

Ericaceous shrubs on abandoned block-cut peatlands: Implications for soil water availability and *Sphagnum* restoration

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ABSTRACT

Following harvesting by manual block-cut methods and subsequent abandonment, Cacouna bog has undergone a natural vegetation succession, with ericaceous shrubs covering more than 90% of the surface. The abundance of shrubs plays a major role in the soil water flux and availability at the site, impacting *Sphagnum* regeneration. From June 1 to August 22, 2007, field measurements indicate that transpiration represented the largest water loss from the shrubs at 1.7 mm day⁻¹, comprising 142 mm (42%) of rainfall, compared to 93 mm of evaporation (28%) from bare soil. The rainfall interception from the canopy (62 mm) and litter (15 mm) accounted for 23% of seasonal rainfall. Thus after transpiration and interception losses are accounted for, only 115 mm of the 334 mm of rain (34%) remained available for other processes (recharge/soil evaporation). In the field, the litter layer prevented 17 mm from being lost over the summer as it reduced evaporation by 18%. Laboratory experiments using intact soil monoliths with and without shrubs and litter indicate that at depths below 10 cm the water content from the shrub monoliths decreased 27% versus 20% in the bare peat monoliths because of root water uptake. As a management prescription, raising the water table within 20 cm of the surface would provide water to the most active root uptake zones, reducing the need for extraction from the upper 10 cm of the peat. At this level sufficient water can be supplied to the surface through capillary rise, providing adequate water for the reestablishment/survival of *Sphagnum*. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS ecohydrology; ericaceae; cutover bog; rainfall interception; restoration; litter layer; litter interception; climate change

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INTRODUCTION

In the Bas-Saint-Laurent region on the south shore of the St. Lawrence River, Québec about 62% of the peatlands have been harvested for horticultural peat (Poulin *et al.*, 2004). The hydrology of bogs after peat-harvesting (Price and Whitehead, 2004) is unsuitable for the reestablishment of *Sphagnum* mosses (Rochefort *et al.*, 2003), the dominant peat-forming vegetation in undisturbed bogs (Kuhry and Vitt, 1996). Higher bulk density of the old cutover peat imparts higher water retention (Price, 1997), lower hydraulic conductivity (Van Seters and Price, 2002), and low water table levels (Price, 1997) which limit the water availability for mosses. Ericaceous shrubs native to undisturbed bogs, however, regenerate vigorously on many cutover peatlands (Lavoie and Rochefort, 1996). The seed bank left behind after harvesting can result in ericaceous shrubs covering more than 80% of the total surface (Girard *et al.*, 2002; Poulin *et al.*, 2005). The high abundance of these shrubs could influence water storage and distribution in the peat through canopy and litter interception, transpiration and changes in soil water evaporation although their role in

the water balance of cutover peatlands is not documented. The shrubs may influence the amount of water available at the peat surface which is essential for the regeneration of *Sphagnum* (Price and Whitehead 2001).

Interception (*I*) by vegetation canopies has been well described for a number of trees and forested ecosystems (Crockford and Richardson, 2000) but not so well for smaller plants such as shrubs and grasses. Návar and Bryan (1990) and Martinez-Meza and Whitford (1996) observed *I* of 27 and 33% of rainfall for three species of desert shrub, while Domingo *et al.* (1998) recorded 40% *I* losses for *Anthyllis cytisoides*, a single shrub species in a semi-arid dryland. We are aware of only one study of interception for peatland shrubs (Päivänen, 1966), which measured *I* as 24% of rainfall. In various ecosystems leaf-litter has also been shown to intercept between 0.3 and 6.7% of incoming rain (Sato *et al.*, 2004), having a water storage capacity between 1.5 and 2.8 mm of water kg⁻¹ of litter (Putuhena and Cordery, 1996; Tobón-Marin *et al.*, 2000; Sato *et al.*, 2004).

Evapotranspiration (*Et*) is the major water loss observed in natural and cutover peatlands (Lafleur, 1990; Van Seters and Price, 2001; Lafleur *et al.*, 2005), with considerable losses occurring from the *Sphagnum* surface. However, shrubs may increase peatland *Et*. Romanov (1968) and Lafleur *et al.* (2005) noted that *Et* decreased when the water table dropped 60 cm below the

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surface, the limit of the shrub root. Takagi and Tsuboya (1999) reported an increase in E_t with increasing vascular plant abundance in a peatland. The enhanced E_t by shrubs occurs as direct loss through transpiration (T), which in ericaceae can be more than 50% of E_t (Miranda *et al.*, 1984). To meet daily T requirements, plants remove water from soil, resulting in a decrease in volumetric water content (θ) and soil water pressure (ψ). The amount of water extracted is related to rooting depth (Sharp and Davies, 1985; Coelho and Or, 1999) and is greatest at the highest root densities (Moore *et al.*, 2002).

Leaf litter can also affect the moisture dynamics of a soil. It has higher surface albedo than soil under both wet and dry conditions (Murphy and Lodge, 2001), which reduces energy available for evaporation (Facelli and Pickett, 1991) from the underlying soil. The moisture dynamics of mulch, which is analogous to litter, has been studied in more detail and shown to reduce net radiation and temperature (Bristow, 1988; Price *et al.*, 1998), as well as evaporation from the soil (Price *et al.*, 1998; Shangning and Unger, 2001), which results in higher soil water content (Bristow, 1988; Price, 1997; Cook *et al.*, 2006). Though interception by the litter layer reduces the amount of water reaching the soil surface, energy used to evaporate intercepted litter-water is unavailable to evaporate water from the soil (Price *et al.*, 1998).

Much work has been done on the conditions needed to restore *Sphagnum* on abandoned harvested peatlands (Price *et al.*, 2003; Rochefort *et al.*, 2003). ψ over -100 cm in the upper 2 cm soil layer is necessary for *Sphagnum* establishment (Price and Whitehead, 2001). Furthermore, vascular plants have been shown to act as nurse plants aiding in the reestablishment of *Sphagnum* (Ferland and Rochefort, 1997; Boudreau and

Rochefort, 1999; Lavoie *et al.*, 2005) creating more suitable microclimatic and hydrological conditions (Lavoie *et al.*, 2005). Shrubs may also act as scaffolding allowing the moss carpet to rise above the water table, promoting the growth of *Sphagnum* (Malmer *et al.*, 1994). Therefore, while interception by, and transpiration from ericaceous shrubs reduce the total available water for *Sphagnum*, the shading, structural support for mosses, and leaf-litter may ameliorate the conditions and encourage moss regeneration. This study aims to provide a better understanding of how ericaceous shrubs affect the moisture dynamics at the soil surface of cutover peatlands. More specifically we will quantify how ericaceous shrubs affect: (1) rainfall interception by the canopy and by the litter layer that develops beneath it; (2) transpiration rates; (3) soil water evaporation through its litter layer; and (4) changes in volumetric water content and soil water pressure from the peat substrate.

STUDY AREA

The Cacouna peatland ($47^{\circ}53'N$, $69^{\circ}27'W$) is located approximately 10 km north-east of Rivière-du-Loup, Québec (Figure 1). It is a domed bog, covering an area of 172 ha at an average elevation of 83 m above sea level (Girard *et al.*, 2002). Mean annual precipitation (1971–2000) at a weather station in nearby St. Arsène was 963 mm, 28% of which fell as snow (Environment Canada, 2007). Mean annual temperature (1971–2000) was $3.2^{\circ}C$, (Environment Canada, 2007). The growing season occurs from May to October, when the mean daily temperature is above $5^{\circ}C$ (Environment Canada, 2007).

Peat harvesting began in 1942 with the installation of primary and secondary drainage ditches, and continued

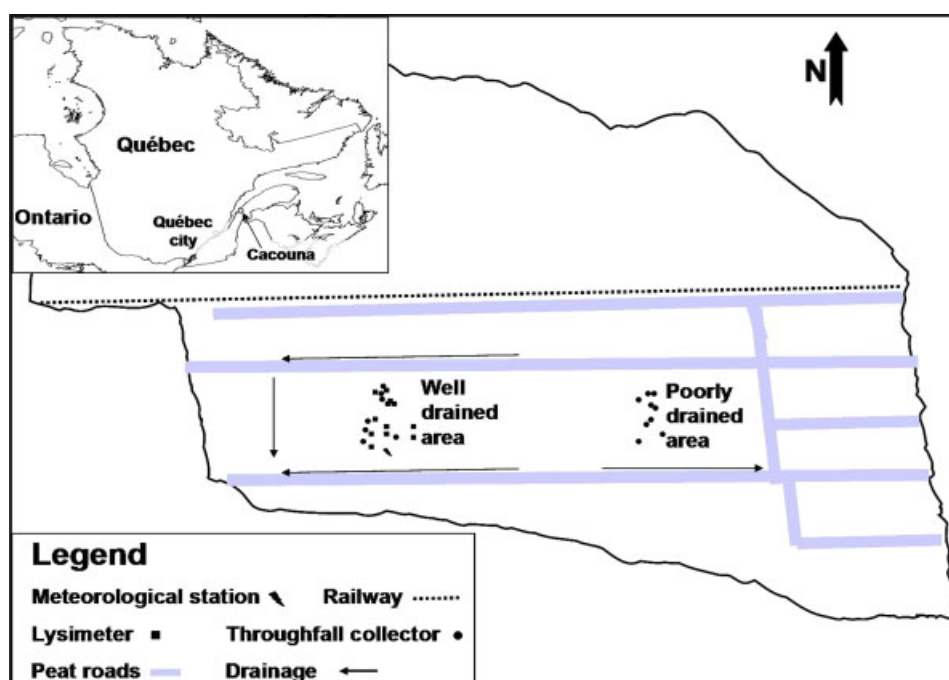


Figure 1. Location of the Cacouna bog, and position of measurements in relatively poorly and well-drained sections.

until 1975 using traditional block-cut methods. This method involved cutting the peat by hand to form trenches approximately 10 m wide and 200 m long. The Cacouna bog currently consists of 445 baulks (ridges approximately 1 m high and 6 m wide that separate the trenches; 511 trenches and 16 vacuum-harvested fields (Girard *et al.*, 2002). In October of 2006, the main drainage ditches were blocked in an effort to rewet the site.

Following abandonment in 1975, the Cacouna bog has undergone natural vegetation succession. Plants typical of peatlands in that region have recolonized most of the bare peat surface. Ericaceous shrubs, such as leather leaf (*Chamaedaphne calyculata*), sheep laurel (*Kalmia angustifolia*), and labrador tea (*Ledum groenlandicum*) are the dominant plant species covering *ca* 90% of the surface (Lavoie and Rochefort, 1996; Girard *et al.*, 2002). The surface below the shrubs has a 0.5–5 cm thick and a 0.01–0.5 kg m⁻² dense litter layer (Farrick, 2008), overlying roughly 3–4 m of peat. Trees including, tamarack (*Larix laricina*), black spruce (*Picea mariana*), and jack pine (*Pinus banksiana*) cover less than 20% of the surface and have a generally patchy distribution across the site, but are more abundant along the bog periphery and the earliest abandoned areas. The distribution of *Sphagnum* moss is sparse (<10%) and generally limited to wet areas of trenches and topographic depressions in the bog (Girard *et al.*, 2002).

METHODS

Field methods

Data were collected during the main growing period from June 1 to August 22, 2007, at the well drained and poorly drained sites (Figure 1). The well drained area is dominated by ericaceous shrubs and other vascular plants with most of its water draining to the west (Figure 1). The poorly drained area is dominated by *Sphagnum* and is located on the crest of the peat dome which has a lower water table gradient, resulting in poor drainage of water from this section. These areas were selected as they have been used in the past to collect meteorological data and conduct research (Van Seters and Price 2001; Price and Whitehead, 2004). A meteorological station was set up at the well drained site and monitored continuously using a Campbell Scientific Inc CR10X data logger. Precipitation was measured using 2 Texas Electronics Inc TE525WS-L tipping buckets and 2 manual rain gauges situated approximately 1 m above the peat surface. The manual gauges were located within 3 m of the nearest tipping bucket gauge.

Canopy interception was measured as the difference between gross rainfall (P) and throughfall (TF) collected under ericaceous shrubs after each rainfall event using twelve 100 × 3.8 cm and six 44.5 × 3.8 cm V-shaped troughs, which were approximately 2 cm deep. The collectors were placed under the plants, at approximately 10 cm above the ground surface. The water collected by

the troughs was measured 1 to 2 h after rainfall ceased. The rain gauges and TF collectors were positioned in areas where trees were more than 2 m in proximity from the instruments. This reduced the potential error in precipitation and throughfall measurements due to rainfall interception by the trees.

Et for ericaceous shrubs was measured daily using six 0.24 m² × 0.22 m deep bladder lysimeters sunk level to the peat surface. A large plastic bladder was filled and placed at the bottom of the containers. A clear plastic tube, extending to the outside of the container was connected to the water outflow of the bag and measuring tape attached along the length of the tube. The inside of the container was sealed with plastic sheeting, which protected the bladder. A 0.15-m deep monolith was cut to fit, and then placed in the lysimeters, which were then returned to the pit from where the monolith was extracted. The water level in the tube was monitored daily and represented a change in mass of the sample equivalent to the depth of water lost by Et. Direct evaporation (E) for natural ericaceous litter cover and bare peat was measured using 0.032 m² × 0.15 m deep plastic weighing lysimeters, six each with litter and three with bare peat. A 0.15-m deep monolith was cut to fit, and then placed in the lysimeters. Vegetation was clipped at the base and removed from the monoliths. The samples were weighed every 2–3 days to record mass change, then were inspected using a Campbell Scientific Inc HydroSense water sensor to determine if water should be added or removed to maintain moisture content similar to the surrounding peat, and adjusted accordingly. Both lysimeter types were isolated from the surrounding soil and water table, preventing capillary rise during Et. Transpiration (T) was estimated as Et from the shrubs minus E from the litter.

The Priestley and Taylor (1972) combination method was used to estimate daily evapotranspiration (Et) (mm d⁻¹) as

$$Et = \alpha[s/(s + q)][(Q^* - Q_G)/L\rho] \quad (1)$$

where, L is the latent heat of vaporization (J kg⁻¹), ρ is the density of water (kg m⁻³), s is the slope of the saturation vapour pressure versus temperature (T) curve (Pa °C⁻¹), q is the psychrometric constant (0.0662 KPa °C⁻¹ at 20 °C), Q^* is the net radiation flux (Wm⁻²), and Q_G is the ground heat flux (Wm⁻²). Net radiation (Q^*) was measured using a REBS Q7-1 net radiometer installed *ca* 1 m above the *Sphagnum*-ericaceae surface. Q_G was measured with a soil heat flux plate inserted 1 cm under the *Sphagnum* surface. Q^* , Q_G , and T were measured every minute and the average recorded every 20 min. Ideally, net radiation would have been measured over ericaceae; however, the equipment could not be moved as it was concurrently being used in a three year study of the site. This may have induced slight error. However, Van Seters (1999) recorded a less than 1% difference in Q^* between *Sphagnum* and ericaceae surfaces at this site. Here

we assume a similar relationship and use unadjusted Q^* values from *Sphagnum* to calculate shrub Et . The coefficient α is empirically derived as the ratio of Et measured in the lysimeter and equilibrium Et calculated from Equation (1) when α is set to unity. α was averaged at 0.57 over the season.

Potential errors were likely to occur with the measurements of TF and estimations of Et and T . Splash-out from TF collectors may account for an overestimation of I requiring an increase in the size, depth, and angle of collectors to reduce error (Helvey and Patric, 1966; Llorens *et al.*, 1997). Ensuring accurate estimates of Et depends on error from lysimeter analyses. Measurements derived from small lysimeters ($<1 \text{ m}^2$) provide a good estimate of actual evaporation during the growing season (Dugas and Bland, 1989). Lysimeters are sufficiently accurate to estimate T from smaller plants, reducing the need to employ stomatal conductance and sap flow measurements as direct measurements of T (Dugas, 1990).

Laboratory methods and analysis

Litter layer interception and evaporation. The interception storage capacity (I_c) of litter was measured using a rainfall simulator over reconstituted layers of litter of various thicknesses. According to Putuhena and Cordery (1996) I_c can be separated into two categories; (1) C_{\max} , the maximum interception storage capacity and (2) C_{\min} the minimum storage interception capacity. C_{\max} is the amount of water (mm) detained within the litter layer when interception stops increasing during rainfall and includes gravitational water, while C_{\min} is the amount of water (mm) retained in the litter when free drainage stops after rainfall ends and does not include gravitational water. C_{\min} may vary as a consequence of partial wetting depending on the litter matrix structure and the nature of the wetting event. Thus, an interception event may not hydrate all spaces, instead wetting preferred flow-paths. Hydrologically, C_{\min} is more important than C_{\max} as water is readily drained within 30 min after rainfall ceases, and represents the actual water that is held within the litter (Putuhena and Cordery, 1996). In our experiment, rainfall was produced by irrigating with a rainfall simulator in which the intensity (5, 10, and 25 mm h^{-1}) was adjusted by manipulating the water flow and the distance of the sampling tray from the water source. Interception was measured for litter thickness and litter mass combinations of 0.5 cm and 0.5 kg m^{-2} , 1 cm and 0.8 kg m^{-2} , and 2 cm and 1.4 kg m^{-2} , respectively. The litter was placed in a 25 × 25 cm tray with 5 mm mesh and placed over a Texas Electronics Inc TE525WS-L tipping bucket rain gauge, which recorded water draining through the litter at 2 min intervals over a 90 min simulated event. The simulated rainfall was stopped after 90 min and the depth of water (mm) collected at this time was the C_{\max} . The sample was allowed to drain over the gauge for 30 min and the difference between the C_{\max} and this drained water was the C_{\min} (mm). This interception represents a minimum effect, as the field litter

layer also consists of finer material that has greater water retention which could increase the overall I_c .

Given the C_{\min} from laboratory analyses, overall seasonal I was estimated as

$$I = P - \text{TF} + C_{\min}(\text{mm}) \quad (2)$$

E from litter covered peat was measured in $0.0038 \text{ m}^2 \times 16 \text{ cm}$ deep containers. Milled *Sphagnum* peat (Premier Sphagnum Peat Moss) was used to ensure sample homogeneity. The peat was initially saturated by inundating and mixing the peat to remove air, and then packed into columns with a dry bulk density of approximately 0.4 g cm^3 . Four replicates of bare-peat were used, filling the 16 cm high container. Similarly, four replicates of 15, 14, and 12 cm columns of peat were packed into the remaining columns with 1, 2, and 4 cm depth of litter, respectively, to fill the 16 cm deep containers. The litter densities were 0.1, 0.2, and 0.3 kg m^{-2} , respectively. A sample container filled with water was used to estimate potential evaporation. Samples were placed 20 cm below a grow light and were weighed every 1–2 days to record water loss and calculate E . Air temperature and relative humidity (RH) in the laboratory were kept at approximately 25 °C and 36%, respectively, and was also recorded above the surface of the samples every two days using a Vaisla HMI41 Humidity Indicator. θ of the soil in the lysimeters was determined gravimetrically.

Soil water fluxes

To examine ψ and θ response to surface sources and sinks of water under a shrub cover, six $0.07 \text{ m}^2 \times 0.32 \text{ m}$ deep peat monoliths were extracted from the field using an empty 23 l pail with the bottom cut out, as a saw guide to cut the sample—the bucket being progressively pushed down as the cut was made. One bare-peat (no shrubs present) and two shrub-covered (*Kalmia angustifolia*) samples were obtained in October, 2007 from randomly selected locations along a baulk, and similarly from a trench in the relatively well drained section of the peatland, which had a higher shrub density (Figure 1). Sheep laurel was selected as it is one of the most abundant ericaceae species at this site (Lavoie and Rochefort, 1996). The extracted monoliths were transferred into an experimental column (see Farrick 2008 for details) containing a 5 cm layer of glass beads (60–110 μm) positioned over a 2-cm layer of coarse sand (Figure 2). Samples were transported to the University of Waterloo and stored outdoors for 2 months (October–November). Most of the larger litter ($>2.8 \text{ mm}$) was removed from the surface of the bare peat and shrub monoliths. The fine litter was difficult to remove completely from under the shrubs and consequently remained on its surface. Removal of litter allowed us to estimate the T rate from the shrubs as the difference between shrub Et (bare peat and shrub column) and bare peat (bare peat only column) evaporation (E). Grow lamps were placed ~20 cm above the top of the shrubs and 60 cm from the bare peat for 12 h per day in a chamber with a temperature

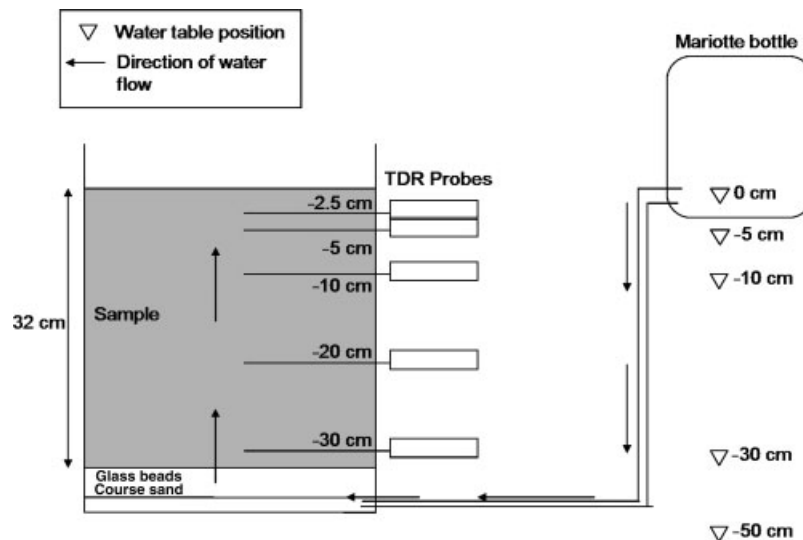


Figure 2. Mariotte bottle and TDR location in experimental columns (tensiometers are located at the same depths as TDR probes).

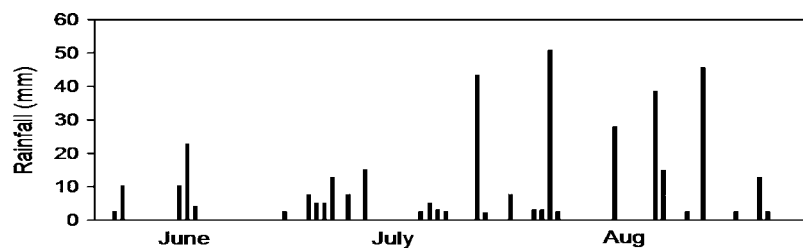


Figure 3. Average daily rainfall (mm) for the 2007 season.

of $25 \pm 0.3^\circ\text{C}$ and relative humidity at 36%. Vapour pressure deficit (VPD) was calculated from temperature and RH data.

A mariotte bottle device was connected to a nipple at the base of the column to provide a constant supply of water, and to allow us to set the position of the water table (Figure 2). Et rates were measured daily by measuring the water loss from the mariotte bottle.

θ was measured using Campbell Scientific Inc 605 Time Domain Reflectometry (TDR) probes inserted horizontally at 2.5 cm, 5 cm, 10 cm, 20 cm, and 30 cm below the peat surface (Figure 2). θ was calculated using a linear calibration for peat from the same site (Whitehead, 1999). ψ in the peat profile was measured with L-shaped tensiometers inserted horizontally at the same depths.

The water table within the column was manipulated using the mariotte bottle and initially raised to the surface to saturate the peat, then lowered to 5 cm below the surface (Figure 2). θ of the shrub monoliths were monitored hourly, while that of the bare peat monolith was measured once daily (due to problems with loggers). ψ was measured every 1–2 days. The experiment was run for 17 days at -5 cm after which the water table was lowered to -10 (15 days), -30 (36 days), and -50 cm (12 days) (Figure 2). The water table was left longest at -30 cm as it was thought that at this level diurnal redistribution of water from the lower to upper layer may readily be observed.

Statistical analysis

Student's t-test and one way analysis of variance (ANOVA) were used to determine significant differences for litter evaporation and field shrub Et data.

RESULTS

Meteorological conditions

A total of 334 mm of rain fell between May 25 and August 22, 2007 (Figure 3). Rainfall in June and July (228 mm) was 21% higher than the 30 year average (1971–2000) of 179 mm for the same months (Environment Canada, 2007). Precipitation events ≤ 3 mm occurred 12 times over the season, while events > 30 mm occurred 3 times. Rainfall intensity varied between 2 and 25 mm h^{-1} . Rainfall between 7 and 9 mm h^{-1} occurred most frequently with 17 events, while rainfall between 22 and 25 mm h^{-1} occurred only 3 times over the season. The difference between adjacent tipping bucket and manual rain gauges was less than 10%, while spatial differences between tipping buckets gauges was less than 20%. Average daily temperature for June to August was within 0.2°C of the 30 year mean (16.4°C).

Canopy and litter layer rainfall interception

The amount of rainfall intercepted by the shrub canopy increased with increasing rainfall depth, ranging from 0.7–15 mm. TF increased as the depth of rainfall

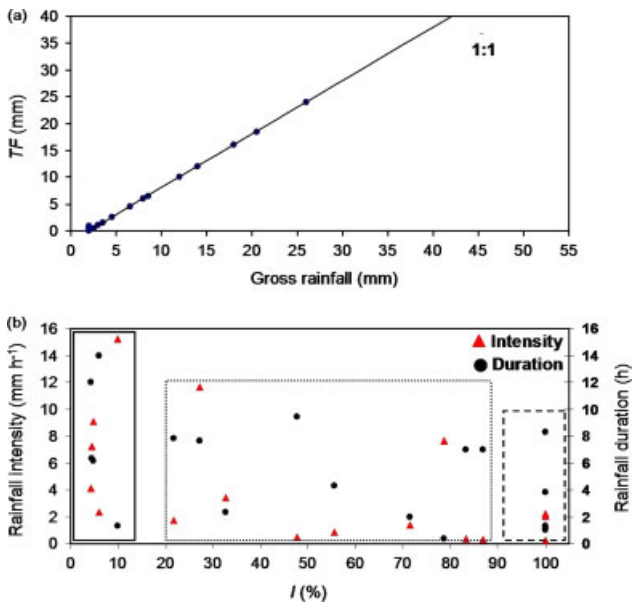


Figure 4. a) Average throughfall (mm) versus gross rainfall (mm) b) Effect of rainfall intensity (mm h^{-1}) and duration (h) on percent interception. (Interception was determined from P -TF. The slope of the relationship between TF and P was adjusted to 1:1 from 0.73 based on the assumption that splashout caused a systemic water loss. This is discussed further in the Discussion).

increased and ranged from 0 to 46 mm (Figure 4a). Using TF data, the interception storage capacity was estimated at 2 mm (\times -intercept in Figure 4a). Given this storage capacity, the cumulative interception loss for 31 events over the summer is estimated at 62 mm. Therefore, the rainfall that reached the litter/peat surface is $\text{TF} = P - I = 272$ mm.

The combined effects of rainfall intensity and duration on canopy I were examined (Figure 4b). I for the low intensity, low duration event (dashed line) was the highest (100%). The lower range of I ($\leq 10\%$) featured events of higher intensity and low duration or long duration lower intensity (solid line). The middle group (dotted line) of I (20–90%) has a mixed range of intensity and duration values.

Litter interception was a function of litter mass and rainfall character. The amount of water retained in the litter increased as litter depth/mass increased (Figure 5a, Table I). For a given litter mass/thickness the amount of rainfall detained increased as the rainfall intensity increased (Figure 5b). However, the proportion of water retained decreases as intensity increases. The amount of rainfall intercepted increased rapidly over the first 40 min and became consistent around 90 min. When rainfall ceased, 0.1–0.3 mm of water was drained from the litter (Figures 5a,b). The 0.5 kg m^{-2} litter layer (most representative of field conditions) intercepted 0.2–1.2 mm (mean of 0.7 mm) of simulated rainfall (Figure 5b). Given the lab storage capacity, field litter I was calculated from rainfall events where TF was greater than 2 mm (canopy storage) and estimated at 15.4 mm over the season.

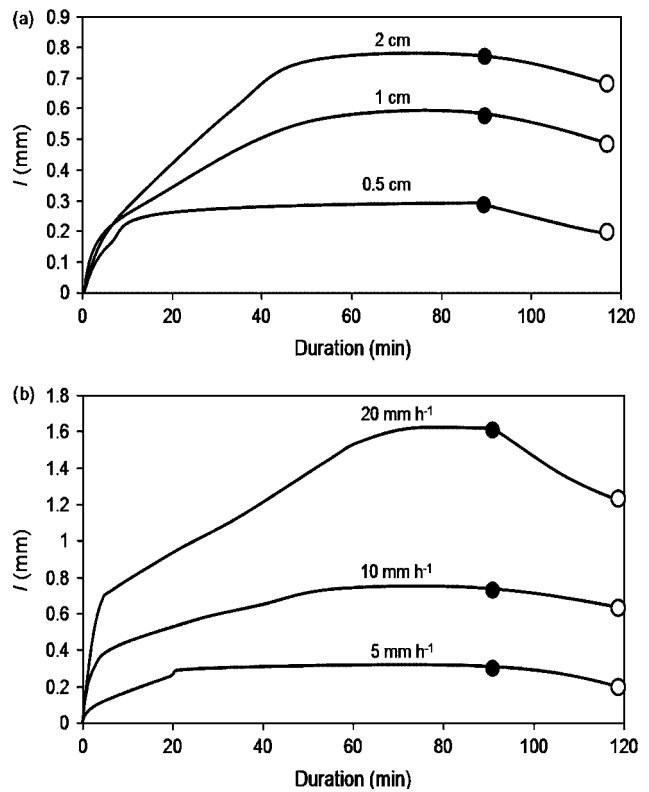


Figure 5. a) Rainfall interception for 0.5, 1 and 2 cm thick litter layers for a 5 mm h^{-1} event b) Rainfall interception for a 0.5 kg m^{-2} dense layer for 5, 10 and 20 mm h^{-1} events (black and white circles indicate C_{max} and C_{min} respectively).

Table I. Minimum interception storage capacity (C_{min}) of the litter layer at different thicknesses, densities, and rainfall intensities.

Litter mass (kg m^{-2})	Litter depth (cm)	Rainfall intensity (mm h^{-1})		
		5	10	20
0.5	0.5	0.2	0.6	1.2
0.8	1	0.5	1.2	1.4
1.4	2	0.7	1.6	2.6

Table II. Average field evapotranspiration rates (mm day^{-1}) from shrub lysimeters and litter layer lysimeters from the baulk and trench microtopography.

Surface type	Location	Evapotranspiration rate (mm day^{-1})
Ericaceous shrub	Baulk	2.8
Ericaceous shrub	Trench	2.3
Ericaceous litter	Baulk	0.6
Ericaceous litter	Trench	0.9

Field and laboratory evapotranspiration, evaporation, and transpiration

Based on field lysimeter data, daily Et from ericaceous shrubs averaged $2.5 \pm 1.6 \text{ mm day}^{-1}$ or 211 mm over the season, representing 63% of precipitation. Et from trenches (2.3 mm day^{-1}) was less ($P > 0.05$) than that

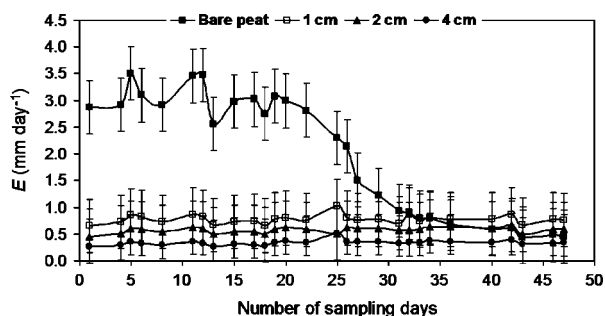


Figure 6. Average evaporation rate (mm day^{-1}) from the bare peat (2 mm day^{-1}), 1 cm (0.7 mm day^{-1}), 2 cm (0.5 mm day^{-1}) and 4 cm (0.3 mm day^{-1}) litter cover over the 47 day sample period (cumulative water loss from these layers were 91, 35, 27 and 15 mm respectively).

from baulks (2.8 mm day^{-1}) (Table II). E from litter-covered peat from baulks (i.e. excluding shrubs) averaged $0.6 \pm 0.3 \text{ mm day}^{-1}$, while from trenches averaged $0.9 \pm 0.4 \text{ mm day}^{-1}$ (Table II). The average E from litter-covered peat (0.7 mm day^{-1}) resulted in 67 mm of water loss over the summer season.

Transpiration (T) estimated as the difference between E_t and E was approximately 1.7 mm day^{-1} (142 mm over the season) or 42% of precipitation, accounting for 68% of the total E_t losses over non-*Sphagnum* surfaces.

Comparison of E from litter-covered and bare peat trench sites, $0.9 \pm 0.4 \text{ mm day}^{-1}$ and $1.1 \pm 0.5 \text{ mm day}^{-1}$, respectively, were significantly different ($P < 0.05$), resulting in 17 mm less water lost under litter-covered trench surfaces over the season.

In the laboratory experiment E from litter-covered peat was also lower than that from bare peat over the first 33 days and declined sharply around day 25, eventually becoming lower than litter E by day 34 (Figure 6). Cumulative water loss over the duration of the experiment from bare peat of 1, 2 (most representative of field conditions), and 4 cm litter depths corresponded to 91, 35, 27, and 15 mm of water, respectively. By comparison the total free-water E for this period was 141 mm. E from the litter-covered surfaces remained relatively consistent over the experiment (Figure 6), with E from 1 cm litter depth higher ($P < 0.05$), when compared to that from 2 and 4 cm litter layers. The differences in θ under the litter samples over the study period were not statistically significant ($P > 0.05$) and showed a linear relationship with litter thickness ($R^2 = 0.83$, $y = 0.0515x + 0.6056$). RH at the surface of the samples showed similar trends as E , being significantly ($P < 0.05$) higher over bare peat

up to day 25, thereafter becoming lower than that over the litter samples.

Soil water fluxes

The average E and E_t rates from baulk and trench laboratory columns decreased as the water table (WT) was lowered, with the E_t rates being higher than E at all WT (Table III). T increased as WT was lowered to -30 cm but decreased when the WT was at -50 cm . T was 50% of E_t losses over the experiment and ranged from 11 to 80% (Table III). Cumulative water loss from E_t , E , and T was 77.2, 38.9, and 38.3 mm, respectively. Cumulative water loss from T showed a steady increase until the WT was lowered to -50 cm while the increase in water loss due to E was reduced at progressively deeper WT (Figure 7).

The ψ decreased as the water table was lowered from 0 to -50 cm (Figure 8a and b). At WT of -5 and -10 cm only a small drop in ψ was observed for both bare and shrub covered peat (Figure 8a and b). When WT was lowered to -30 cm , there was a distinct drop in ψ , 11 days later, in the bare peat which continued to decline rapidly at the 2.5, 5, and 10 cm tensiometer depths (Figure 8a). Unlike bare peat, ψ of shrubs showed a slow and steady decrease at WT = -30 cm and only at -50 cm was there a distinct drop in ψ (Figure 8b). ψ at 2.5 cm depth in the bare peat reached -100 cm by day 57 under a -30 cm WT, while the shrub column never reached -100 cm over the sample period (Figure 8b).

Volumetric water content (θ) was consistently higher deeper in the peat profile and decreased at all levels within the monolith for both bare and shrub covered peat throughout the study period. The loss in θ from all samples decreased from the surface to the base of the monolith (Table IV). However, the overall percentage

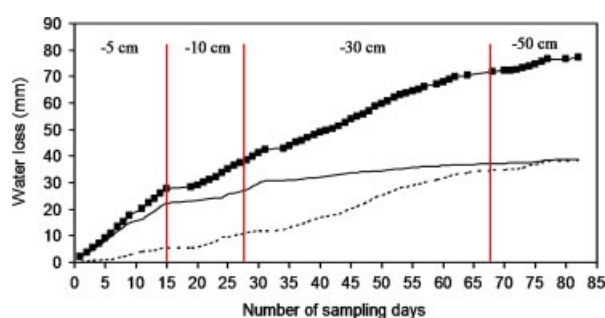


Figure 7. Cumulative water loss from E_t (squares), E (solid line) and T (dotted line) at four water table levels over the sampling period.

Table III. Average laboratory evapotranspiration rates of shrubs and bare peat monoliths under various water table depths (parenthesized quantities are the percentage of evapotranspiration).

Water table (cm)	Shrub evapotranspiration rate (mm day^{-1})	Bare peat evaporation rate (mm day^{-1})	Transpiration rate (mm day^{-1})
-5	1.8	1.6 (89)	0.2 (11)
-10	1.1	0.6 (55)	0.5 (45)
-30	1	0.2 (20)	0.8 (80)
-50	0.5	0.2 (40)	0.3 (60)

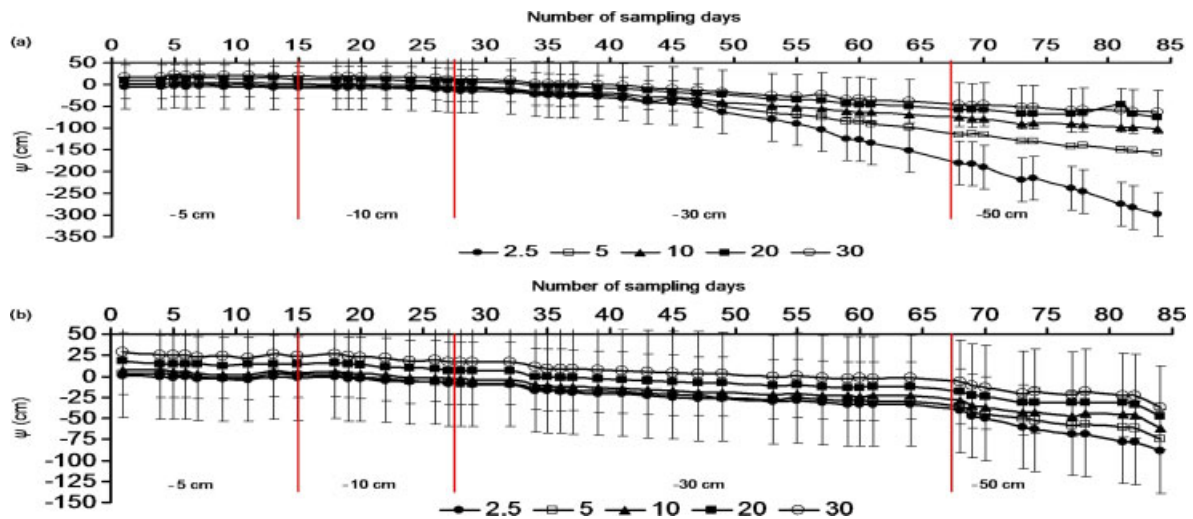


Figure 8. Average daily soil water pressure (ψ) at all tensiometer depths for a) bare peat and b) ericaceous shrubs.

Table IV. Percentage loss in volumetric water content for bare and shrub covered peat at different depths in the peat profile over the study period.

Sampling depth (cm)	Percentage loss of volumetric water content	
	Bare peat	Ericaceous shrubs
2.5	60	41
5	53	39
10	33	40
20	22	30
30	5	11

loss of θ through the profile was higher in bare peat (60 & 53%) than in shrubs (41 & 39%) at 2.5 and 5 cm below the surface, while at greater depths (10, 20, and 30 cm) losses were larger from the shrubs than from bare peat (Table IV).

DISCUSSION

Canopy and litter layer rainfall interception

Interception (I) by shrubs accounted for 62 mm of incoming precipitation during the summer months. The rates were similar to values for non-peatland shrubs observed by N avar and Bryan (1990), Martinez-Meza and Whitford (1996), and Domingo *et al.* (1998). The canopy has an interception capacity of ~ 2 mm (Figure 4a) compared to 1.4 mm recorded for another ericaceae species, *Calluna vulgaris* (Calder *et al.*, 1984). The larger capacity was likely a result of higher leaf area index (LAI) measured in this study, 2.4 (Farrick, 2008) versus 1.8 (Calder *et al.*, 1984).

Raw TF versus gross rainfall data exhibited a 2 mm intercept (suggestive of the interception capacity). However, the slope was 0.73 (R^2 of 0.99) suggesting systematic under-catch from the 2-cm deep v-shaped troughs. This could have been reduced with deeper troughs, and Reigner (1964) and Helvey and Patric (1966) suggested

that the base angle of v-shaped troughs be between 90° and 120° , and sloped at an angle of $>25\%$ to reduce splash-out. Studies for a variety of plant types indicate that the slope of TF versus gross rainfall ratio is typically 1 : 1 (N avar and Bryan, 1990; Llorens *et al.*, 1997; Holwerda *et al.*, 2006), and there is no logical explanation for slopes less than this other than splash-out. Accordingly, we adjusted the slope of the TF versus gross rainfall relationship to 1 : 1 (Figure 4a) and the associated estimates of interception.

Rainfall of similar amount results in different rates of I (Figure 4a) and indicates that rainfall depth was not the only determinant of the amount of rain intercepted. It is likely that the intensity and the duration of rainfall were also important in determining I . Distinct interception classes are observed with changing intensities and rainfall duration (Figure 4b). These trends are similar to those of Llorens *et al.* (1997), who indicated that short events with high intensity, long events with low intensity, and medium events with low intensity produced increasingly higher I rates.

A greater mass/thickness of the litter increases the minimum amount of water retained, C_{\min} (Figure 5a) due to the increase in pore-space and changes in the distribution of flow channels within the litter (Sato *et al.*, 2004). As litter mass and thickness increase, the number of flow channels within the litter increases causing more lateral flow and distribution and retention of water throughout the litter. At higher mass/thickness, the surface area and number of pore spaces are increased providing a greater capacity for water to be held by adhesion and capillary action (Figure 5b).

At a given thickness and mass the C_{\min} is expected to remain constant. However, at increasing rainfall intensities C_{\min} increased (Figure 5b). This is most likely explained by the water travelling through different flow paths within the litter matrix. At greater intensities the water flows through a larger number of pathways within the matrix and is stored over larger area, while at low intensities water flows through a lower number of

pathways and is distributed and stored over a smaller spatial scale.

The study was conducted in a wet year, where the average rainfall was 50 mm higher than the 30-year average (Environment Canada, 2007). However, interception becomes more of a concern during drier or drought years and may have a substantial impact on the water availability during that period. Based on the interception capacity of the canopy and litter, events ≤ 3 mm are completely intercepted. We see that these small events were the most frequent, and thus the interception of small events, which would otherwise have provided potentially critical wetting of mosses, is substantially much more important than what the small magnitude suggests. The larger more intense events over 3 mm are therefore important for increasing or maintaining the water content at the soil surface.

Field and laboratory evapotranspiration

Average daily Et was 2.5 mm day^{-1} over the season, which represents 63% of precipitation. The rates are comparable to those recorded by Van Seters and Price (2001) of 2.4 mm day^{-1} for similar surfaces, although their study found Et from baulks was lower than that from trenches. Baulks are a higher relief element and may experience greater turbulence and higher Q^* than trenches. LAI of shrubs is higher for baulks (2.7) than trenches (1.5) (Farrick, 2008) thus providing a greater transpiring surface. Given the relatively wet conditions of this study, water availability for Et may have been greater. Moreover, the drainage ditches were blocked 6 months prior to this study, raising the water table by 30 cm (Ketcheson, personal communication, May 2008) increasing the overall wetness of the site. Wetland Et is controlled by water table levels and vegetation cover (Lafleur and Roulet, 1992) and it may be safe to assume that if soil water was not a limiting factor, and was coupled with higher turbulence, Q^* and LAI, Et would be higher from the baulks than trenches. Transpiration as a percentage of Et was higher than E (Figure 6), which is typical of this relationship (Liu *et al.*, 2002; Lauenroth and Bradford, 2006; Yopez *et al.*, 2007) and suggests that the upper soil (0–30 cm) water balance is influenced more by plant transpiration than direct soil water loss.

In the lab experiments, Et and E for shrubs and bare peat decreased as the WT was lowered (Table II). These reduced rates were likely caused by a decrease in the supply of water to the evaporating surface via capillary rise, associated with the lower WT. For natural peatlands a distinct decline in the dynamic upward flow of water through capillary rise occurs when WT falls beyond 30 cm from the surface (Romanov, 1968; Schouwenaars, 1993). With low capillary rise, the rate at which water can be supplied to the atmosphere is reduced, lowering E . Although Et and E losses are reduced with lower WT, T and the ratio of T/Et increased until the WT fell below -30 cm (Table III). Increased T at lower WT shows that it becomes the major water loss under falling WT and

the influence of shrubs on water availability becomes more substantial at these lower levels. When capillary rise decreases and water loss from E is reduced, soil water can still be extracted from the root system by T . At WT of -50 cm the ratio of T/Et decreased and it may be a result of the WT occurring beyond the root zone or increased soil water deficit. The former is supported by Lafleur *et al.* (2005) who recorded a reduction in Et when water table fell below the rooting depth (50–60 cm) of shrubs.

The litter layer reduced water loss from evaporation by 18% in the field and 60% in the lab. The greater water loss in the field setting is likely due to a stronger capillary effect in the field litter, which contained more fine materials. The fine litter has small pore spaces and acts as a bridge between the peat and larger litter maintaining capillary flow. However, in the lab the absence of fine litter produces a gap between peat and large litter reducing the capillary effect and subsequent E loss. While 7 mm of water was intercepted by field litter over the season, the litter reduced evaporation by 17 mm, thus more than compensating for the intercepted water. E from litter-covered peat was lower than that from bare peat (Figure 6), analogous to other studies using mulch (Bristow, 1988; Shangning and Unger, 2001) and litter (Murphy and Lodge, 2001; Price and Whitehead, 2004). The laboratory experiments indicate that by day 47, E from the bare peat was lower than that from the litter covered surfaces (Figure 6), since the larger initial water loss from the bare peat left little to sustain longer-term evaporation losses. Comparable trends were observed by Shangning and Unger (2001), who noted that E from bare soil decreased over time, eventually becoming lower than the mulched soil suggesting that mulch is important for short term (8–10 days) water conservation. However, using the E rate to indicate short-term storage can be misleading, as the rates do not specify changes in θ , which is critical for survival of plants. Higher θ under mulched surfaces have been recorded (Bristow, 1988; Price, 1997; Cook *et al.*, 2006) and similarly our results indicate that litter maintains greater θ within the soil. Because of the greater cumulative water loss from bare peat than from litter-covered surfaces θ was significantly ($P < 0.05$) lower under bare peat by day 10.

Soil water flux

The greater cumulative Et water loss from shrub-peat monolith compared to the bare peat monolith (Figure 7) suggests that drying of the soil is greater under shrubs than under bare peat. However, in the upper soil layers θ and ψ were consistently higher for shrub-covered peat than those for bare peat (Figure 8). The presence of a fine litter layer (Farrick, 2008) and lower net radiation under the canopy (McNeil and Waddington, 2003) reduces water loss from the surface of shrub covered peat. The greater daily changes in θ at the 10, 20, and 30 cm depth below the shrub-peat surface (Table IV) indicate that the greatest water loss occurs from these levels. The higher water losses from the lower part of the profile is

likely a result of greater root density and distribution at these depths as water loss under shallow rooted plants are generally related to root length distribution and density (Sharp and Davies, 1985; Coelho and Or, 1999). The root distributions for our samples are unknown. However, Moore *et al.* (2002) recorded maximum root depth and density at 50 and 30 cm, respectively, in a natural bog. Lance (2008) reported maximum root densities between 10 and 15 cm for the Cacouna bog. Under saturated conditions provided at high water table levels the greater density of roots occurring between 10 and 30 cm in the monolith may preferentially be using these depths in the profile. The greater water use from these deeper layers coupled with the effects of the litter layer and canopy, reduced water loss from the surface layer under a falling water table.

CONCLUSION

From June to August 2007, the direct water loss from ericaceous shrubs by interception (77 mm) and transpiration (142 mm) was 219 mm (66% of rainfall). The presence of ericaceous shrubs leave only 115 mm or 34% of the total rainfall available for other soil processes over the summer months. Interception values reported here were a feature of the rainfall regime for the 2007 season and will be different in ensuing years. However, the canopy and litter interception capacity have little seasonal or inter-annual variability and are applicable under changing rainfall regimes. The evapotranspiration rates from the shrub surface, similar to those from the studies of Van Seters and Price (2001), and Lafleur *et al.* (2005) show that evapotranspiration is fairly consistent over 5 years in a natural bog. Because of this consistency, sufficient water must be supplied to the roots to meet the daily transpiration requirements. The lab experiments show that water loss at soil depths between 10 and 30 cm was higher for the shrubs than for bare peat. Therefore, by maintaining the water table within these levels we can supply water to the most active uptake zones, reducing the need of the roots to extract water from the surface.

The main goal of peatland restoration is to return harvested sites to a naturally peat generating ecosystem through the reestablishment of *Sphagnum* mosses (Rocheffort *et al.*, 2003). In the lab experiment with the monolith covered with shrubs we demonstrated that under a falling water table, ψ is held above -100 cm of water, which is thought to be necessary for *Sphagnum* regeneration (Price and Whitehead 2001). The shrubs may provide benefits to the moss by shading (Crum, 1988) and reducing wind speed (Heijmans *et al.*, 2001), lowering surface evaporation and therefore, water losses from the soil surface. As such, the introduction of ericaceous seeds or rhizomes with *Sphagnum* diaspores as a restoration strategy may benefit the moss as it grows.

Furthermore, northern peatlands are expected to become drier under climate change (Roulet *et al.*, 1992), leading to an increase in the cover of vascular plants.

Given the interception and transpiration values recorded, this study can provide valuable insight into the effect an increase in shrub cover would have on the soil water balance and availability of peatlands under a climate change scenario.

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