process of evaporation, part is transformed into sensible heat which warms the air, water, soil, and plants; and part is used by the plants in their metabolic processes. This can be expressed as:

$$R_n = E + A + G + M$$

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* U.S.D.A. Forest Service, North Central Forest Experiment Station, Grand Rapids, Minn., unpublished data.

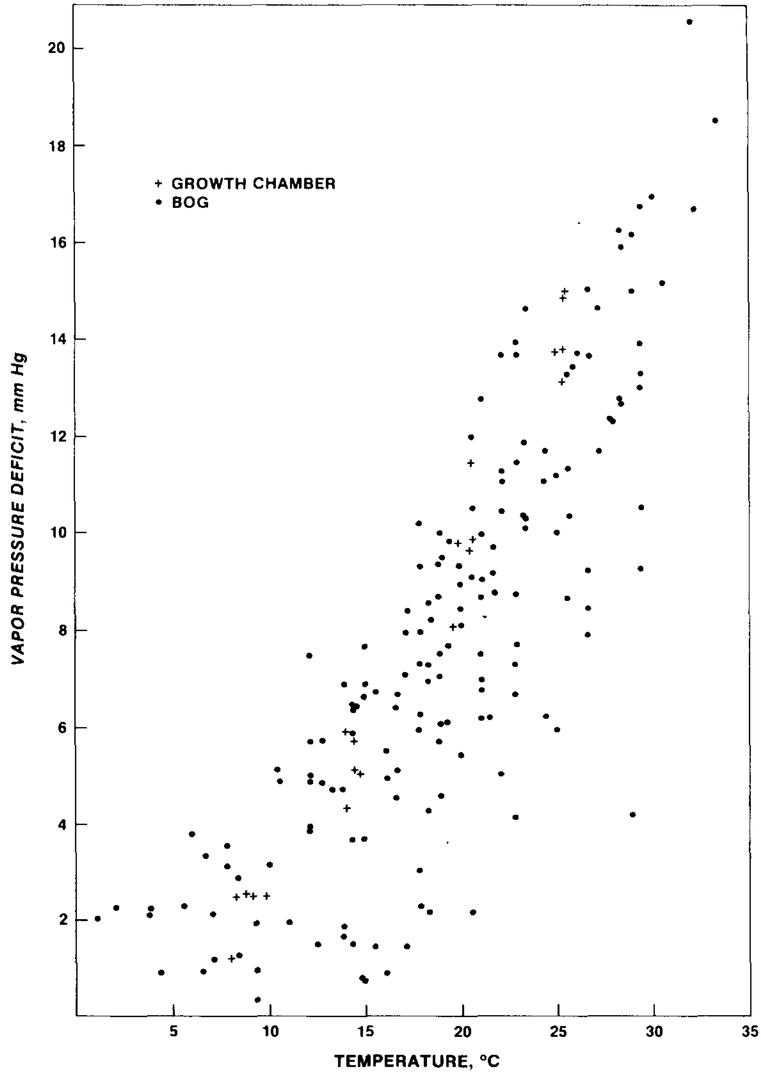

Fig. 2. Temperature and vapor pressure deficit in growth chamber and in a bog in north-central Minnesota.

where R_n = rate at which net radiation is received at the surface; E = rate of energy utilization in evaporation; A = energy flux that goes into heating the air; G = rate at which heat is stored in the soil, water and plants; and M represents energy use in other processes such as respiration and photosynthesis (Hillel, 1971).

The ratio of the transport of sensible heat from the surface to the air to the transport of latent heat from the surface by evaporation is called the Bowen (1926) ratio:

$$\beta = A/E = \gamma[(T_s - T_a)/(e_s - e)]$$

where β = Bowen ratio; γ = psychrometric constant, 0.49 mm Hg $^{\circ}C^{-1}$; T_s = temperature of the surface; T_a = air temperature; e_s = saturation vapor pressure at T_s; e = vapor pressure of the air. It is assumed that the eddy diffusivities for heat and water vapor are the same.

Net radiation was fairly constant throughout the study. There was essentially no difference between the amounts of net radiation at the moss and water surfaces. Net radiation increased slightly with temperature, from an average of 18.5 cal. cm^{-2} $hr.^{-1}$ at 9°C to an average of 22.2 cal. cm^{-2} $hr.^{-1}$ at 25°C. From the evaporation rates and the Bowen ratios an approximate energy balance was calculated that shows the fate of the net radiation received by the moss and water surfaces (Table I).

For example, at 9°C ~50% of the net radiation received at the water surface was used in evaporation. The Bowen ratio indicates that sensible heat transferred from the water surface to the air was ~42% of the latent heat transferred by evaporation, or ~21% of the net radiation. The remaining net radiation, 29%, was apparently stored in the water as heat (Table I). Over the 8-hr. measurement periods the temperature of the water at and near the surface was found to increase by several degrees. Since only the surface and near-surface temperatures were measured, however, an accurate estimate of heat transfer to the water could not be made. With increasing temperature more of the net radiation went into evaporation and less heat was transferred to the air (71 and 1%, respectively, at 25°C). The proportion of the net radiation that was stored in the water as heat remained about the same. As previously stated, evaporation from the moss was approximately twice that from the water at all temperatures. At all temperatures but the lowest, 9°C, more energy was used in evaporation from the moss than was received as net radiation. Under these conditions an amount of heat equivalent to from 6 to 18% of the net radiation is calculated to have been transferred from the peat to the moss surface and used in evaporation. Only at 9°C was part (28%) of the net radiation received by the moss transported as sensible heat to the air. At 20° and 25°C considerable energy (25 and 41% of the net radiation, respectively) was transferred from the air to the evaporating surfaces.

There were essentially no differences in evaporation between the moss with the grass and sedge overstory intact and the moss alone with vascular plants removed. Evaporation from the moss increased by 23% when the water level in the peat was lowered from the surface to 5 cm below the surface (significant at the 0.05% level). Further lowering of the water to 15 cm below the surface had little or no effect (Table II).

As in the first study, in which the water level was maintained at the surface of the peat while the temperature was varied, evaporation was greater from the moss at all water levels than from the water. These differences, however, were less than in the first study. Evaporation from the water surface in the second study averaged about 87% of that measured in the first study at the same temperature (20°C), while evaporation from the moss, with the water level at the surface of the peat, averaged only 58% of that measured at 20°C in the first study.

TABLE II

Evaporation[*1] from water and moss (with and without grass-sedge overstory) and energy relations at four water levels in the peat, at 20°C[*2]

Water level in peat	Air temperature (°C)	Surface temperature (°C)	Vapor pressure deficit (mm Hg)	Evaporation (mm hr.$^{-1}$)	Bowen ratio (E/A)	E/R_n	A/R_n	G/R_n	Ratio of moss to water evaporation
Moss:									
Surface	19.5	19.5	10.81	0.277	−0.018	0.78	−0.01	0.23	1.30
−5 cm	19.3	19.2	10.50	0.340	0.003	0.96	0	0.04	1.59
−10 cm	19.4	19.6	10.51	0.323	−0.015	0.92	−0.01	0.09	1.47
−15 cm	19.7	20.2	10.82	0.323	−0.001	0.93	0	0.08	1.51
Water:									
Surface	19.5	20.6	10.81	0.214	0.044	0.60	0.03	0.37	
−5 cm	19.3	20.6	10.50	0.216	0.053	0.60	0.03	0.38	
−10 cm	19.4	20.7	10.51	0.220	0.052	0.62	0.03	0.35	
−15 cm	19.7	20.9	10.82	0.217	0.048	0.62	0.03	0.38	

[*1] Average of two treatments.

[*2] An average of 2.53 g living grass and sedge, and 4.55 g dead grass and sedge (oven-dry) was removed from each tub.

Net radiation averaged $\sim$20.7 cal. cm^{-2} $hr.^{-1}$ over both the moss and water surfaces compared to $\sim$21.5 cal. cm^{-2} $hr.^{-1}$ measured at 20°C in the first study. The distribution of the net radiation received at the water surface was similar to that calculated for the first study at 20°C; a little over 60% went into evaporation and most of the remainder was apparently stored as heat in the water (Table II). As in the first study, the temperature of the water at and near the surface was observed to increase by several degrees during each 8-hr. measurement period, but actual heat transfer could not be estimated accurately since only surface and near-surface measurements were made. Heat transfer to the air accounted for only a small percentage. In contrast to the first study, energy use by evaporation from the moss surface did not exceed net radiation. From 78 to 96% of the net radiation received at the moss surface was used in evaporation (Table II), compared to 131% at 20°C in the first study (Table I). The rest was transferred to the peat. There was essentially zero heat flux between the moss and the air.

DISCUSSION

In order to relate the results of this study to evaporation in a natural situation, it is necessary to compare the conditions in the growth chamber to natural conditions. Evaporation has long been known to increase linearly with vapor pressure deficit (Dalton, 1802; Fitzgerald, 1886; Meyer, 1915; Horton, 1917), other factors remaining constant. The relation between temperature and saturation vapor pressure, however, is a curvilinear one (Goff and Gratch, 1946) which, over the temperature range of this study, can be approximated fairly well ($r^2 = 0.9997$) by an exponential equation, $Y = ae^{bx}$. Thus, under conditions of limited moisture supply such as in a growth chamber, vapor pressure deficit and consequently, evaporation, might be expected to increase exponentially with temperature. As Fig. 2 shows, however, this did not occur. While the vapor pressure deficit in the growth chamber at any particular temperature was somewhat higher than the average observed in the bog at the same temperature, growth chamber conditions fell well within the range of natural mid-day conditions.

Air was continuously recirculated through the 102-cm high by 127-cm long by 56-cm deep growth chamber, entering through the bottom at about 9.9 m^3 $min.^{-1}$ and exiting through the top. Assuming an evenly distributed flow, air moved through the chamber at a velocity of about 14 m $min.^{-1}$ (0.84 km $hr.^{-1}$). The chamber was vented to the outside so that the entire volume of air in the chamber was exchanged for outside air approximately hourly. Thus the vapor pressure deficit in the chamber was fairly stable through the 8-hr. measurement period. Increasing wind speed generally increases the rate of evaporation, primarily through the removal of water vapor (Gray et al., 1970), although Romanov (1968), in his study of evaporation from bogs in the U.S.S.R., found that an equilibrium is generally reached at low wind velocities, and that an increase above 90 m min.$^{-1}$ does not increase evaporation unless it causes a temperature inversion. While the velocity of air flow in the chamber was considerably less than natural winds, the constant movement of air in the chamber, in combination with the small size of the tubs of moss and water, likely minimized the accumulation of water vapor in the air adjacent to the evaporating surfaces.

The net radiation over the tubs of moss and water was ~75—85% of the average daytime net radiation measured continuously over a grass surface from May through September, 1967—1969, on the Marcell Experimental Forest* and ~45—55% of the average fair weather, midday (approximately $10^h 00^m$ a.m. to $3^h 00^m$ p.m.) net radiation reported by Brown (1972) over a sphagnum, grass and ericaceous shrub surface in August, 1969, and June and September, 1970, also on the Marcell Experimental Forest. Consequently, the ratio of the input of advected sensible heat to that of radiant heat in the chamber was probably somewhat higher than under natural conditions, especially at the higher temperatures.

Because there were differences between growth chamber conditions and natural conditions, the evaporation rates reported here may not be directly applicable to the natural environment. However, the relative differences between the two surfaces and among the various conditions of temperature and water level should still be valid.

Under seemingly similar conditions, evaporation from the moss in the second study was substantially less than in the first study. Due, apparently, to slightly different conditions in the growth chamber, evaporation from the water surface in the second study was ~13% less than in the first study at 20°C. However, even if a 13% correction factor is applied to the moss data, the evaporation from the moss in the second study was still only 67% of that measured in the first study at similar temperatures and with the water table at the surface of the peat.

The unforeseen delay between the end of the first study and the beginning of the second undoubtedly accounts for much of the difference in evaporation observed between the two studies. Following the temperature control study, the peat cores were maintained in their plastic tubs in the greenhouse for almost a year before they were used in the water level control study. Due to the warmer temperature in the greenhouse, peat decomposition was greater than it would have been under natural conditions. Having initially been even with the rims of the tubs, the peat settled 2—4 cm below the rims. The physical characteristics of the moss mat may also have changed after growing in the greenhouse for many months. Just the change in the position of the peat surface and the moss mat relative to the rims of the tubs could change the evaporation rate. In spite of this and the large amount of natural variation

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* U.S.D.A. Forest Service, North Central Forest Experimental Station, Grand Rapids, Minn., unpublished data.

among the tubs of peat, evaporation from the moss surfaces was significantly greater than that from the water surface.

Clymo (1973) found that evaporation from beakers of sphagnum moss stems was greater than evaporation from beakers with only water. He also found considerable variation in evaporation rates from one species of sphagnum to another, perhaps due to differences in their surface area and configuration. A number of studies in lakes and ponds have shown that when emergent or floating vegetation is present, water loss by evapotranspiration is greater than loss by evaporation from an open-water surface (Penfound and Earle, 1948; Timmer and Weldon, 1967; Brezny et al., 1973; Van der Weert and Kamerling, 1974; Benton et al., 1978). Evapotranspiration from stands of cattails (*Typha* sp.) has been found to be more than, equal to, or less than evaporation from open water, depending upon stage of growth, stand density, etc. (Braslavskii and Vikulina, 1963; Eisenlohr, 1966; Shjeflo, 1968; Linacre et al. 1970). Sturges (1968) found that evapotranspiration from a Wyoming mountain sedge bog was 27% greater than evaporation from a 6-ft. (~1.8-m) diameter pan. Evapotranspiration from a New Hampshire bog was 1.7 times greater than evaporation from open water (Rutherford and Byers, 1973). In contrast, in a study at a more northerly latitude near Hudson Bay, Rouse et al. (1977) found that evaporation from a shallow lake slightly exceeds that from a wet sedge meadow.

As calculated in Tables I and II, from 28 to 41% of the net radiation at the water surface was utilized in warming the water. In comparison, evaporation from the freshly-collected moss surface resulted in a heat flux from the peat to the vaporating surface equal to from 6 to 19% of the net radiation (Table I). The data reported here are only for periods of 8 hr. with the growth chamber lights on. Evaporation and heat transfer between the air and the tubs of water and peat during the 16-hr. dark period were not measured. Due to the large surface area/volume ratio of the tubs of peat and water compared to that of a bog or a body of water, the flux of heat to and from the water and peat could occur much more rapidly in the growth chamber than under field conditions. The relatively large fluxes of heat to and from the water or peat reported here would not be expected to occur in the field.

For both the water and the moss, the increase in evaporation with increasing air temperature was accompanied by a decrease in the transfer of sensible heat from the surface to the air, as indicated by the decrease in the Bowen ratios with increasing temperatures. At higher temperatures the Bowen ratio from the moss was negative as considerable heat from the air was used in evaporation.

Williams (1968) measured heat and moisture exchange, from August to November, 1964, over 4-ft. (~1.2-m) diameter tanks of saturated sphagnum moss placed in a peat bog near Ottawa, Canada. He found that the heat required for evaporation exceeded measured net radiation by almost 50%. This additional heat was gained from the air. There was little heat exchange between the evaporating surface and the underlying peat.

An inverse relation between air temperature and Bowen ratio has also been noted by Stewart and Rouse (1976) in a wet sedge meadow near Hudson Bay. During July, 1972, with an average daylight temperature of about 10°C, Stewart and Rouse (1976) found that 66% of the net radiation was used in evaporation, 26% was transferred to the air, and 8% to the organic soil. These results are fairly similar to the results from the present study for evaporation from the moss at 9°C, except that the cold soil at the latitude of Hudson Bay apparently constitutes an appreciable heat sink during the summer, while the tubs of peat in the growth chamber appeared to reabsorb heat from the air during the 16-hr. dark period and function as a heat source during the 8-hr. measurement period.

From these field studies and the present growth chamber investigations, it appears that during the warm season the majority of the net radiation received by a sphagnum bog is used in evaporation or evapotranspiration. Relatively little heat is transferred to or from the soil. Heat flux between the evaporating surface and the air is quite variable, depending upon air temperature and evaporation rates.

Evaporation from the moss and the moss plus grasses and sedges was lowest when the water level was at the surface of the peat and increased significantly when the water level was lowered to 5 cm below the surface. Due to the irregular micro-relief, about half of the peat surface was covered by standing water in this treatment. The reduction in evaporation under these conditions was probably due to the reduction in the surface area available for evaporation. Lowering the water table from 5 to 15 cm below the surface of the peat resulted in no significant change in evaporation. However, some dessiccation and browning of the moss did occur following the 8-hr. test period at the −15-cm water level, especially when a cover of grasses and sedges was not present to provide some shelter for the moss.

Virta (1966) reported that lowering the water level from ~2 cm below the surface to ~6 cm below the surface resulted in a substantial decrease in evapotranspiration. A similar effect was not seen in this study. Boelter (1964) feels that water does not rise more than 20 cm by capillary action in undecomposed peat. This opinion is shared by Romanov (1968) who, in a study of bogs in the U.S.S.R., found little change in evapotranspiration as the water table was lowered to ~30 cm below the surface, or ~15—20 cm below the roots of the paludine dwarf shrubs which dominated the study areas. But, when the depth to the water table increased beyond ~30 cm, evapotranspiration decreased markedly. It is felt that desiccation observed in this study would have increased and evaporation would have decreased sharply if the water table had been lowered more than 15 cm.

In a field study of evapotranspiration from a bog surface of sphagnum moss and low-growing vascular plants, Boelter (1972) found that when the water table was lowered to 30 cm below the surface, the mosses became desiccated and evapotranspiration was less than 40% of that occurring when the water table was maintained at or near the surface. The lower evapotranspiration was attributed, primarily, to the lower evaporation from the moss. It appears that evaporation from a sphagnum bog could be reduced somewhat, making more water available for streamflow, by flooding the surface, or by lowering the water table to more than 15—20 cm below the surface.

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