The Role of Ericaceous Shrubs in the Surface Water Balance and Soil Water Availability of a Cutover Peatland, Québec

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is the true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Peatlands are carbon sinks and occupy approximately 13% of Canada's terrestrial surface of which 0.02% have been harvested for horticultural peat. The extraction of peat from natural peatlands alters the hydrology which affects the growth and survival of *Sphagnum* the primary peat forming vegetation. Ericaceous shrubs do not require specific water content and soil water pressure conditions for their existence and in cutover peatlands they occupy more than 70% of the surface. Rainfall interception, transpiration and root water uptake and redistribution are processes that alter water availability at the soil surface. The high abundance of shrubs at cutover peatlands will influence the surface water balance and more importantly soil water availability and, inevitably determine the success of *Sphagnum* reestablishment at the site. This study seeks to understand the role that ericaceous shrubs play in the surface hydrological balance at a cutover site and how these changes impact *Sphagnum* development.

Rainfall interception, transpiration, litter layer evaporation and soil water flux was investigated in the field and lab. Approximately 334 mm of rainfall was measured over the season. The shrub canopy and litter had a maximum storage capacity of 4 and 1.2 mm respectively and intercepted ca. 36.7% (120 mm) of rainfall over the season. The effects of rainfall intensity and duration were more important than gross rainfall in determining the amount of water intercepted by the canopy, while the thickness and mass of the litter layer largely determined the storage capacity. Evapotranspiration from shrubs averaged 2.5 mm day^{-1} with a total of 211 mm over the season. Transpiration was 68% (142 mm) of total evapotranspiration losses, and represented the greatest water loss from the shrub canopy. From these analyses only 22% (72 mm) of rainfall is available for other soil processes and moss development. The evaporation under a litter cover is lower than bare peat and in the field represents water storage of 17 mm over the season. Reduced water input by litter interception is offset by the increased water storage under the litter.

Laboratory analyses of soil water flux under ericaceous shrubs show that water loss under the shrubs was greater than bare peat. Water use under the shrubs was highest between -10 and -30 cm and was ca. 2 times greater than bare peat at the same levels. Volumetric water content (θ) decreased throughout the day and water use by shrubs during the day was twice that at night. The shrubs also maintained θ and soil water pressure (ψ) above the threshold values of 50% and -100 cm, respectively, needed for *Sphagnum* survival.

Based on these analyses the shrubs will be beneficial to *Sphagnum* reestablishment and survival once the primary water losses have been compensated. I recommend raising the water table above -20 cm. In peatland restoration activities, at this level, water used between -10 and -30 cm can quickly be recharged and surface moisture maintained above threshold by capillary rise helping to offset water loss by interception and transpiration through capillary rise.

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Preface

Following the introduction, literature review and site description, chapters 4 and 5 are written in manuscript form ready for submission to journals for publication. Figures and tables not included in the chapters, as a means of conciseness, are presented in the Appendices.

1.0 Introduction

Peatlands comprise 50% of the world's wetlands, and contribute greatly to biodiversity by regulating hydrological functions (Joosten and Clarke 2002). Peatlands are CO_2 sinks, hosting one third of global soil carbon (Joosten and Clarke 2002), and it is known that hydrology plays an important role in the carbon budget (Moore *et al*. 1998). Canadian peatlands cover about 13% of the land surface (Tarnocai *et al*. 2005), of which approximately 0.02% has been used for horticultural peat (Keys 1992). Peat extraction techniques involve the removal of the acrotelm, altering the hydrological processes of the peatland (Price *et al*. 2003). Changes in hydrology after harvesting create unsuitable conditions for the regeneration of *Sphagnum*, the primary peat building vegetation. Although many peatlands have undergone natural vegetation succession, this has been limited to the reestablishment of naturally occurring vascular plants, with *Sphagnum* typically not regenerating well (Rochefort 2000). Removal of the upper layers by harvesting exposes the highly decomposed peat characterized by higher bulk densities and water retention capacities and lower specific yield and hydraulic conductivities than the upper layers (Price *et al* 2003). These properties occur primarily as a result the smaller pore size distribution of the decomposed peat. Drainage and subsequent lowering of the water table further disturbs the natural hydrological functions of the peatland. Subsidence, which causes shrinkage above and compression below the water table, further exacerbates the changes in soil physical properties and overall soil hydrology, as bulk density increases and hydraulic conductivity and specific yield decreases (Price 2003; Kennedy and Price 2005). With reduced vertical and horizontal movement, deeper water table and higher water retention, harvested sites can no longer supply the necessary water to meet evaporative demands. As a result, soil water pressure drops below -100 cm, which inhibits *Sphagnum* development (Price and Whitehead 2001).

Ericaceous shrubs such as *Chamaedaphne calyculata, Kalmia angustifolia*, and *Ledum groenlandicum* are the dominant vascular plants found at cutover peatlands, representing more than 70% of the total surface cover in trenches and baulks of the manually block-cut peatlands in Quebec (Girard *et al*. 2002; Poulin *et al*. 2005). Vascular plants alter hydrological processes by influencing the water balance and overall water availability in an ecosystem. They reduce the amount of precipitation that reaches the soil surface through interception by the leaves, stems and litter (Crockford and Richardson 2000), and may increase water loss through transpiration (Takagi and Tsuboya 1999). The water balance equation for bogs can be represented by;

$$P = Et + R + \Delta S + \varepsilon \qquad \text{Equation 1.1}$$

where P, is precipitation, Et, is evapotranspiration, R, runoff, ΔS, is change in storage and ε is the residual term. In cutover peatlands, evapotranspiration is the major source of water output in the post-snowmelt summer period, accounting for 92% of total water loss (Van Seters and Price 2001). The inclusion of interception in the general water balance equation is important as shrubs may intercept as much as 33% of precipitation (Martinez-Meza and Whitford 1996). The water balance of cutover peatlands should include rainfall interception of the ericaceous shrubs, due to their abundance on these sites. The previous equation can be modified by including precipitation interception (I) and may be represented as

$$P - I = Et + R + \Delta S + \varepsilon \qquad \text{Equation 1.2}$$

Plants alter the microclimate by reducing soil temperature and the amount of solar radiation reaching the soil surface. Though plants are directly responsible for water loss through transpiration, they have the potential to reduce evaporation (water loss) from the soil surface, as less heat and energy, necessary for evaporation, is available at the soil surface (Breshears *et al* 1998). The litter layer may play an important role by increasing soil water storage by reducing evaporation from the soil (Murphy and Lodge 2001). In cutover peatlands, with ericaceous shrubs covering 70 – 90% of the land surface, it is important that we understand how ericaceous shrubs affect the water balance and water availability, as the availability and volume of soil water are key in the reestablishment and growth of *Sphagnum* (Price and Whitehead 2001; McNeil and Waddington 2003). The hypothesis for this thesis is: ericaceous shrubs reduce the amount of rainfall available in the soil at the end of the summer through interception and transpiration losses. Therefore, the specific objectives of this study are to 1. Quantify the rainfall interception by the shrub canopy; 2. Quantify the evapotranspiration rates of ericaceous shrubs versus bare peat; 3. Quantify the water storage capacity of leaf litter, including its rainfall interception capacity, as well as understand how it impedes water flow to the soil surface; and 4. Determine how ericaceous shrubs redistribute soil water during diurnal transpiration fluxes.

2.0 Literature Review

2.1 Hydraulic properties of harvested peatland

Natural bogs are characterised by a two layer soil structure (Ivanov 1981) composed of an upper layer, or acrotelm and a lower layer, or catotelm. The acrotelm consists of living, dead and partially decomposed mosses usually 0 – 50 cm thick, characterised by higher hydraulic conductivity (*K*) and larger pore sizes which decrease greatly with increasing depth. The catotelm consists of relatively decomposed peat, which has lower *K* as a result of smaller pore sizes (Ingram 1978). Peat extraction techniques involve the removal of the acrotelm, exposing the catotelm and altering the hydrological processes of the peatland (Price *et al*. 2003). Before harvesting, a network of drainage ditches is typically established, allowing water to be drained from the peatland, resulting in a lower water table. Surface subsidence (an inadvertent effect of drainage) occurs as a result of shrinkage and oxidation of peat above the water table and compression below the water table (Schothorst 1977). Bulk density in cutover peat is higher than at undisturbed sites and values of 0.11 g cm^{-3}, 0.06 g cm^{-3}, 0.13 g cm^{-3} versus 0.04 g cm^{-3}, 0.05 g cm^{-3}, 0.07 g cm^{-3} have been recorded for harvested and natural peatlands respectively (Price 1996; 1997; Van Seters and Price 2002). Specific yield (Sy) is the ratio of the volume of water yielded by gravity drainage to the volume of the block of soil and is high in the acrotelm where there are many large pore spaces. Harvested peatlands have a low Sy due to their small pore size. Price (1996) found values ranging from 0.55 near the surface to about 0.25 at 0.3 m in the undisturbed peat, while harvested peat has very low Sy, displaying little variability with depth, ranging between 0.04 and 0.06. Van Seters and Price (2002) demonstrated a Sy of 0.14 and 0.06 on undisturbed and bare peat respectively. The decrease in Sy results in enhanced water table fluctuations due to loss in storativity (Van Seters and Price 2001; 2002). Price (1996) recorded water tables of –5 cm and –44 cm in the natural and cutover bog respectively, while Price (1997) recorded levels of –62 cm and –107 cm by late August in undisturbed and drained sites respectively. *K* of harvested peatlands is lower than undisturbed areas. Van Seters and Price (2002) observed values of 4.1×10^{-5} and 1.3×10^{-5} cm s^{-1} at undisturbed and abandoned sites, respectively. Changes in the volume of peat has significant affects on *K*. Price (2003) noted that for a 1% volume change, a decrease in *K* by two orders of magnitude occurred. The low *K* values are a result of smaller pore sizes and higher bulk density, where due to subsidence and compression, the larger pores collapse, reducing connectivity, limiting flow (vertical and lateral) to smaller pores.

Sphagnum does not have a vascular system and obtains water through capillary flow from below the peat surface. However, at harvested sites, the low upward movement of water is insufficient to replace the surface water loss through evapotranspiration (Price 2003). Although the small pore size distribution increases the water retention capacity of the soil, it makes the removal of water from these pores more difficult (Price 2003). As the growing season progresses, the water table levels lower and the peat surface becomes increasingly dry. When water table levels fall below -30 cm the soil water pressures drops below -100 cm. However, a pressure above -100 cm is needed to ensure the survival of *Sphagnum*, as water is drained from hyaline cells within the moss at pressures greater than this (Price and Whitehead 2001). It is these changes in the hydraulic properties of cutover peatlands that create harsh conditions, which make the reestablishment of *Sphagnum* more difficult. *Sphagnum* alters its environment, reducing pH and nutrient availability and increasing the overall “wetness” (van Breeman 1995). These changes limit the establishment and abundance of vascular plants (van Breeman 1995). Without the establishment of *Sphagnum*, vascular plants are able to grow without competition from the moss. In many cutover sites a natural seed bank for the ericaceous shrubs was unintentionally retained at the site during harvesting, acting as a source for future shrub populations. Unlike *Sphagnum*, the vascular system of shrubs can actively extract water from the soil and prevent water loss through closure of their stomata, which provides an advantage for their re-colonization compared to *Sphagnum*.

2.2 Ericaceous shrubs and hydrology

2.2.1. Shrub anatomy and water movement

Ericaceous shrubs can be considered as having two components: 1. above-ground biomass including leaves, stems, litter and 2. below-ground, including roots. Here we consider how each component may contribute to various hydrological processes occurring on in the peatland (Fig 1).

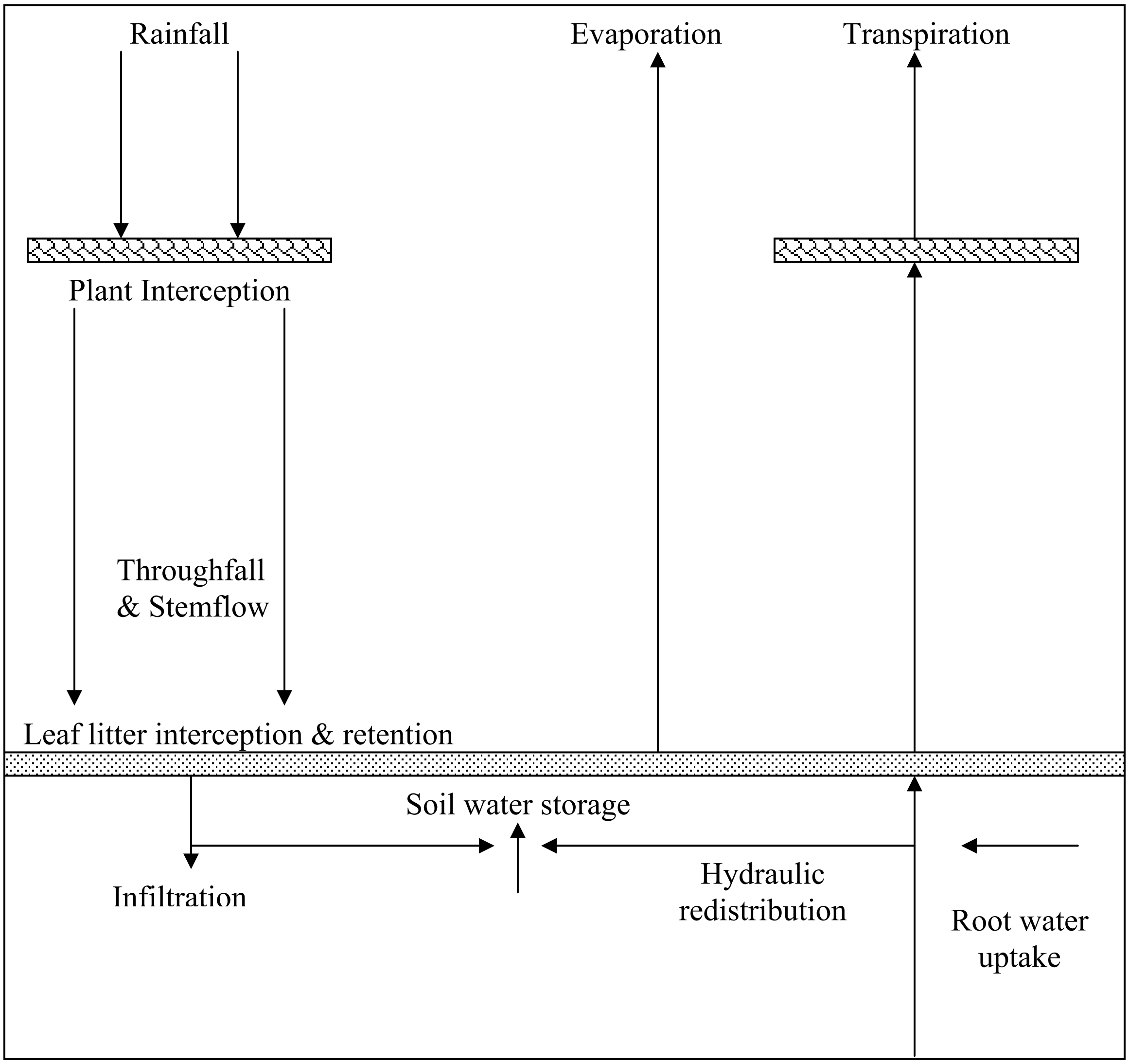


Figure 2. 1. Conceptual diagram of water balance as influenced by plant communities

2.2.2. Leaves and stems

Leaves and stems of vascular plants have a role in hydrology through their effect on precipitation, microclimate and evapotranspiration. Precipitation, which is the primary input in bogs, can be partitioned into three processes (Crockford and Richardson 2000);

a. Interception; is that which remains on the plant and is evaporated during and after rainfall.
b. Stemflow; is that which flow to the ground via stems or trunks.
c. Throughfall; is that which may not contact the canopy and which falls to the ground between the various components of the vegetation.

The mass balance of partitioning of rainfall is generally expressed;

$$I = P - TF - SF \qquad \text{Equation 2.}$$

where I, is interception, P, is gross precipitation, TF, is throughfall and SF, is stemflow. Interception studies have been demonstrated in variety of ecosystems and plants, and it is generally affected by the plant species, intensity and duration of the precipitation, air temperature and humidity, wind speed and direction (Crockford and Richardson 2000) and the leaf area index and density of the plant community (Gómez *et al*. 2001). For three shrub species Návar and Bryan (1990) recorded total interception as 27% of precipitation, with throughfall and stemflow accounting for 69.7% and 3.1% of the total rainfall, respectively. They noted that interception was more variable for small rainfall events, which is due to differences in climatic conditions before the start of the event. Martinez-Meza and Whitford (1996) observed rainfall interception of 33% for three species of Chihuahuan shrubs. Throughfall was 58% of precipitation, while stemflow represented 8.3% of rainfall. Domingo *et al*. (1998) recorded 40% interception with throughfall and stemflow being 40 and 20 % of gross precipitation for *A. cytisoides*, while for *R. sphaerocarpa* 72% of gross rainfall was throughfall, 7% stemflow and 21% interception loss. They also showed a linear relationship with rainfall volume for both species. These studies indicate that throughfall was more important than stemflow which was typically <10%. Studies of shrub rainfall interception in peatlands are limited to only one study (Päivänen 1966). He measured interception for rainfall events of different magnitudes and recorded values of 46, 28, 13, 7% for 1mm, 5mm, 10mm and 15mm events, respectively. Shrubs have also demonstrated the ability to channel water along the stems via stemflow and root channels into the soil. Martinez-Meza and Whitford (1996) recorded root water channelization depths of up to 37 cm below the soil surface, with most of the dye indicating water movement found along the main roots of the shrubs. Root water channelization may benefit the plant by allowing it to store water deeper within the soil profile, which can be accessed during drier periods. If such a process occurs with ericaceous shrubs in cutover peatlands, it may be beneficial to the regeneration of *Sphagnum* as there would be more available water during dry cycles that the moss can use for its growth and maintenance.

Plants alter the microclimate, including soil temperature, moisture and evaporation. Naot and Mahrer (1991) measured temperature profiles in a cotton field and recorded decreasing temperature from above the canopy (39°C) to the soil surface (29°C). Breshears *et al* (1997) recorded near ground solar radiation values under shrub canopies that were 40% less than that of open spaces within the canopy. However, their study also suggests that precipitation interception and not radiation (evapotranspiration effects) as the major factor affecting soil moisture among canopy and inter-canopy patches. Breshears *et al* (1998) recorded lower soil temperatures (max 27.2°C) under plant canopies than inter-canopy patches (max 38.5°C) for April - September. The most noticeable difference occurred from 12:00 to 8:00 pm. The evaporation rate of soil under the canopy was lower than the inter-canopy patches, indicating that the higher temperatures in the patches were responsible for more water loss.

The major water losses attributed to plants are as a result of transpiration losses. Water movement in plants follow a water potential gradient from the soil to the atmosphere. Soil water enters the root system because of lower water potential (osmotic potential), and moves along the xylem up to the leaves where it is evaporated and released to the air through stomata. The rate of wetland evapotranspiration for a given energy supply is controlled by water table levels and vegetation cover (Lafleur and Roulet 1992). Shrubs may increase the evapotranspiration of peatlands. Romanov (1968) noted that evapotranspiration rates were reduced when the water table dropped 15 – 20 cm below the surface, which is the limit of the root structure of vascular plants, while Lafleur *et al.* (2005) similar trends as the water table dropped below the root system. Takagi and Tsuboya (1999) reported a higher evapotranspiration rate with an increase in vascular plant abundance in a peatland. Evapotranspiration from the vascular site was 4.6 mm day^{-1} compared to 4.2 mm day^{-1} at the moss site. Heijmans *et al.* (2001) measured evapotranspiration rates for *Sphagnum* and vascular plants in field and laboratory experiments. They recorded lower evapotranspiration rates for vascular plants in the outdoor experiments, while evapotranspiration rates for laboratory experiments increased with an increase in vascular plant biomass. They also recorded lower evapotranspiration rates for vascular plant monocultures (≈ 0.7 mm day^{-1}), versus *Sphagnum* monocultures (≈ 2.0 mm day^{-1}) and a vascular plant/ *Sphagnum* mix (1.9 mm day^{-1}). This indicates that *Sphagnum* may be responsible for most of the evapotranspiration rates in bogs. They also suggest that lower evapotranspiration rates under the vascular plants are a result of reducing temperature and wind speed over the moss surface, however, with an increase in biomass these effects are negated by transpiration losses. Contrary to this, Price (1991) recorded low evapotranspiration rates of 1.7 mm day^{-1} over a *Sphagnum* dominated blanket bog, which is considered low for this type of wetland (Price personal communication 2008), and suggests that *Sphagnum* transpires at very low rates. In cutover peatlands little is known about the actual transpiration from shrubs, and this study quantifies values of ericaceous shrub transpiration.

2.2.3. Mulches and Leaf Litter

Mulches are an artificial barrier placed on the soil surface to ameliorate moisture and temperature of the soil, and in this respect are similar to naturally occurring leaf litter. Mulches are commonly used in agriculture, being important to the survival of drought-intolerant crops, by reducing soil water loss. Mulches have been shown to increase soil water content and reduce evapotranspiration rates when applied to bare soils. Bristow (1988) recorded lower volumetric water content (θ) under bare soil (16.6%) than under a horizontal mulch (21.5%), while Cook *et al*. (2006) recorded water content being 0.10 m^{3} m^{-3} more than the bare soil. Shangning and Unger (2001) recorded greater water accumulation rates under mulch cover than bare soil. They manipulated the potential evapotranspiration (PET) rates and application rates of water used in the treatments and noted that under the highest PET rate and lowest water application that no water accumulated in bare soils, however, a 3-6% accumulation rate occurred in soils with 4.0 Mg ha^{-1} of mulch. Shangning and Unger (2001) also suggest that the importance of mulches in water conservation may be more important for small precipitation events, as greater difference in water accumulation occurred under small water inputs. Evaporation under mulches is generally lower than for bare soils. Shangning and Unger (2001) recorded lower overall evaporation rates under mulched soil. However, they noted that though the initial evaporation rate of bare soil was higher than the mulch, the rate decreased over time, eventually becoming lower than the mulched soil, thus suggesting that mulch is important for short term (8 – 10 days) water conservation. In peatlands mulching is common practice in restoring harvested sites. A study on the effect of mulch on soil water in cutover peatlands (Price 1997), indicated that under mulch θ was maintained above 30% compared to bare surface, and that soil water tension remained above -100 cm, 97% of time. Price *et al.* (1998) recorded evaporation rates for mulch that were 2.6 mm day^{-1} versus 3.1 mm day^{-1} for bare cutover peat surface. It is important to understand processes that lead to increased water storage under mulches. The energy balance over bare soil is altered by the presence of mulch. Hares and Novak (1992 b) recorded higher Net radiation (Q^*) values for bare (1.8 MJm^{-2}) versus mulched (1.4 MJm^{-2}) soils, while Price *et al.* (1998) recorded lower Q^* (1.66×10^{-3} MJm^{-2} and 1.44×10^{-3} MJm^{-2}) and soil heat flux (2.16×10^{-4} MJm^{-2} and 2.88×10^{-6} MJm^{-2}) values for bare and mulched peat surfaces respectively. Bristow (1988) studied the energy flux of bare and mulched soil under wet and dry conditions. He recorded higher initial Q^* values under bare soil (14.5 MJm^{-2}) than mulched soil (12 MJm^{-2}). However, this trend reversed with the onset of drying, which is due to changes in the proportion of shortwave radiation reflected by the bare soil. Under wet conditions the net radiation of both bare and mulched soil increased, with radiation being higher over the bare soil. Soil heat flux for both bare and mulched soil was ca. 90 Wm^{-2} under wet conditions. However, under dry conditions the heat flux for bare soil increased to ca. 150 Wm^{-2} while the mulched soil only increased to 100 Wm^{-2}. Soil temperature under mulched soil is generally lower, during the day, and warmer at night than bare soil. Under mulched soil, temperature at the surface, 2.5 cm, and 10 cm under the surface was 14, 8 and 0.6 °C cooler than bare soil (Bristow 1988). However, under wet conditions the temperature of bare soil was similar to that under the mulch, but with drying, temperature of bare soil showed a greater diurnal increase than the mulched soil. Though mulches decrease water loss through the storage of soil water and reduction of evaporative losses, they cause interception which may decrease the volume of water reaching the soil surface. Cook *et al*. (2006) recorded a 10% loss in precipitation by mulch interception, while Price *et al*. (1998) demonstrated that straw mulch intercepted 44% of total precipitation. However, they suggest that the effects of interception are cancelled due to energy used to evaporate water from the mulch instead of the soil.

Research on the role of leaf litter on water and energy balance of soils is quite limited when compared to mulches. Litter can be placed into two categories (i) an upper layer of moderately undecomposed matter and (ii) a lower layer of mainly decomposed and fractured material (Sato *et al*. 2004). Leaf litter has the capacity to store water from rainfall events. Sato *et al*. (2004) recorded maximum storage capacities of 1.6 mm and 1.5 mm per unit litter mass (1 kg/m^2) for *C. japonica* and *L. edulis* respectively, while Putuhena and Cordery (1996) measured an interception capacity of 2.8 mm and 1.7 mm for pine and eucalypt litter respectively. The maximum storage capacity of litter is directly proportional to the litter mass. Murphy and Lodge (2001) demonstrated that under dry conditions leaf litter had higher evaporation rate (2.1 mm day^{-1}) than bare soil (1.1 mm day^{-1}) when the soil was dry. However, when the soil was wet evaporation from litter (2.3 mm day^{-1}) was less than bare soil (3.5 mm day^{-1}). Their study also indicated that litter increased the surface albedo for both wet and dry conditions. Ginter *et al*. (1975) recorded lower evapotranspiration rates for a pine needle covered monolith than bare soil. The response of litter covered soil was slower as it absorbed light rain and retarded soil water evapotranspiration. The processes responsible for the increased storage and reduced evaporation may generally may the same as for mulches. To my knowledge, nothing is known about the litter dynamics, including depth and mass, and how it affects the water balance on abandoned harvested peatlands. This study would provide a first in depth look at how the litter layer alters the peatland hydrology (Fig 2)

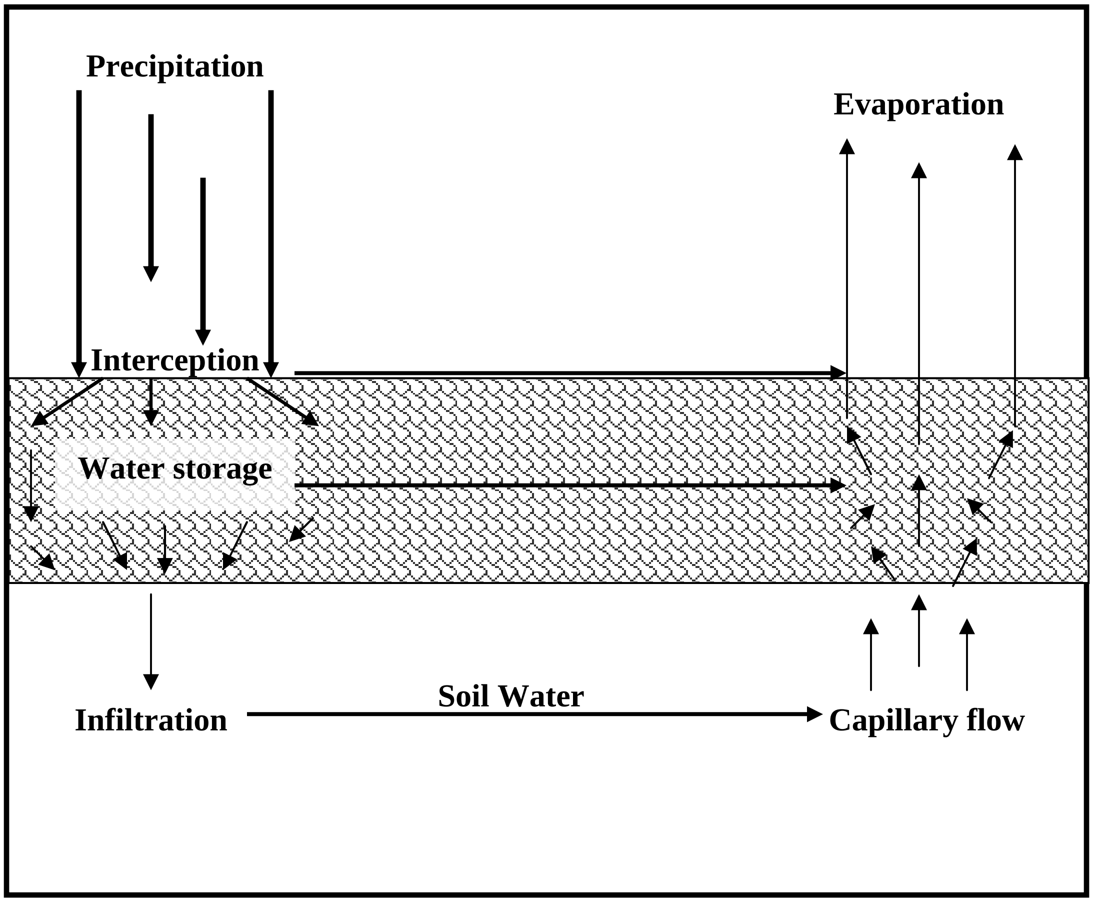


Figure 2. 2 Conceptual model of the influence of the litter layer in the water balance

2.2.4. Roots

To meet daily transpiration requirements, plants must remove water from soil (upper and lower). Water moves from soil to roots along a water potential gradient. Water initially enters the root system from the soil along a potential (osmotic) gradient. As water is lost from the leaves during transpiration, a water potential deficit is created as it becomes increasingly negative. To meet these demands water enters the roots (low or more negative water potential) from the soil (high or more positive water potential) along a water potential gradient. However, water absorption by the roots also lowers the soil water potential (Ψ_s). Hydraulic lift is the process of water movement from relatively moist to dry soil layers using plant root systems as a conduit (Caldwell *et al* 1998). The main premise behind hydraulic lift is the reverse flow of water from the roots into the soil, which occurs once the xylem water potential in the roots is greater than that of the soil. This takes place once transpiration is reduced and the deeper roots maintain contact with moist soil. Hydraulic lift has been well demonstrated among a variety of trees and shrubs. Richards and Caldwell (1987) observed diurnal fluctuations in Ψ_s during the summer, while Dawson (1993) recorded similar diurnal Ψ_s fluctuations (0.66 – 0.82). These fluctuations ceased after heavy rains, which increased θ. Wan *et al*. (1993) conducted field studies of hydraulic lift on shallow rooted species and noticed a decrease in θ between 7:00 am and 8:00 pm indicating water uptake by the plants due to transpiration. They covered the shrubs between 9:00 am and 12:00 pm, preventing photosynthesis and transpiration, which resulted in an increase in θ by 7.7 – 14.7%. Topp *et al* (1996) demonstrated diurnal fluctuations in θ using Time Domain Reflectometry (TDR). They noted that the highest water content values occurred at night, and were >0.01 $m^3 m^{-3}$ higher than the maximum daily value. Hydraulic lift may also be important as a source of water for neighboring plants. Caldwell and Richards (1989) found deuterated-water from the deep roots of *Artemisia* in the stems of neighboring plants. In natural peatlands water movements have been described by Yazaki *et al*. (2006). They recorded relatively constant θ values of 0.15 and 0.20 $m^3 m^{-3}$ over the sampling season at 0.05 and 0.15 m below the hummock surface, respectively. This occurs despite consistently lowering water table depths. This upward water movement and storage has been attributed to the capillary water-transport capacity of *Sphagnum*. However, this movement has never been linked to hydraulic lift caused by shrubs. In peatlands, little work has been done on the distribution and depth of ericaceous shrubs roots. Moore *et al.* (2002) recorded a maximum shrub rooting depth of up to 60 and 40 cm for hummocks and hollows respectively. Coarse roots accounted for 86 and 70% of the biomass for hummocks and hollows respectively. Based on hydraulic lift theory, once the water table remains just above the lowest root depth, water may be distributed to the upper peat and moss layers when transpiration stops. In cutover sites the rooting depth has not to my knowledge been recorded and therefore is a gap to be filled by research.

2.3 Restoration conditions and the effect of shrubs on restoration

Restoration of *Sphagnum* on harvested sites is important as they are the primary peat forming vegetation. They generally cover less than 10% of harvested sites in harvested peatlands in Quebec (Rochefort 2000). To return some of the ecological and carbon sink functions to these sites, the hydrological conditions must be modified. Methods including amending microtopography (Price *et al*. 1998), mulching (Quinty and Rochefort 1997; Rochefort *et al*. 1997) and the use of companion species (Ferland and Rochefort 1997) have all been used as restoration techniques. Hydrologically, soil water pressure above -100cm and θ above 50% are required for recolonisation and re-establishment of *Sphagnum* (Price and Whitehead 2001). McNeil and Waddington (2003) established that under wetter conditions in peat, 5.6-8.2% (*θ*), the gross ecosystem production and net ecosystem CO_2 exchange of *Sphagnum* was greater than in drier sites, 1.7-2.4% (θ). This indicated the importance of wet conditions to the growth and productivity of *Sphagnum*. The typical approach towards active restoration of peatlands (bogs) in North America involves the use of *Sphagnum* diaspores (fragments). There are typically four steps involves in restoration (Rochefort *et al*. 2003). 1. Site preparation; involves microtopography changes and providing a sufficient supply of water to maintain the necessary hydrological conditions needed for moss growth and establishment, 2. Collection of diaspores from natural peatlands, 3. Spreading of diaspores on the peat surface and 4. Protection of the diaspores and fertilization. A straw mulch is placed over the diaspores, which protects them and enhances growth by increasing water availability and reducing temperature. This approach is suitable for sites where active restoration is taking place. However, at sites such as the Cacouna bog, which was left to regenerate naturally, the establishment *Sphagnum* by spores may be more common. Sundberg and Rydin (2002) looked at the establishment of *Sphagnum* spores over bare peat and various litter surfaces. Their data proved that spores can be important in the reestablishment of *Sphagnum* in harvested sites, and under mulches, which provide a consistent phosphate supply while decomposing, which can enhance growth of spores. As discussed earlier, the litter layer may reduce water loss from the peat surface of harvested bogs by lowering evaporation rates. However, the litter layer may act as a barrier, cutting off or reducing capillary flow to the peat surface. In harvested sites where a litter layer has been established before *Sphagnum*, the spread of air borne spores and fragments at the peatland may be limited to the surface of the litter (Price and Whitehead 2004). With the litter acting as barrier to capillary rise, recolonisation by *Sphagnum* may be impossible except for areas that are frequently inundated with water (Price and Whitehead 2004). Shrubs have successfully been used as nurse plants, increasing the θ and survival of tree seedlings when compared to bare soil (Castro *et al* 2002). In harvested peatlands shrubs have shown potential as nurse plants, increasing the percent cover of growing adjacent *Sphagnum* diaspores (Ferland and Rochefort 1997). In harvested peatlands, the shading of moss by shrubs allows sufficient energy the reach the surface for proper growth of the *Sphagnum* and, coupled with a cooling effect, enhances the growth of the moss (McNeil and Waddington 2003).

3.0 Site description

The Cacouna peatland (47°53' N, 69°27' W) is located approximately 10 km north-east of Rivière-du-Loup, Québec. 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 962.9 mm, 28% which fell as snow. Mean annual temperature (1971-2000) was 3.2°C, with mean maximum temperatures in January and July of -8.5 and 22.9°C respectively (Environment Canada 2007). The peatland has been disturbed several times in the past 200 years including the construction of roads, development of agricultural fields and the building of a railway in the 1800s. The railway was built over a natural groundwater divide, greatly compressing the peat creating a flow divide that separated the bogs into two hydrologically distinguishable halves. Harvesting of the bog began in 1942 with the installation of primary and secondary drainage ditches, and continued until 1975 using traditional block-cut methods. This method involved cutting the peat by hand from trenches approximately 10 m wide and ca. 200 m long. Peat blocks were piled on uncut mounds or baulks (ridges approximately 1 m high and 6 m wide) separating adjacent trenches, while the remaining vegetation (skag) was placed in the centre of the trench. Over time the skag settled and decomposed, becoming rounded, and acted as a seedbank for vegetation reestablishment. Following the introduction of vacuum machines the block cut method was quickly abandoned and the northwestern half (16 ha) of the peatland was harvested using vacuum machines between 1983 and 1989 (Girard *et al*. 2002). The site was completely abandoned in 1989. The Cacouna bog currently consists of 511 trenches, 445 baulks and 16 vacuum fields (Girard *et al*. 2002). In October of 2006, the primary drainage ditches were blocked while of forest was cut, in an effort to rewet the bog.

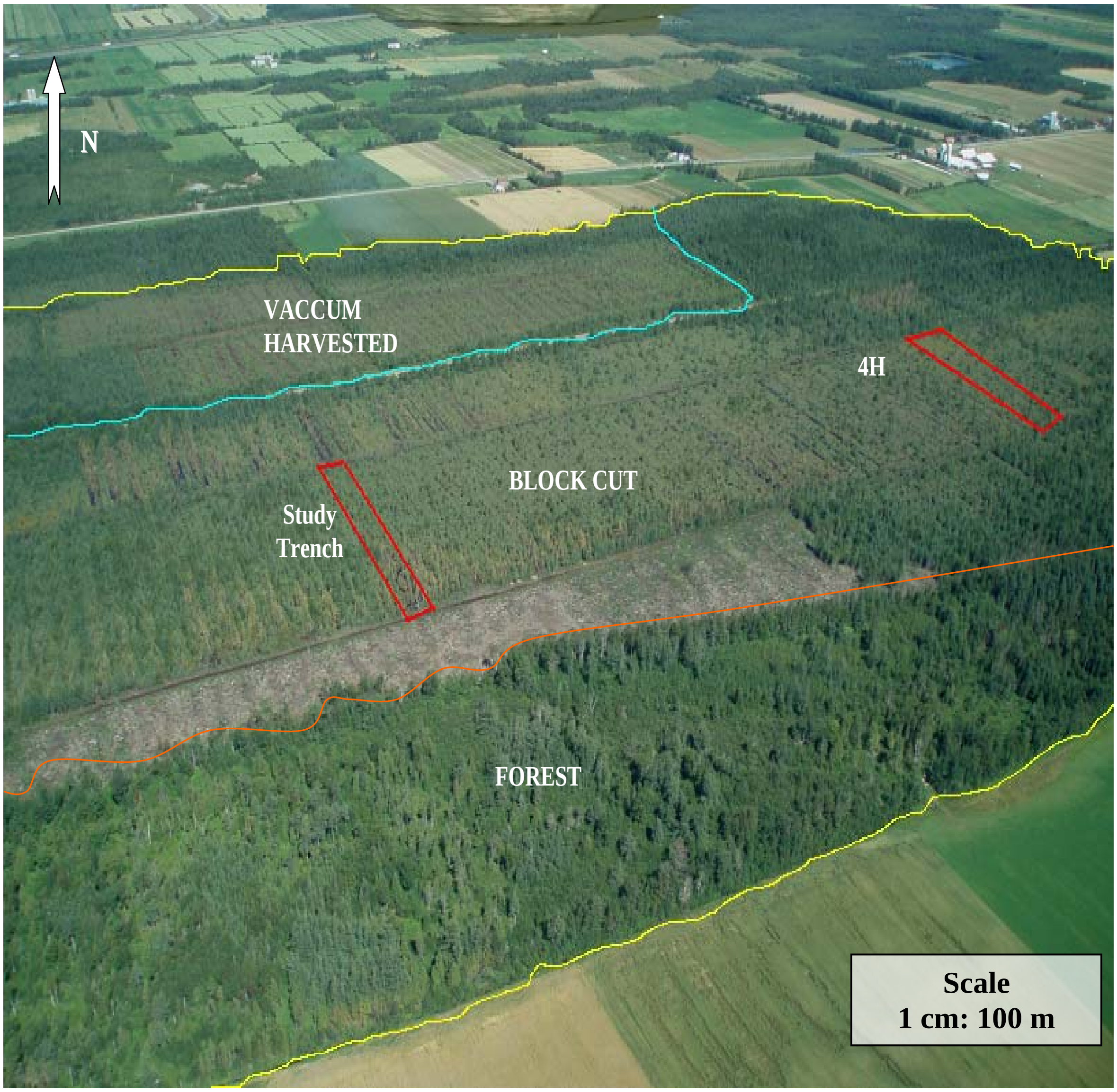


Figure 3. 1. Aerial view of the Cacouna peatland showing the study areas (red boxes)

Following abandonment, the Cacouna bog has undergone a natural vegetation succession. Plants typical of peatlands in that region have recolonized most of the bare peat surface. Ericaceous shrubs, such as *Chamaedaphne calyculata, Kalmia angustifolia*, and *Ledum* *groenlandicum* are the dominant plant species covering ca. 79-90% of the surface (Girard *et al*. 2002). Trees including, tamarack (*Larix laricina*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), grey birch (*Betula populifolia*) and white birch (*Betula papyrifera*) are especially dominant 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).

Throughfall collectors, lysimeters and micrometeorological (continuously recording) equipment were set up along the study trench and 4H areas (Fig 3.2). These areas were selected as they have previously been used to collect meteorological data and conduct research in earlier years (Van Seters; Whitehead 1999) and from May to August 2005 – 2006. The study trench area is characterised by two trenches bordered by three baulks and the surface is covered primarily by ericaceous shrubs. The study trench housed 7 throughfall collectors and 21 lysimeters placed at randomly selected locations along the trenches and baulks. The 4H area is characterised by a relatively flat topography since the baulks were harvested prior to abandonment, and covered primarily by *Sphagnum* and a low density layer of ericaceous shrubs. Nine throughfall collectors were randomly set up and were used to understand the spatial differences in interception across the site.

In October, 2007, six monoliths (706 cm^2 x 32 cm) were collected from the study trench area. Two shrub- and one bare peat- samples (no shrubs present) were obtained from randomly selected locations along a baulk (raised area) and then repeated for a trench (more deeply cut area between baulks). These monoliths were used in the laboratory to run a series of experiments testing the water uptake by shrubs (see Chapter 5).

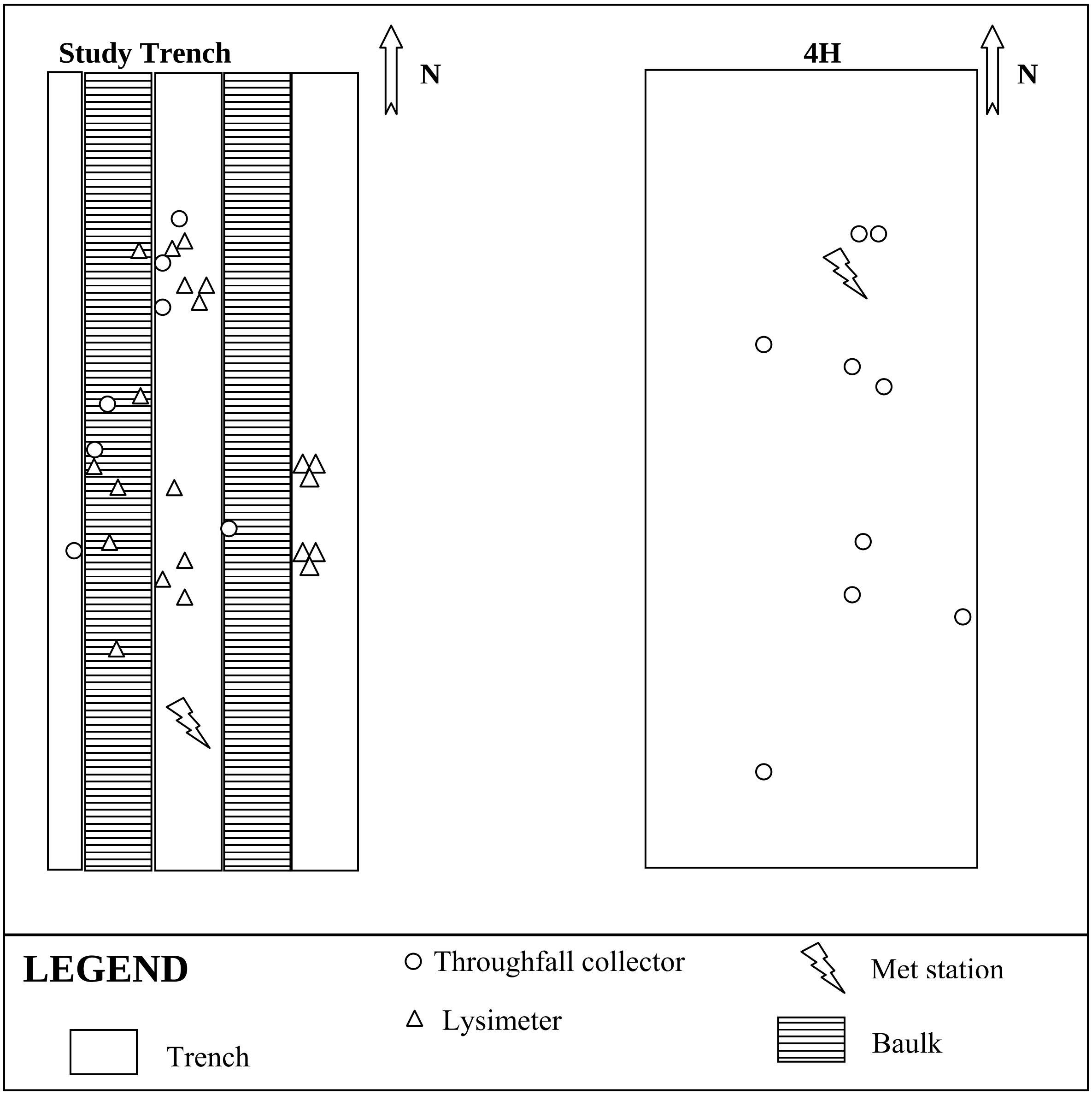


Figure 3. 2. Instrument locations along the main study areas

4.0 Interception and Evapotranspiration: The effects of Ericaceous Shrubs on the surface water availability of a Cutover Peatland

4.1 Introduction

Approximately 13% of the Canadian land surface is covered by peatlands (Tarnocai *et al*. 2005), of which 0.02% has been used for horticultural peat extraction (Keys 1992). Peat extraction techniques involve the removal of the acrotelm, altering the hydrological conditions of the peatland (Price *et al*. 2003). Changes in hydrology after harvesting, creates unsuitable conditions for the regeneration of *Sphagnum*, the primary peat building vegetation, while ericaceous shrubs have become the dominant plants found at cutover peatlands, representing more than 70% of the total surface cover of the manually block-cut peatlands in Québec (Girard *et al*. 2002; Poulin *et al*. 2005). The high abundance of shrubs produce a litter layer found below the canopy at the surface of cutover peatlands. The canopy and litter layer may directly influence the water balance through interception (***I***) (Crockford and Richardson 2000; Sato *et al*. 2004), transpiration (***T***) (Dingman 2002) and changes in soil evaporation (***E***) (Murphy and Lodge, 2001). Currently the role ericaceous shrubs and their litter play in the water balance of cutover peatlands is not understood. More importantly the shrubs may influence the hydrologic conditions important for the regeneration of *Sphagnum*. This study aims to understand how ericaceous plants affect the moisture dynamics at the soil surface of cutover peatlands.

Interception by vegetation canopies has been well described for a number of trees and forested ecosystems (Crockford and Richardson 2000) but is limited for smaller plants such as shrubs and grasses. *I* has been well documented for desert shrub species. 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 a single species. These studies indicate that throughfall was more important than stemflow, which was < 10% of gross rainfall. *I* by shrubs in peatlands is limited to one study by Päivänen (1966), who found *I* was 46, 28, 13 and 7% for rainfall events of 1mm, 5mm, 10mm and 15mm, respectively. Litter has also been shown to intercept between 0.3 and 6.7 % of incoming rain (Sato *et al*. 2004) and has a water storage capacity between 1.5 and 2.8 mm kg^{-1} (Putuhena and Cordery 1996; Tobón-Marin *et al*. 2000; Sato *et al*. 2004).

Evapotranspiration (*Et*) is the major water loss observed in natural (Price and Maloney 1994) and cutover peatlands (Van Seters and Price 2001). In natural peatlands considerable evaporative losses occur 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 15 – 20 cm below the surface, which is the limit of the shrub root structure (Romanov 1968). Takagi and Tsuboya (1999) reported an increase in *Et* with increasing vascular plant abundance in a peatland. The enhanced *Et* by shrubs occur as direct loss through *T*, which in ericaceae is more than 50% of *Et* (Miranda *et al.* 1984). The moisture dynamics of mulch, which is analogous to litter, have been studied in more detail than natural litter layers. Differences in net radiation (Bristow 1988; Price *et al*. 1998) and temperature (Bristow 1988) reduce *E* from soil under a mulch cover (Shangning and Unger 2001; Price *et al*. 1998), resulting in higher soil water content (Bristow 1988; Price 1997; Cook *et al*. 2006). As with mulches, litter generally has higher surface albedo than soil under both wet and dry conditions which reduces loss (Murphy and Lodge, 2001). Though the litter layer reduces the amount of water reaching the soil surface, the effects of interception are offset because energy used to evaporate litter-water is unavailable to evaporate water from the soil (Price *et al*. 1998).

The abundant distribution of ericaceae at cutover peatlands may significantly impact the water balance at the site through water losses incurred by *I* and *T*. Alteration to water storage at the peat surface influences *Sphagnum* development and survival. This study seeks to understand how ericaceous shrub canopy and litter layer affect water availability at the peat surface of a cutover peatland. Specifically I intend to: 1. understand and quantify the rainfall interception of the shrub canopy and litter layer; 2. quantify transpiration losses from the shrubs; 3. quantify the effects of the litter layer on soil evaporation rates: and 4. use the interception and transpiration values to estimate the amount of water available in the soil.

4.2 Study Area

The Cacouna peatland (47°53' N, 69°27' W) is located approximately 10 km north-east of Rivière-du-Loup, Québec. It is a domed bog, covering an area of 172 ha at an average elevation of 83m (Girard *et al*. 2002). Mean annual precipitation (1971-2000) at a weather station in nearby St. Arsène was 962.9 mm, 28% of which fell as snow. Mean annual temperature (1971 – 2000) was 3.2°C, with mean maximum temperatures in January and July of -8.5 and 22.9°C, respectively (Environment Canada 2007). Harvesting of the bog began in 1942 with the installation of primary and secondary drainage ditches, and continued until 1975 using traditional block-cut methods. This method involved cutting the peat by hand from trenches approximately 10 m wide and ca. 200 m long. The Cacouna bog currently consists of 511 trenches, 445 baulks (ridges approximately 1 m high and 6 m wide) and 16 vacuum–harvested fields (Girard *et al.* 2002). In October of 2006, the primary drainage ditches were blocked in an effort to rewet the site.

Following abandonment, 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 *Chamaedaphne calyculata, Kalmia angustifolia*, and *Ledum groenlandicum* are the dominant plant species covering ca. 79-90% of the surface (Girard *et al*. 2002). Trees including, tamarack (*Larix laricina*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), grey birch (*Betula populifolia*) and white birch (*Betula papyrifera*) are especially dominant 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).

4.3 Methodology

4.3.1 Field methods

4.3.2 Micrometeorological measurements

Data was collected during the main growing period from June to 22 August 2007, at the study trench and 4H sites (Fig 3.1; 3.2). A meteorological station was set up along the main study trench and monitored continuously using a Campbell Scientific Inc™ data logger. Precipitation was measured using two tipping bucket and manual rain gauges situated approximately 1m above the peat surface (Fig 3.2). The manual gauges were located within 3 metres of the tipping bucket gauge. Net radiation (*Q**) was measured using a net radiometer installed ca. 1 m above a relatively homogenous *Sphagnum*-ericaceae surface. Soil heat flux was measured with a soil heat flux plate inserted 1cm under the *Sphagnum* surface. Ideally net radiation would have been measured over ericaceae, however, the equipment could not be moved as it was currently being used in a three year study of the site. 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 *Q** values from S*phagnum* to calculate shrub *Et*.

4.3.3 Rainfall interception

I, measured as the difference between gross rainfall (*P*) and throughfall (*TF*), was measured under ericaceous shrub after the rainfall event. Twenty-three *TF* collectors were used over the study period. The collectors were placed under the shrubs, as close to the ground surface as possible, at an angle of ca. 10 degrees from the surface. Twelve 100 x 3.8 cm (380 cm^2) troughs were used to represent *TF* under mixed shrubs, while six 44.5 x 3.8 cm (169.5 cm^2) troughs were used to measure *TF* under specific shrub species. Six 40 x 2.3 cm (92 cm^2) troughs were also used under shrubs growing on *Sphagnum* hummocks. This smaller size was chosen as the gaps between the stems were much narrower and the larger collectors caused more spacing between stems increasing the size and number of gaps in the canopy. The volume of water obtained in the collectors after a rainfall event was measured and expressed as depth (mm). This value is the *TF*. *I* is the difference *P* and *TF*.

4.3.4 Ericaceous shrub canopy and litter layer evapotranspiration and transpiration

The Priestley and Taylor (1972) combination method was used to estimate daily evapotranspiration by applying the alpha parameter (α), the ratio of actual (Et_a) and equilibrium (Et_{eq}) evapotranspiration (mm d^{-1}), to the formula;

$$Et_a = \alpha(s/(s+q))((Q^*-Q_G)/L\rho) \qquad \text{Equation 1.}$$

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 vs. temperature 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}). The determination of α requires an estimation of actual evaporation from the desired surface type, and was estimated using plastic lysimeters set into various surfaces as described below: *Et* for ericaceous shrubs were estimated using six 60 x 40 x 22 deep cm lysimeters. A large plastic bladder was filled with water 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 a measuring tape attached along the length of the tube. The inside of the container was sealed with plastic sheeting, which protected the bladder and isolated it from atmospheric additions or abstractions of water. A 15 cm peat monolith was placed inside the lysimeter, which was then returned to the pit from where the monolith was extracted. The water level in the tube was monitored daily, and represented a change mass of the sample equivalent to the depth of water lost by *Et*. At the end of the season the lysimeters were calibrated by adding known volumes of water and recording the changes in water levels within the tube. Direct evaporation (*E)* for natural ericaceous litter cover and bare peat were measured using 18 cm x 18 cm x 15 cm high plastic lysimeters, six each with litter and three with bare peat. The litter samples were collected along the length of the baulk and trench. A 15 cm 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 and the mass change recorded. After weighing the samples were inspected using a HydroSense® water sensor to determine if water should be added or removed to maintain moisture content similar to the surrounding peat. Transpiration (*T*) was estimated as *Et* from the shrubs minus *E* from the litter. To understand the shading effect provided by the shrubs, we removed living shrubs from four bladder lysimeters. For two lysimeters the removed vegetation was sprayed with green paint and reattached in their previous orientation. *E* of the reattached lysimeters was compared to the bare peat.

4.3.5 Litter thickness and mass distribution

Leaf litter depth was measured at 58 randomly selected locations with a 50 cm x 50 cm quadrat between 8 – 18 August, 2007. The leaf litter depth was measured at four locations within the quadrat by placing a measuring tape within the litter until it reached the peat surface. The litter was subsequently removed and taken by to the laboratory where small twigs and decomposed litter was separated using a 2.80 mm screen. The samples were weighed to determine their mass per unit area. The relative humidity (*RH*) was measured at 3 points inside the quadrat at the surface and within the litter layer using a using a Vaisla HMI41 (micro-probe) Humidity Indicator.

4.3.6 Laboratory methods and analysis

4.3.7 Maximum water storage capacity (*MSC*) of the litter layer

The maximum water storage capacity (*MSC*) represents the potential maximum amount of water that can be absorbed and stored within the leaf itself (i.e. excluding the matrix between leaves). Litter density of 0.05, 0.1, 0.2 and 0.5 kg m^{-2} were used. For each litter density air dried litter was added and spread evenly across a 25 x 25 cm sample rack with a 5 mm screen, with nine replicates for each density. The samples were soaked in water for 24 h and removed and allowed to drain for 30 min, removing gravitational water held within the litter. After 30 min the sample was reweighed and the maximum water storage capacity calculated as the wet mass minus the air dried mass.

4.3.8 Litter interception storage capacity

Interception storage capacity (*I*) of the litter layer was measured using a rainfall simulator. According to Putuhena and Cordery (1996) and Sato *et al.* (2004) *I* can be separated into two categories; 1. C_{max}, the maximum interception storage capacity and 2. C_{min} the minimum interception capacity. C_{max} is the amount of water detained within the litter layer when interception stops increasing during rainfall and includes gravitational water, while C_{min} is the amount of water retained when free drainage stops after rain and does not include gravitational water. C_{min} is subject to partial rewetting depending on the litter matrix structure and the nature of the wetting event and differs from *MSC* where all pore spaces and leaf material is saturated by complete immersion. Hydrologically, C_{min} is more important as water is readily drained within 30 min after rainfall ceases, and represents the actual water that is held within litter Putuhena and Cordery (1996). 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 of 0.5, 1 and 2 cm and 0.5, 0.8 and 1.4 kg m^{-2}, respectively. The litter was placed in a 25 x 25 cm tray with 5 mm mesh and placed over a 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 sample was allowed to drain over the gauge for 30 min. Field litter *I* was estimated using *TF* and its respective intensity (Equation 2).

$$\text{Litter } I = C_{min}\ (\%) \times TF\ (\text{mm}) \qquad \text{Equation 2.}$$

4.3.9 Litter layer evaporation rates

Laboratory experiments were performed in 7 cm diameter x 16 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 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 *RH* was kept at approximately 25 ˚C and 36%, respectively, and recorded above the surface of the samples every two days using a Vaisla HMI41 Humidity Indicator. Volumetric water content (θ) of the lysimeters was determined gravimetrically.

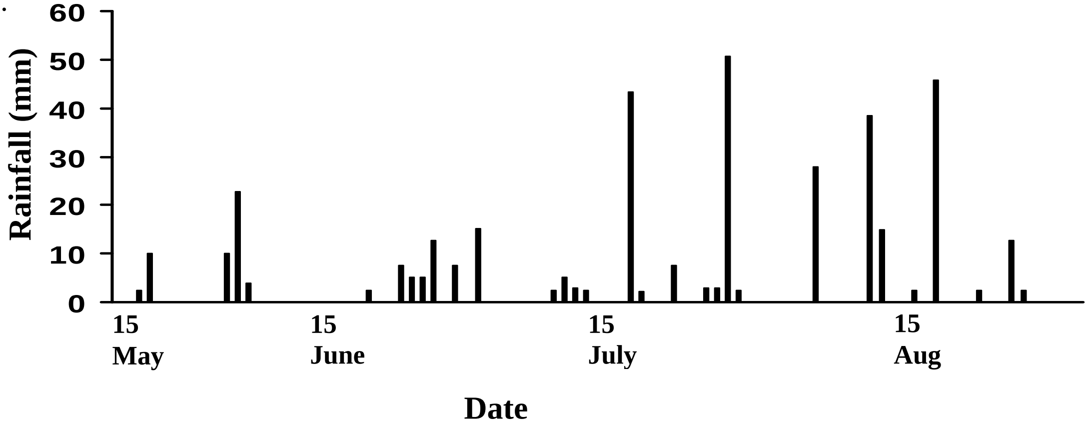
4.3.10 Statistical analysis

Student`s t-test and analysis of variance (ANOVA), at P = 0.05, were used to determine if significant differences occurred for the rainfall interception and evapotranspiration/evaporation data. Regression values and equations for the curves were determined using Microsoft®EXCEL.

4.4 Results

A total of 334 mm of rain fell between 25 May – 22 August, 2007. Rainfall in June and July (228.2 mm)was 21% higher than the 30 year average (1971 – 2000) of 179.1 mm for the same months (Environment Canada, 2007) (Table 4.1). The period between 7 and 16 June (Fig 4.1a) represented the longest period without rainfall over the season (10 days). Precipitation events < 3 mm occurred 9 times over the season, while events > 30 mm occurred 4 times (Fig 4.1b). Rainfall events < 20 mm accounted for ca. 45% of the gross rainfall while events > 20 mm accounted for 55%. Rainfall intensity varied between 2 and 25 mm h^{-1}. Rainfall between 6 and 10 mm h^{-1} occurred most frequently with 18 events, while rainfall between 21 and 25 mm h^{-1} occurred only 3 times over the season (Fig 4.1c). 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%. The average daily temperature for June and July were 0.2 and 0.3°C higher than the 30 year mean, respectively, while the August average was 0.6°C lower than the 30 year mean (Table 4.1). Average temperature increased from May (14.2°C), peaking in July (18.1°C) and decreased in August (15.9°C).

a.



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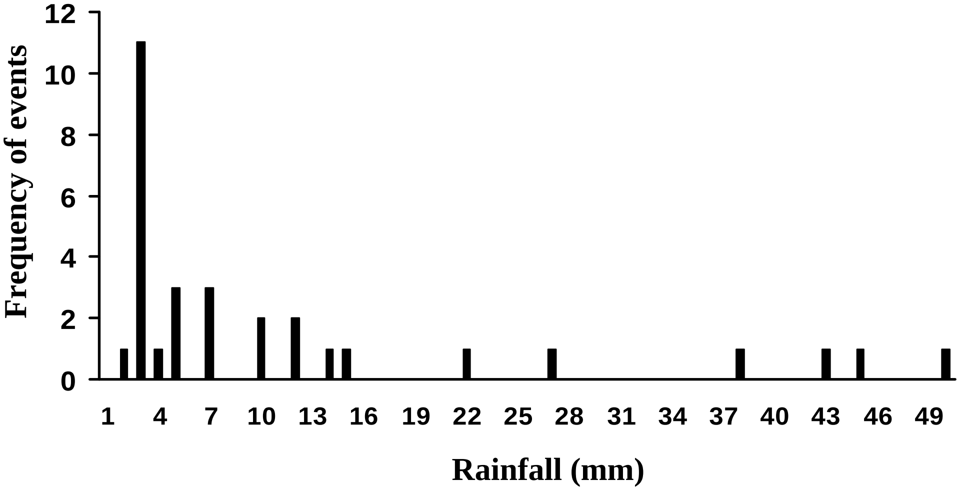


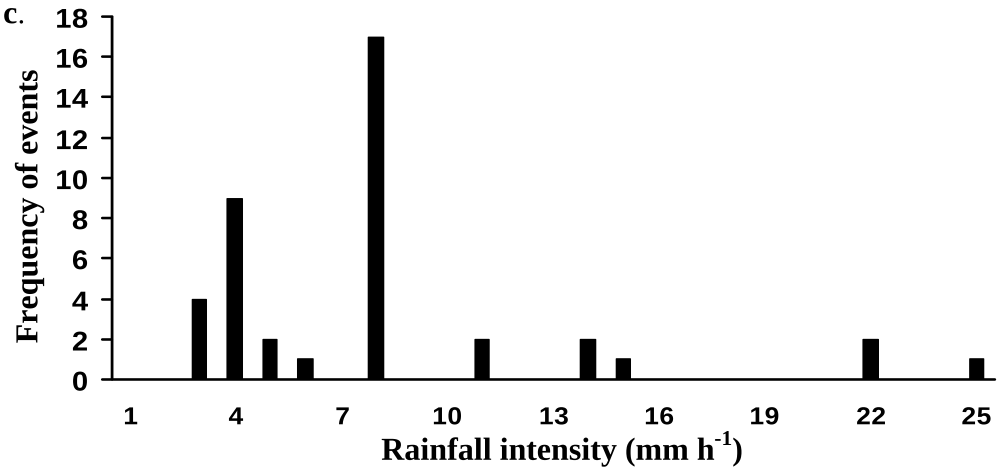


Figure 4. 1. a. Average daily rainfall (mm), b. rainfall size frequency and c. rainfall intensity frequency (mm h^{-1}) for 2007 season. In b and c the x-axis shows the upper boundary of the class interval.

*Q** averaged 204 Wm^{-2} over the season, generally increasing from 15 May to 25 July then decreasing thereafter. *Q** was consistently higher in July than the other months, averaging 263 Wm^{-2} compared to 155, 165 and 217 Wm^{-2} for May, June and August respectively.

Table 4. 1. Average temperature (°C) and total precipitation (mm) for 2007 season and 30 year running average

Month	Temperature (°C) 2007 season	Temperature (°C) 30 yr average	Precipitation (mm) 2007 season	Precipitation (mm) 30 yr average
June	15.1	14.9	92.4	87.1
July	18.1	17.8	135.8	92
Total			228.2	179.1

Ericaceous shrub throughfall and interception

The amount of rainfall intercepted by the shrub canopy increased with increasing rainfall volume, ranging from 0.7 – 15 mm. *TF* increased as the depth of rainfall increased and ranged from 0.3 to 38 mm (Fig 4.2 a). Using *TF* data, the interception capacity was ≈ 4 mm estimated as the difference between solid and dashed (envelope) curves (Fig 4.2 a). Cumulatively, shrubs intercepted 102 mm of rainfall for 24 rainfall events over the 2007 season, which represents 33.7% of the total rainfall. Therefore 200 mm or 66.3% of rainfall reached the peat surface as *TF* (Fig 4.2 b). In terms of understanding how rainfall characteristics affect *I*, it is important to look at *I* in terms of percentage of rainfall intercepted. The percent rainfall intercepted decreased as gross rainfall increased and ranged from 26 – 85% (Fig 4.3). Depth of rainfall per event does not fully explain the percentage of rainfall intercepted. For events of similar rainfall volumes (2 – 20 mm) *I* ranged from 30 – 78 %, which indicates that other external factors have a role in determining the interception capacity of a vegetation canopy (Fig 4.3).

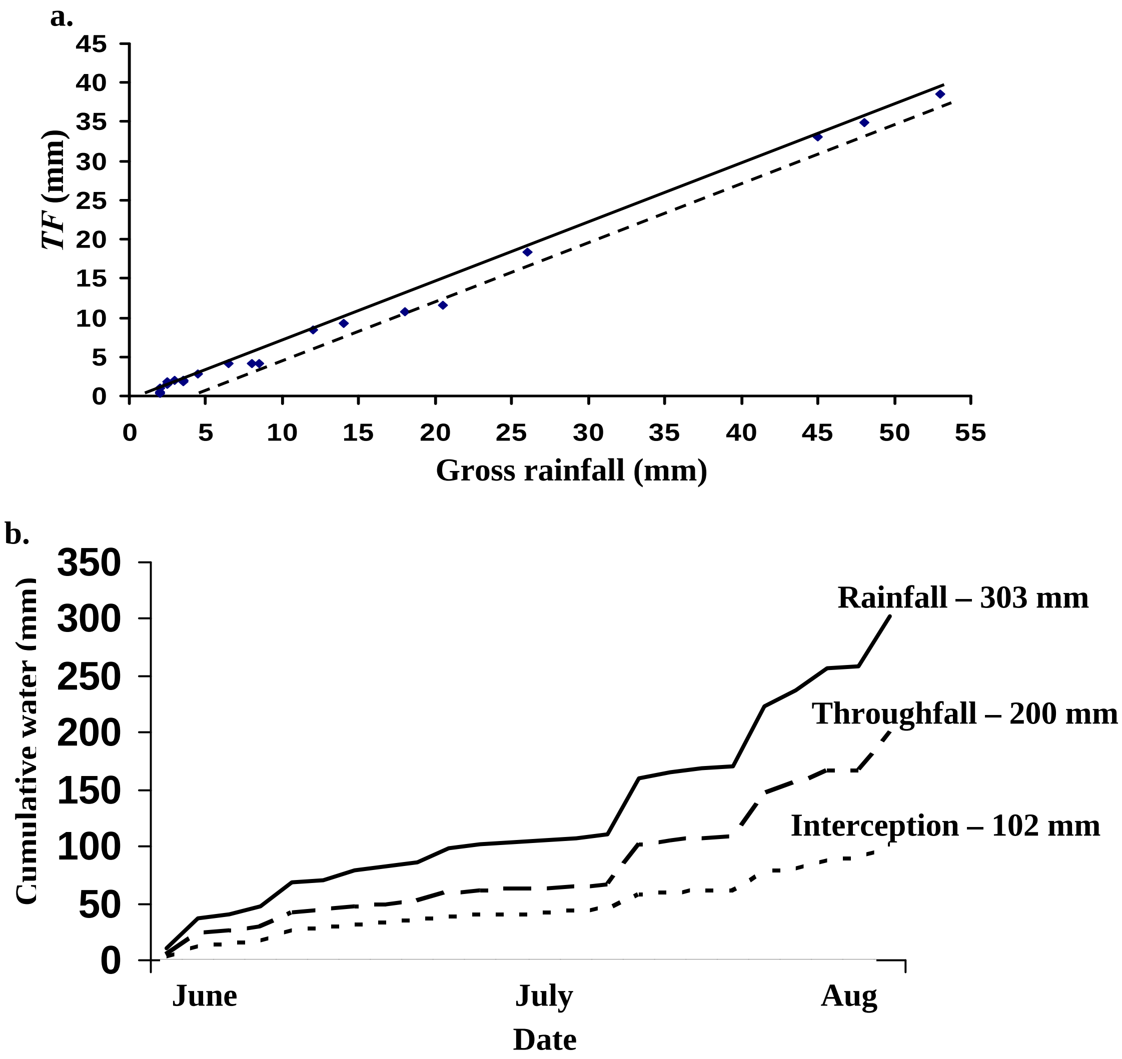


Figure 4. 2. a. Average throughfall (mm) versus gross rainfall (mm) (dashed line is an envelope curve) and b. Cumulative rainfall, interception and throughfall (mm) for 24 events for 24 events from June – August 2007

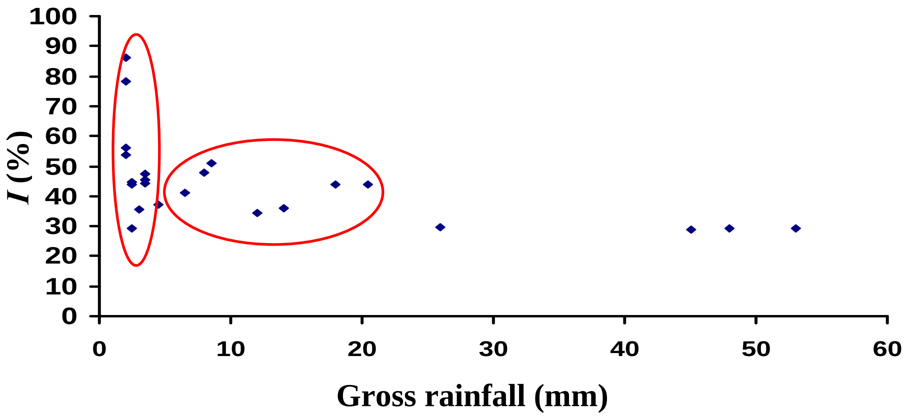


Figure 4. 3. Overall percent interception versus rainfall (mm) for all throughfall collectors

For the previously mentioned rainfall events (2 – 20 mm) the effect of rainfall intensity on *I* was examined. The percentage of rainfall intercepted for these events was higher for lower intensity events and decreased as rainfall intensity increased (Fig 4.4).

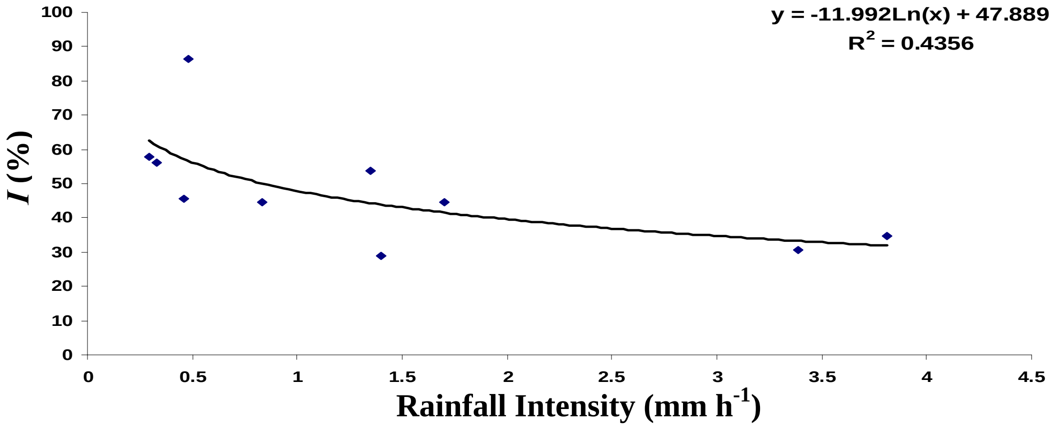


Figure 4. 4. Interception (%) versus rainfall intensity for rainfall events between 2-20 mm

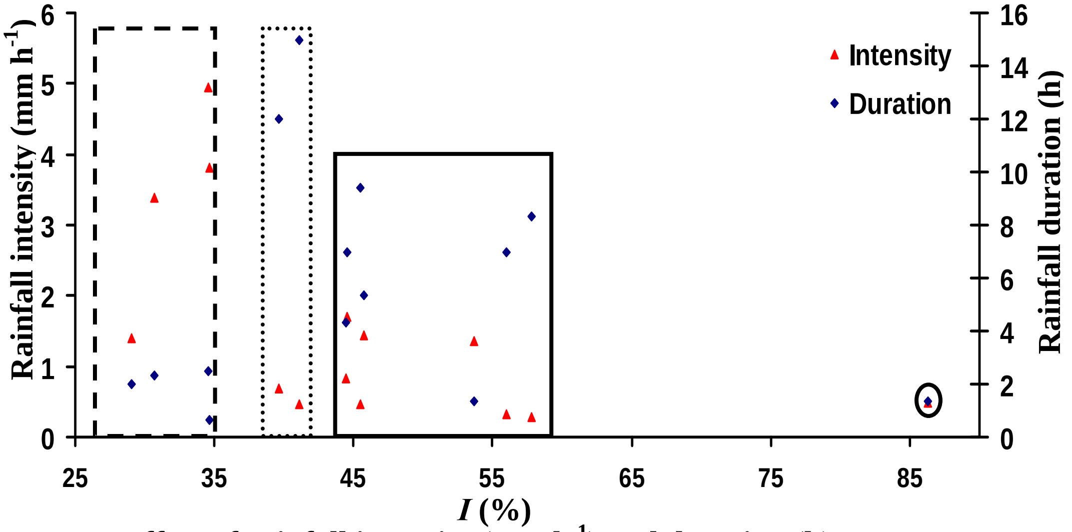


Figure 4. 5. Effect of rainfall intensity (mm h^{-1}) and duration (h) on percent interception (%)

The combined effects of rainfall intensity and duration on *I* were examined (Fig 4.5). *I* for the extreme low intensity, low duration event (circle) was the highest (86%). The lower range of *I* featured events of higher intensity and long duration (dashed line), representing 30% of *I*. Long duration, low intensity events (dotted line) produced medium *I* rates representing 40%, while medium duration, lower intensity events (solid line) produced the highest *I* (50%).

I differed significantly ($P < 0.05$) under similar vegetation cover between the 92 cm^2 and the 380 and 169 cm^2 collectors with the former intercepting more than the latter (Table 4.2).

Table 4. 2. Differences in the percentage of rainfall intercepted for various throughfall collectors. (Values in parenthesis are standard errors)

Collector surface area (cm^2)	Percentage intercepted (%)	Throughfall (mm)
380	49.1	170 (1.8)
169.5	42.4	192.4 (0.5)
92	56.7	144.6 (0.8)

Ericaceous shrub evapotranspiration

Daily *Et* of ericaceous shrub samples ranged from 0.5 to 6.9 mm day^{-1} (Fig 4.6 a), and averaged 2.5 ± 1.6 mm day^{-1} or 211 mm over the season, representing 63% of precipitation over the season. *Et* from trenches (2.3 mm day^{-1}) was less ($P > 0.05$) than baulks (2.8 mm day^{-1}), with the former being 82% that of the latter. The Priestley and Taylor (1972) coefficient, α, recorded over the season for the shrubs was averaged at 0.57.

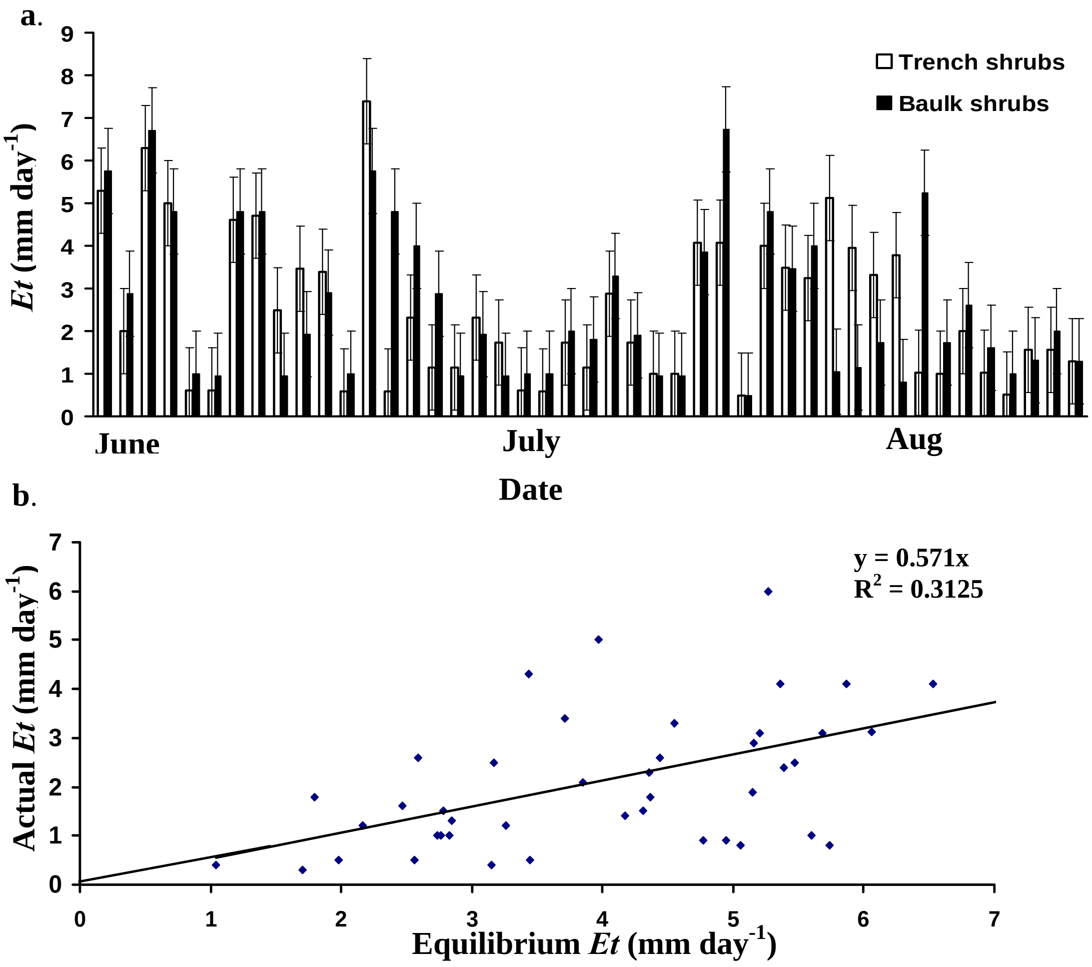


Figure 4. 6. a. Average daily evapotranspiration (mm day $^{-1}$) of ericaceous shrubs from trenches and baulks and b. Actual versus equilibrium evapotranspiration (mm day $^{-1}$) for ericaceous shrubs (each point represents an average from all sites) from June – August 2007

The shading experiments indicate that *E* from clipped (0.9±0.4 mm day^{-1}) was lower than clipped and reattached shrub lysimeters (1±0.6 mm day^{-1}). The differences are not significant ($P > 0.05$) and suggest that shrubs do not prevent substantial water loss by reducing soil *E* through shading.

E for baulk ericaceous litter ranged from 0.1 to 1.3 mm day^{-1} and averaged 0.6 mm day^{-1}, while *E* for trench ericaceous litter ranged from 0.2 to 2.5 mm day^{-1} and averaged 0.9 mm day^{-1}, respectively (Fig 4.7). The litter samples averaged 0.8 mm day^{-1} or 67 mm over the season with no significant differences ($P > 0.05$) between baulks and trenches. *E* from the litter layer in the field was significantly lower (0.9 ± 0.5 mm day^{-1}) than the bare peat (1.1 ± 0.5 mm day^{-1}), over the season totalling 75 and 92 mm of water, respectively ($P < 0.05$).

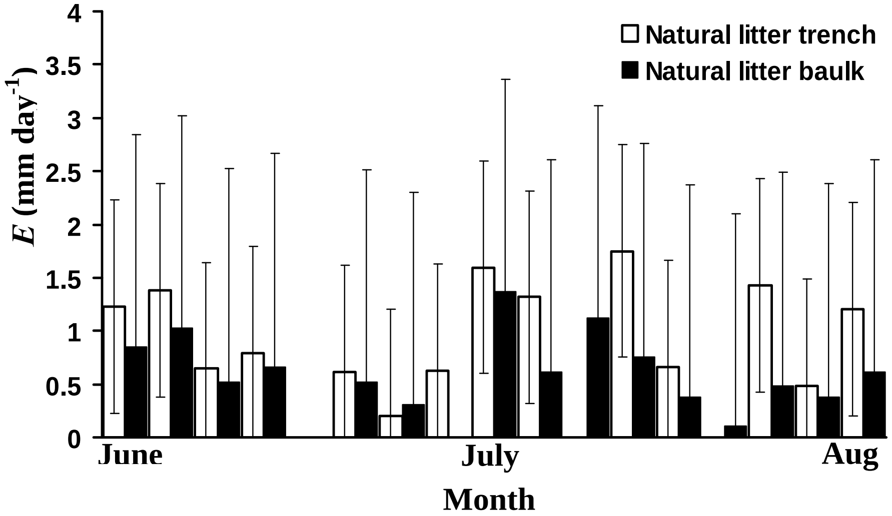


Figure 4. 7. Daily evapotranspiration (mm day^{-1}) for natural litter in trench and baulk from samples from June to August 2007

Ericaceous shrub transpiration

To further asses the role that ericaceous shrubs play in the overall water availability at the Cacouna bog, an estimation of *T* is needed. Based on *Et* and *E* shrubs transpired ca. 1.7 mm day^{-1} (142 mm over season) or 42% of precipitation. *T* accounted for 68% of the total evapotranspiration losses over non-*Sphagnum* surfaces (Fig 4.8).

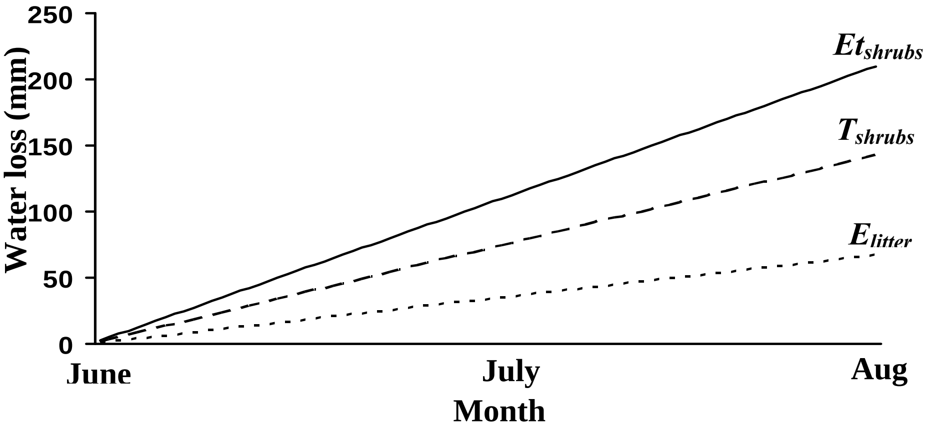


Figure 4. 8. Cumulative water loss by shrub and litter evapotranspiration, litter evaporation and shrub transpiration from June to August 2007.

Litter thickness and mass distribution

The mean litter thickness measured in the field was 2.5 ± 0.9 cm with maximum and minimum values of 5 and 0.1 cm respectively. Baulk litter (2 cm) was significantly thicker ($P < 0.05$) than trenches (1.2 cm) (Fig 4.9 a). The average litter mass was 0.2 ± 0.04 kg m^{-2} with maximum and minimum values of 0.5 and 0.01 kg m^{2} respectively. As with litter thickness the litter mass of baulks (0.3 kg m^{-2}) was significantly higher ($P < 0.05$) than trenches (0.1 kg m^{-2}) (Fig 4.9 b).

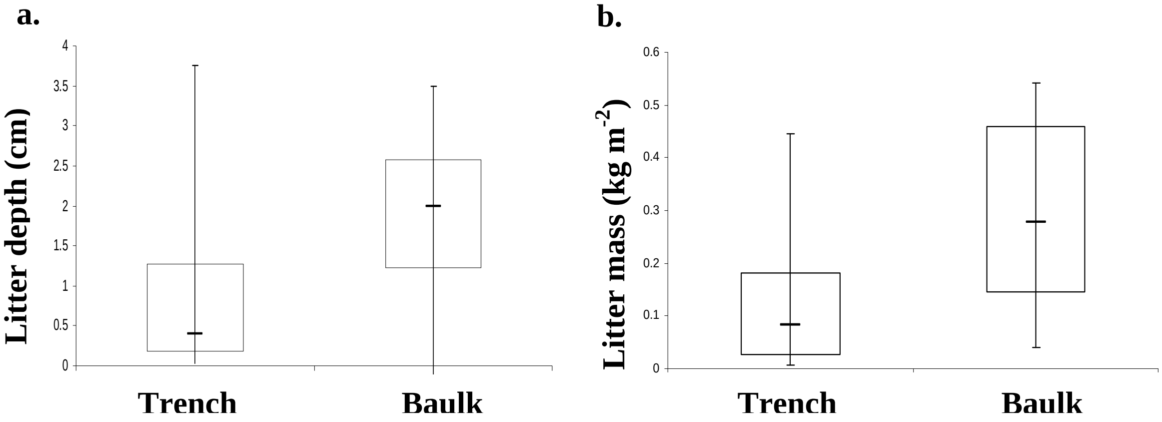


Figure 4. 9. Box plot of a. litter thickness and b. litter mass for baulks and trenches

Maximum storage and Interception storage capacity

The *MSC* of the litter was 2 mm kg^{-1} and ranged between 0.1 – 1 mm for 0.05 to 0.5 kg m^{-2} of litter. *MSC* increased as litter thickness increased ($R^2 = 0.984$).

The 0.5 kg m^{-2} litter layer (most representative of field conditions) intercepted an average of 3% or 0.2 – 1.2 mm of simulated rainfall. Using seasonal *TF* of 196 mm observed under the shrubs, *I* by field litter was ≈ 7 mm over the season. The amount of water retained in the litter increased as the depth/mass increased (Fig 4.10, Table 4.3). For a given litter mass/thickness the amount of rainfall detained increases as the rainfall intensity increases (Fig 4.11). However, the proportion of water retained decreases as intensity increases, though only by 1%. 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.

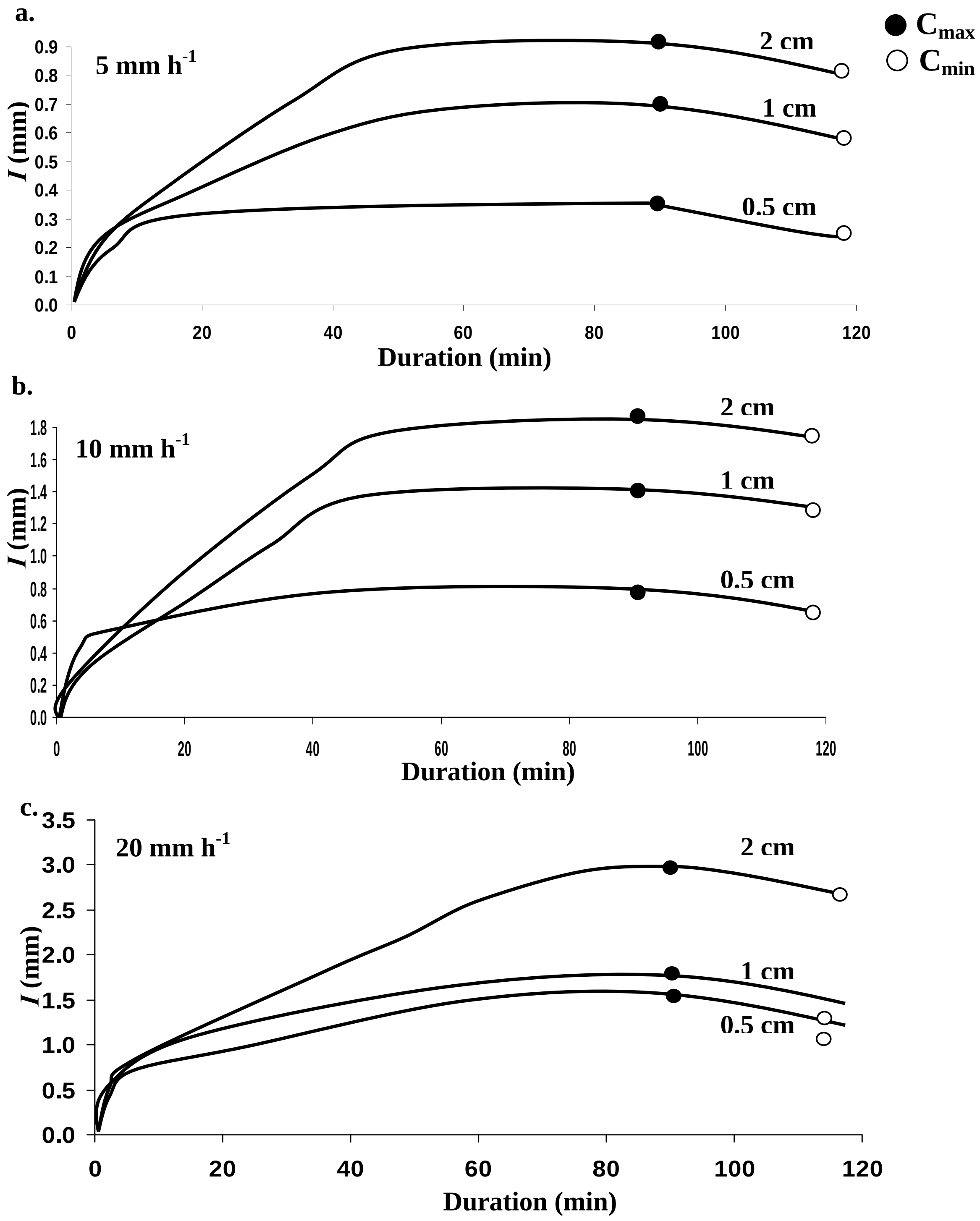


Figure 4. 10. Rainfall interception for 0.5, 1 and 2 cm thick litter layers for a. 5 mm h^{-1} b. 10 mm h^{-1} and c. 20 mm h^{-1}. Black and white circles indicate C_{max} and C_{min} respectively

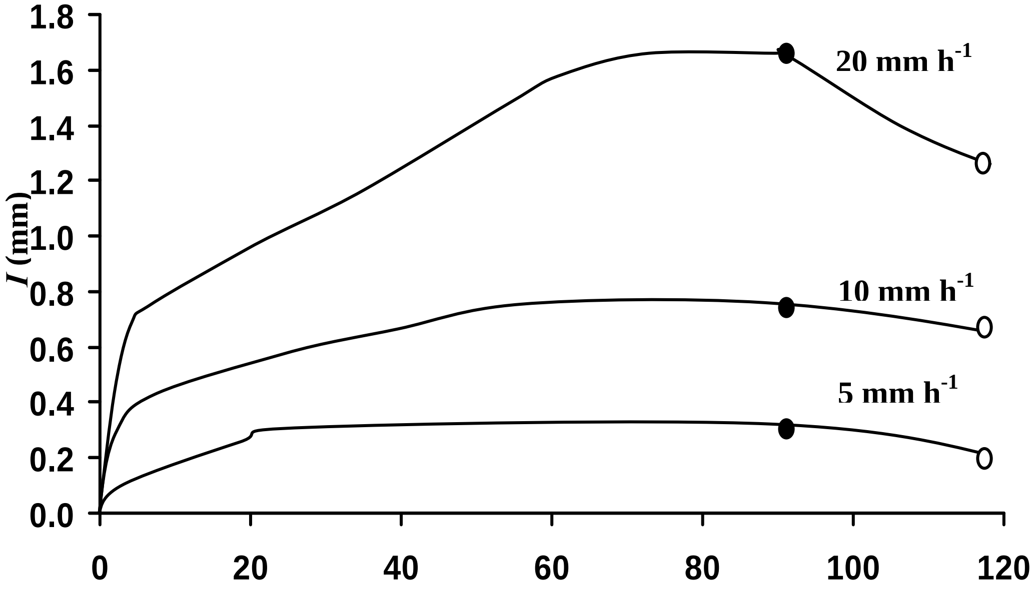


Figure 4. 11. Rainfall interception for 0.5 cm thick litter for 5, 10 and 20 mm h^{-1} events. Black and white circles indicate C_{max} and C_{min} respectively

Table 4. 3. Minimum interception storage capacity (C_{min}) with litter mass and litter depth

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

Laboratory litter layer evaporation rates

In the laboratory experiment *E* from litter-covered peat was also lower than bare peat over the first 33 days (Fig 4.12 a), but bare-peat *E* started declining sharply around day 25, eventually becoming lower than litter *E* by day 34. Between days 1 and 22 *E* from bare peat surface (3 mm day^{-1}) was statistically higher ($P < 0.05$) than litter covered surfaces (0.8, 0.6, 0.3 mm day^{-1} for 1, 2 and 4 cm litter depths, respectively). Cumulative water loss over the duration of the experiment from bare peat, 1, 2 and 4 cm litter depths corresponded to 91, 35, 27 and 15 mm of water respectively (Fig 4.13).

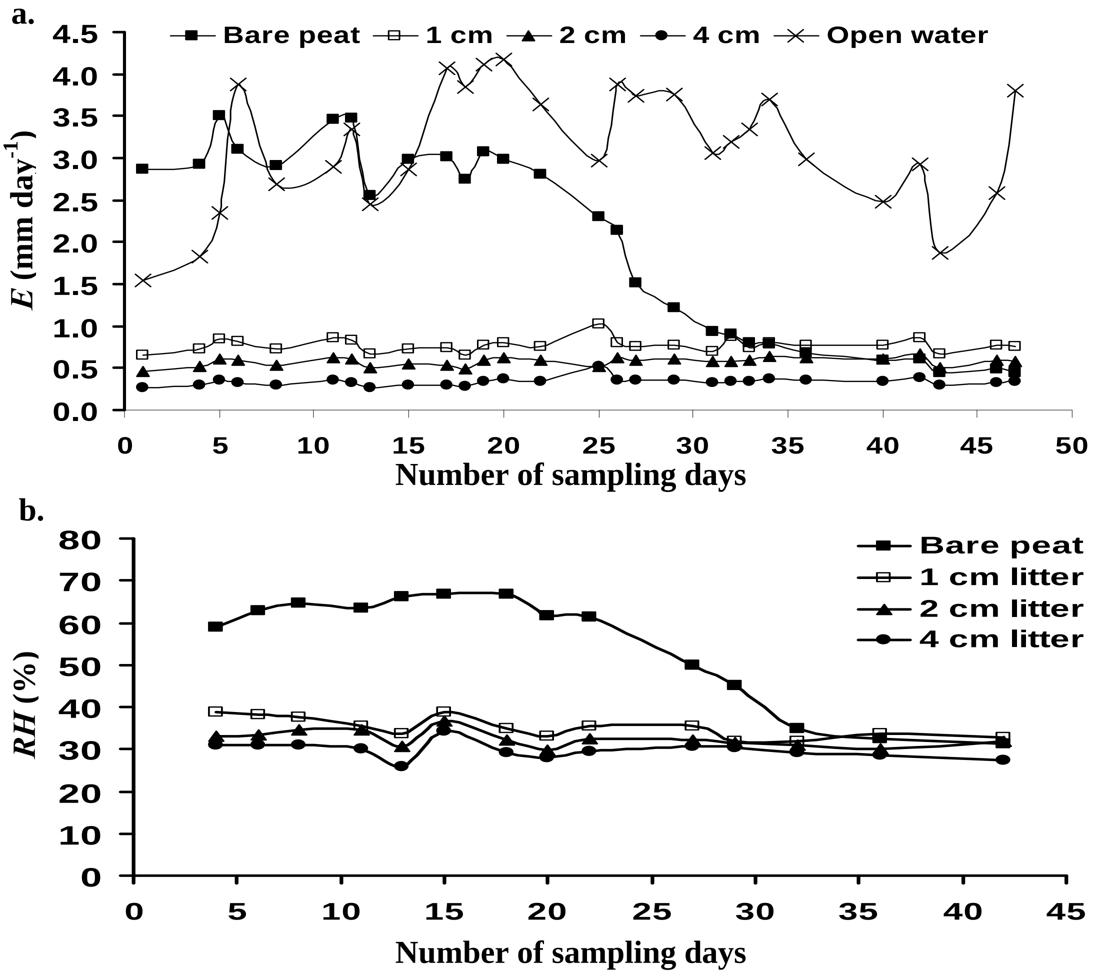


Figure 4. 12. Evaporation (mm day^{-1}) and b. Relative humidity (%) from bare peat, 1 cm, 2cm and 4cm thick litter and water over the 47 day sample period

E from the litter-covered surfaces remained relatively consistent over the experiment (Fig 4.12 a), with evaporation from 1cm litter depth higher than from 2 and 4 cm litter layers. There were significant ($P < 0.05$) differences in *E* between the three samples (Fig 4.13 a). *RH* at the surface of the samples showed similar trends as *E* (Fig 4.13 b). *RH* was significantly higher over bare peat and began to decrease (day 25), becoming lower than the litter samples (Fig 4.13 b). From the field quadrats *RH* at the litter surface (65%) was lower than within the litter (94%) (Appendix A4).

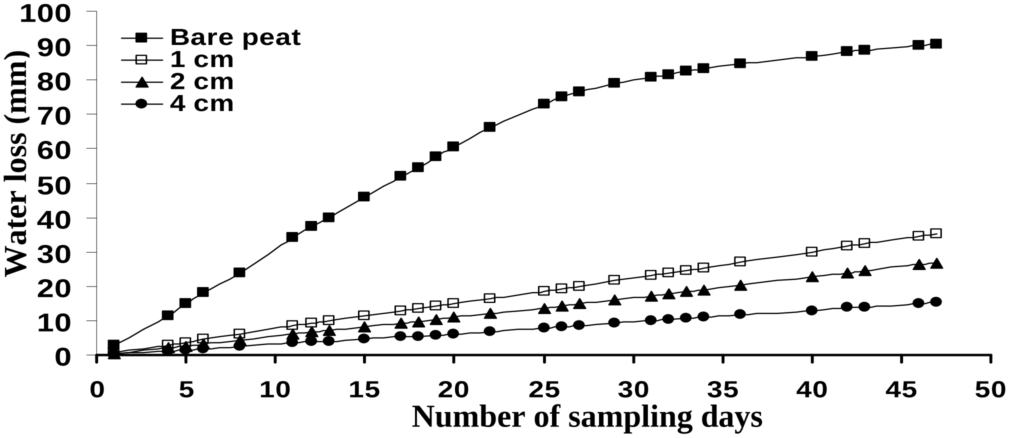


Figure 4. 13. Cumulative water loss from bare peat, 1 cm, 2 cm and 4 cm deep litter samples

θ of the bare peat decreased rapidly over the first four days and by day six was significantly lower ($P < 0.05$) than that of the litter covered samples. 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 ($R^2 = 0.833$).

Water balance

The shrubs intercepted 120 mm from the canopy and litter layer, and transpired approximately 142 mm from June to August. The sum of these, which represents the direct water loss from the shrub canopy is 262 mm or 78% of rainfall over the season. Ericaceous shrubs only make 72 mm or 22% of the total rainfall available for other soil processes over the summer months. Over the summer season we estimate evaporation is reduced by 17 mm by the litter layer.

4.5 Discussion

I by shrubs accounts for 33% or 110 mm of incoming precipitation during the summer months (Fig 4.2 b). No values were found in the literature for comparison but the rates are similar to values for non-peatland species observed by Návar and Bryan (1990), Martinez-Meza and Whitford (1996) and Domingo *et al*. (1998) respectively. The canopy has an interception capacity of ca. 4 mm (Fig 4.2 a) and is higher than 1.4 mm recorded for similar ericaceae species, *Calluna vulgaris* (Calder *et al*. 1984). The larger capacity of our plants is likely a result of higher leaf area index (*LAI*), 2.4 versus 1.8, and larger individual leaf sizes, allowing more rain to be intercepted. Rainfall of similar amount results in different rates of *I* (Fig 4.3). Intensity and the duration of rainfall may be more important than gross rainfall in determining *I.* Distinct interception classes are observed with changing intensities and rainfall duration (Fig 4.4, 4.5). These trends are similar to those of Llorens *et al*. (1997), who indicated that short with high intensity, long with low intensity, and medium with low intensity events produced increasingly higher *I* rates. 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, *I* 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, events ≤ 4 mm are almost completely intercepted. Therefore these events have a greater impact on reducing water availability at the soil surface. Larger more intense events contribute 4 mm to the canopy before the remaining water reaches the surface and events over 4 mm are important for increasing or maintaining the water content at the soil surface. Precipitation events less than 3 mm occurred 9 times over the season compared to 4 times for events greater than 30 mm, while events less than 20 mm accounted for ca. 45% of the gross rainfall (Fig 4.1

a). Coupled with a higher percentage of rainfall intercepted for small events, drier years may have a higher proportion of these events and further reduce water availability at the peat surface. Errors with the interception measurement occurred when there was overflow of *TF* collectors, which occurred for the three events greater than 40 mm. This resulted in an overestimate of interception values for the study by up to 10 mm.

The linear relationship between litter mass and *MSC* in this study was also observed by (Sato *et al*. 2004). The *MSC* (2 mm kg^{-1}) observed in my study falls within the range of the previous studies. Pitman (1989) recorded *MSC* of 4.8 mm for bracken litter, while Putuhena and Cordery (1996) found values of 2.28 mm and 1.38 mm for pine and eucalyptus litter and Sato *et al*. (2004) reported values of 1.59 mm and 1.56 mm for *C. japonica* and *L. edulis,* respectively. The mass/thickness of the litter alters C_{min} (Fig 4.11) due to changes in the distribution of flow channels within the litter (Sato *et al.* 2004). As the mass and thickness increases, 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 is increased providing a greater capacity of water to be held by adhesion and capillary action respectively. C_{min} at 20 mm h^{-1} was greater than *MSC* by 0.2 mm. At this intensity, the highest observed in the field, the litter becomes saturated. The higher value is possibly a combination of water absorbed into the leaves and that held within the litter matrix.

Average daily *Et* was 2.5 mm day^{-1} or 211 mm over the season, which represents 63% of precipitation and the rates are comparable to those recorded by Van Seters and Price

(2001) of 2.4 mm day^{-1} for similar surfaces. *Et* reported from baulks have typically been lower than trenches (Van Seters 1999). Overall, these trends were reversed for this study. However, there were instances where trench *Et* was greater than the baulks (Fig 4.6 a). This may be a result of oscillations between wet and dry periods, where under the wetter regime *Et* from baulks were higher than 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) (see Appendix A3). Moreover, the drainage ditches were blocked for 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 coupled with higher turbulence, Q^* and *LAI*, *Et* would be higher from the baulks than trenches. Low R^2 values (Fig 4.7 b) suggest that *Et* is controlled more by soil matric force and moisture than available radiant energy. Transpiration as a percentage of *Et* was higher than *E* (Fig 4.8), which is typical of this relationship (Liu *et al*. 2002; Lauenroth and Bradford 2006; Yepez *et al*. 2007) and suggest that the soil surface water balance is influenced more by plant than direct soil water loss.

The litter layer reduced water loss by evaporation by 18% and 60% in the field and lab, respectively. *E* from litter-covered peat was lower than bare peat (Fig 4.12 a). These trends were similar to other studies using mulch (Bristow 1988; Shangning and Unger 2001) and litter (Murphy and Lodge 2001). The laboratory experiments indicate that by day 47, *E* from the bare peat was substantially lower than the litter covered surfaces (Fig

4.12 a). Shangning and Unger (2001) observed similar trends, with lower overall evaporation rates under mulched soil. They noticed that the evaporation rate under the bare soil decreased over time, eventually becoming lower than the mulched soil, thus suggesting that mulch is important for short term water conservation. However, using the evaporation rate to indicate short-term storage is misleading, as the rates do not specify changes in soil moisture, which is critical for survival of plants. Higher θ under mulched surfaces have been recorded (Bristow 1998; Cook *et al.* 2006; Price 1997) and my results indicate like these studies, litter maintains greater θ within the soil. Using cumulative water loss and θ show that the litter was indeed important in the short term water storage, as θ was significantly ($P < 0.05$) lower under bare peat by day 6. More importantly, long term storage is evident, which becomes significant under drought conditions. Price and Whitehead (2004) found similar results for θ and soil water pressure (ψ) under litter covered peat and suggest that the litter layer is important in both the short term and long term storage of water in the soil.

The litter acts as a physical barrier, reducing water loss through this layer. Higher *RH* observed within the litter in the field (Appendix A4) and the lower values over litter versus bare peat (Fig 4.12 b) suggest that the litter decreases the upward movement of water vapour, which must now flow through the interstices within the litter before reaching the atmosphere. The thicker litter layers provide a greater distance and more complex flow path for the vapour to follow, resulting in lower evaporation rates.

4.6 Conclusion

The shrubs intercept 120 mm from the canopy and litter layer and transpire approximately 142 mm from June to August, making 22% of rainfall available in the peat surface. These water losses may be critical in their effect on the growth and survival of *Sphagnum*, the primary peat building vegetation. In my analysis of *I* and *T* losses, the primary water supply occurred in the form of rainfall. However, the water table can be considered as another water source for *T*, once kept in close contact to the root system. θ and ψ in the upper 2 cm of soil at the site shows a relatively good relationship with water table depth (Price and Whitehead 2001), and with the rise and increased stability of the water table we expect soil moisture to be higher and more consistent over the summer.

Over the summer season *E* was reduced by 17 mm by the litter layer. Therefore, rainfall interception by litter was offset by the water reduction effects of the litter, suggesting that the litter layer potentially maintained a higher θ in the peat surface over the summer. θ and ψ of over 50% and -100 cm is necessary for *Sphagnum* establishment (Price and Whitehead 2001) at this site and is maintained over a longer period under a litter cover (Price and Whitehead 2004). However, the litter layer may act as a barrier, cutting off or reducing capillary flow to the surface. In harvested sites where a litter layer has been established before *Sphagnum*, the spread of spores and fragments will be limited to the surface of the litter. With the litter acting as a barrier to capillary rise, recolonisation by *Sphagnum* may hindered except for areas frequently inundated with water (Price and Whitehead 2004). The evaporation-retarding effects of the litter is not lost under the saturated conditions of the peat as the difference in evaporation from litter and bare peat is the greatest under saturated conditions and litter experiments that even a very thin layer (< 1 cm) would maintain sufficiently high θ.

Ericaceous shrubs may be beneficial to the growth and survival of *Sphagnum* in natural bogs. Observations in field have shown that *Sphagnum* becomes dry, brittle and in some cases white when vascular plants are removed from the moss surface. Shrubs act as a companion species, aiding in the survival of the moss (Ferland and Rochefort 1997; Boudreau and Rochefort 1999). *Et* rates over *Sphagnum* carpets have been shown to be 6.5% lower when covered by a shrub layer (Crum 1988), and Heijmans *et al.* (2001) concluded that lower *E* rates of *Sphagnum* surfaces with a shrub cover resulted from reduced winds speeds through the canopy. We suggest raising the water table above -25 cm to offset *I* and *T* losses and the capillary barrier effect of the litter. Higher water tables provide the hydrological conditions needed for development of *Sphagnum* (Price and Whitehead 2001) and allow the beneficial features of the shrubs such as shading to proceed.

5.0 Laboratory investigations of Soil Water flux under Sheep-laurel (*Kalmia angustifolia*) at varying Water table depths and its effect on Sphagnum regeneration

5.1 Introduction

Changes in hydrology after harvesting of natural bogs create conditions unsuitable for the reestablishment of *Sphagnum*. Higher bulk densities (Price 1997), lower specific yield and hydraulic conductivity (Van Seters and Price 2002) and low water table levels (Price 1997) reduce upward capillary flow of water needed for the survival of the moss. The growth of ericaceous shrubs is not limited by such conditions, resulting in the shrubs (eg. *Kalmia angustifolia*) representing more than 70% of the total surface cover in manually block-cut peatlands in Québec (Girard *et al*. 2002; Poulin *et al*. 2005). The high abundance of these shrubs has a major influence on water availability. The accessibility of water at the surface of harvested peat is important in the restoration of *Sphagnum* (Price and Whitehead 2001). To date we do not know much about the soil water flux processes under ericaceous shrubs especially in harvested peatlands.

The water availability of soils is affected by interception and transpiration losses from vascular plants (Dingman 2002). In natural and harvested bogs evapotranspiration (*Et*) is the major source of water loss (Price and Maloney 1994 ; Van Seters and Price 2001) and is controlled by the vegetation cover and the water table depth (Lafleur and Roulet 1992). Ericaceous shrubs may be responsible for a substantial proportion of *Et* losses from the surface (Takagi and Tsuboya 1999) and is evident as *Et* decreases when the water table falls below the root system of the vascular plants (Romanov 1968; Lafleur *et al.* 2005). To meet daily transpiration (*T*) requirements, plants remove water from soil. 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 density (Moore *et al.* 2003). Water absorbed by the roots during *T* reduces soil moisture content and the water pressure of the soil, which continue to decrease as long as *T* persists and there is no recharge by precipitation. The greatest moisture loss typically takes place in the upper layers of the soil (Caldwell *et al*. 1998). However, the roots of many plants remain in contact with deeper, moister soil layers and, when *T* is reduced water may be redistributed from deeper to upper layers along a potential gradient and is known as hydraulic lift (Richards and Caldwell 1987; Dawson 1993; Topp *et al* 1996). Hydraulic lift may be an important ecosystem function as water brought to the surface can used by plants unable to access deeper water (Corak *et al.* 1987; Richards and Caldwell 1989), and may be crucial to the survival of the plant in drought periods (Dawson 1993). In natural and harvested bogs little is known about the role ericaceous shrubs play in the water fluxes within *Sphagnum* cushions and peat. The volumetric water content (θ) of the upper layers of *Sphagnum* cushions remain fairly consistent despite the water table lowering over the season (Yazaki *et al.* 2006). This upward water movement and storage can be attributed to the capillary water-transport capacity of *Sphagnum* (Yazaki *et al.* 2006). The moss becomes more decomposed deeper in the cushion with a consequent decrease in pore size (Hayward and Clymo 1982) and higher unsaturated hydraulic conductivities at reduced pressures (Price *et al*. 2008), which aid in capillary water transport. However, this movement has never been linked to hydraulic lift caused by the shrubs.

Much work has been done on the conditions needed to restore *Sphagnum* on abandoned harvested peatlands (Price *et al*. 2003; Rochefort *et al*. 2003) and hydrologically soil water pressure (ψ) over -100mb is necessary for *Sphagnum* establishment (Price and Whitehead 2001). Vascular plants have been shown to act as nurse plants aiding in the reestablishment of *Sphagnum* (Ferland and Rochefort 1997; Boudreau and Rochefort 1999) creating more suitable microclimate and hydrological conditions (Lavoie *et al.* 2005). Therefore the high abundance of ericaceous shrubs in cutover peatlands must play a major role in the soil water flux and availability at the site, thus impacting the regeneration of *Sphagnum*. To provide insight into these processes, monoliths containing Sheep-laurel (*Kalmia angustifolia*) were removed from a cutover peatland and water fluxes within the monoliths studied under artificially manipulated water table levels. This study seeks to determine how Sheep-laurel use soil water during diurnal transpiration fluxes. More specifically I will quantify: 1. the transpiration rates, 2. changes in volumetric moisture content and soil water pressure under a falling water table and 3. the presence of hydraulic lift under the changing water table depths.

5.2 Site description and Methods

The Cacouna peatland (47°53' N, 69°27' W) is located approximately 10 km north-east of Riviere-du-Loup, Québec. It is a domed bog, covering an area of 172 ha at an average elevation of 83m (Girard *et al*. 2002). Following abandonment, the Cacouna bog has undergone a natural vegetation succession. Plants typical of peatlands in that region have recolonized most of the bare peat surface. Ericaceous shrubs, such as *Kalmia angustifolia*, *Chamaedaphne calyculata* and *Ledum groenlandicum* are the dominant plant species covering ca. 79-90% of the surface (Girard *et al*. 2002). 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).

5.2.1 Preparation of experimental bucket

The experimental buckets acted as a tension device, allowing simulation of water tables deeper than the bottom of the bucket. Six 30 cm diameter and 44.5 cm high buckets were used. A brass nipple was inserted at the base of the bucket and the inside orifice was screened using a geotextile cloth to prevent clogging of the nipple. A 2 cm layer of coarse sand covered the bottom of the bucket to provide good hydraulic connection to the inner nipple opening. A 5 cm layer of glass beads (60 – 110 μm) was placed over the sand which formed a tension device that remained saturated at the pressures imposed in this study, ψ being controlled by the position of the flexible manometer tube connected to the brass nipple. Water was added and drained to compact the sand and beads before the sample was put in.

5.2.2 Collection of samples

Six 32 cm deep peat monoliths, consisting of bare peat and Sheep-laurel were collected on 4th October 2007 from the Cacouna peatland (Fig 3.2). Sheep-laurel was selected as it is the most abundant ericaceae species at Cacouna peatland (Please note that hereafter shrubs refer to Sheep-laurel). An empty sample bucket, with the bottom cut out, was used as a saw guide to cut the sample – the bucket being progressively pushed down as the cut was made. Two shrub- and one bare peat- samples (no shrubs present) were obtained from randomly selected located along a baulk (raised area) and then repeated for a trench (more deeply cut area between baulks). Samples were transported to the University of Waterloo and stored outdoors for 2 months (October-November), where they were wet under natural rainfall. Litter was removed from the surface of the bare peat monoliths. Samples were placed ≈ 20 cm below grow lamps for 12 hours per day in a chamber with a temperature of 25±0.3°C and relative humidity (*RH*) at 36%. Vapour pressure deficit (*VPD*) was calculated from temperature and *RH* data.

5.2.3 Evapotranspiration, soil water pressure and volumetric water content

A mariotte bottle device was connected to the nipple at the base of the buckets and provided a constant supply of water, and to set the position of the water table (Fig 5.1). *Et* rates were measured daily by measuring the water loss from the mariotte bottle. *T* from the shrubs was estimated as the difference between shrub *Et* (bare peat and shrub bucket) and bare peat (bare peat only bucket) evaporation (*E*).

θ was measured using Campbell Scientific Inc^{TM} 605 Time Domain Reflectometry (TDR) probes inserted horizontally at 2.5 cm, 5 cm, 10 cm, 20 cm and 30 cm below peat surface (Fig 5.1). The 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 (Fig 5.1).

The water table within the bucket was manipulated using the mariotte bottle and initially raised to the surface to saturate the peat, then lowered to 5 cm below the surface (Fig 5.1). θ of the shrub monoliths were monitored every hour, 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) (Fig 5.1). The water table was left at -30 cm the longest as it was thought that at this level diurnal redistribution of water from the lower to upper layer may readily be observed.

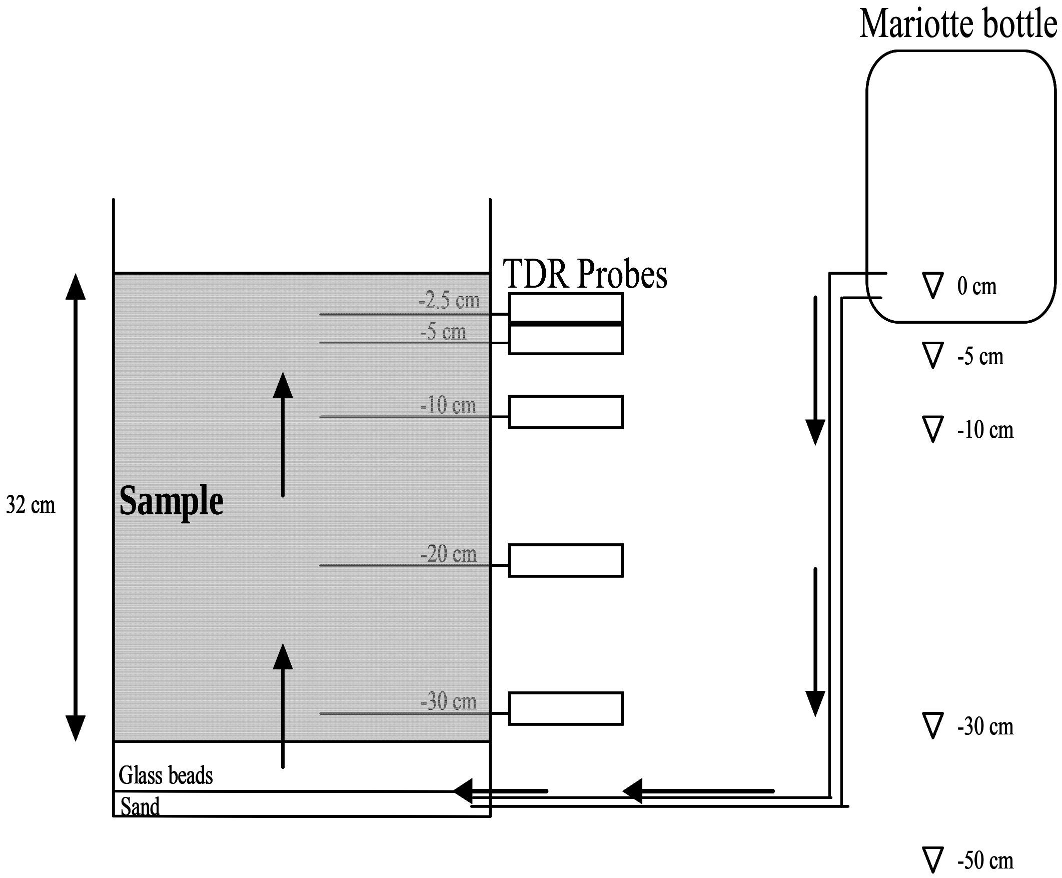


Figure 5. 1. Mariotte bottle and TDR location in experimental buckets (tensiometers are located at the same depth as TDR probes; arrows indicate flow of water)

5.2.4 Statistical analysis

Student's t-test and analysis of variance (ANOVA), at P = 0.05, were used to test significant differences of soil water pressure and volumetric water content from shrub and bare peat monoliths.

5.3 Results

Evapotranspiration.

The average *E* and *Et* rates from baulk and trench buckets decreased as the water table was lowered, with the *Et* rates being higher than *E* at all water table levels (*WT*) (Table 5.1, Fig 5.2).

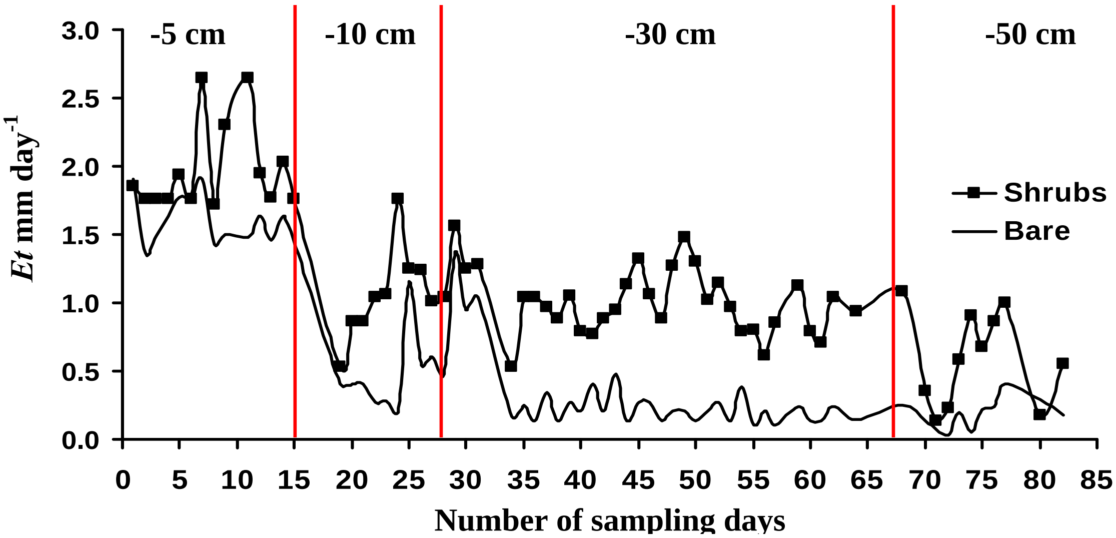


Figure 5. 2. Evapotranspiration rates of ericaceous shrubs (squares) and bare peat (solid line) samples at four water table levels

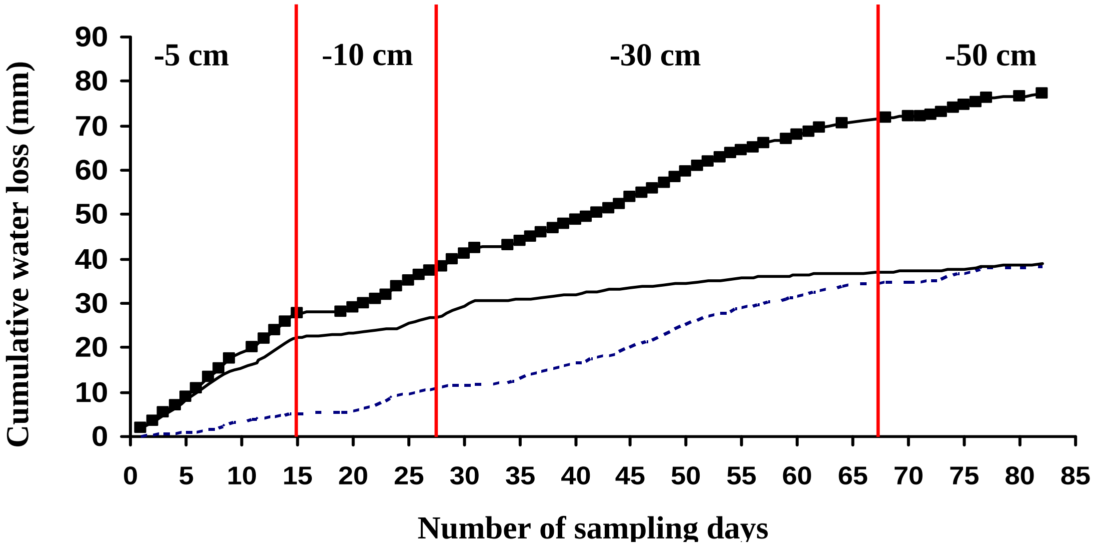


Figure 5. 3. Cumulative *Et* (sqaures), *E* (solid line) and *T* (dotted line) loss at four water table levels

T increased as *WT* was lowered to -30 cm but decreased when the *WT* was at -50 cm. *T* was 50% of *Et* losses over the study and ranged from 11 to 80% (Table 5.1). Cumulative water loss from *Et*, *E* and *T* was 77.2, 38.9 and 38.3 mm respectively. Cumulative water loss from *T* showed a steady increase over the study period while *E* showed a steady increase at *WT* of -5 and -10 cm, but showed a much slower increase at *WT* of -30 and -50 cm (Fig 5.3).

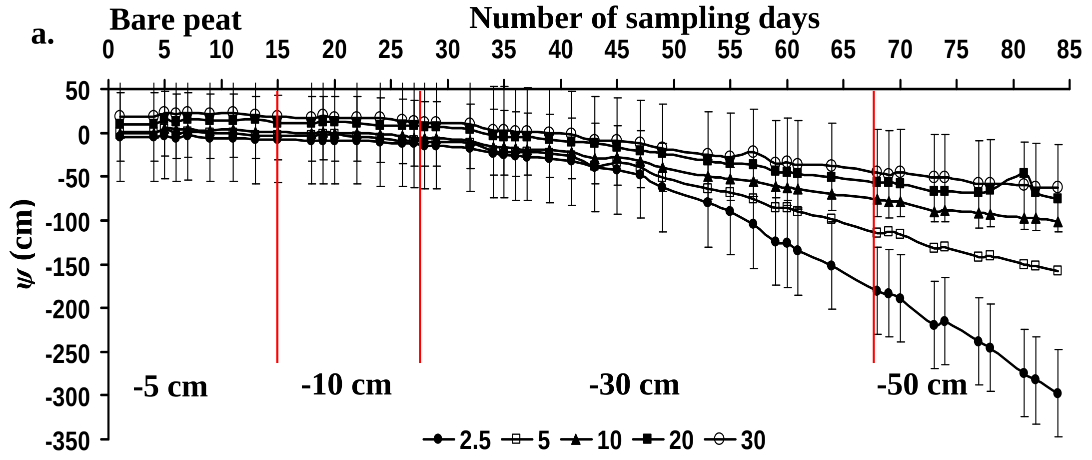
Table 5. 1. Average evapotranspiration rates of shrub and bare peat monoliths under various water table depths (Parentheses is a percentage of evapotranspiration)

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)

Soil water pressure (ψ)

ψ decreased as the water table was lowered (Fig 5.4). At *WT* of -5 and -10 cm a small drop in ψ ($P > 0.05$) was observed for both bare and shrub covered peat (Fig 5.4). An average decrease of 2 and 8 cm for shrubs and 3 and 9 cm for bare peat was observed at *WT* -5 and -10 cm respectively (Table 5.2). When *WT* was lowered to -30 cm there was a distinct drop in ψ after 11 days in the bare peat and continued to decline rapidly at the 2.5, 5 and 10 cm depths (Fig 5.4 a). The ψ became steady at the 20 and 30 cm level 26 days after lowering the *WT* to -30 cm and remained constant until the *WT* was lowered to -50 cm (Fig 5.4 a). Unlike bare peat, ψ of shrub covered peat showed a slow and steady decrease at *WT* = -30cm (Fig 5.4 b) and only at -50 cm was there a distinct drop in ψ (Fig 5.4 b). At *WT* of -30 and -50 cm, ψ was significantly ($P < 0.05$) lower in the bare peat than the shrubs and an average decrease of 24 and 16 cm and 83 and 34 cm was observed for shrubs and bare peat, respectively (Table 5.2).

a.



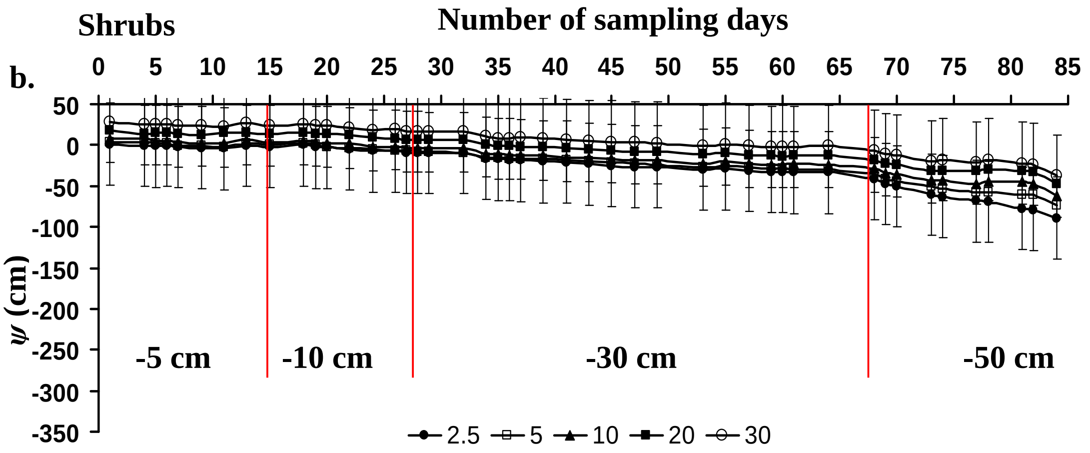


Figure 5. 4. Average soil water pressure (cm) at all tensiometer depths for a. bare peat and b. ericaceous shrub (Standard error bars are for 2.5 and 30 cm depth profile)

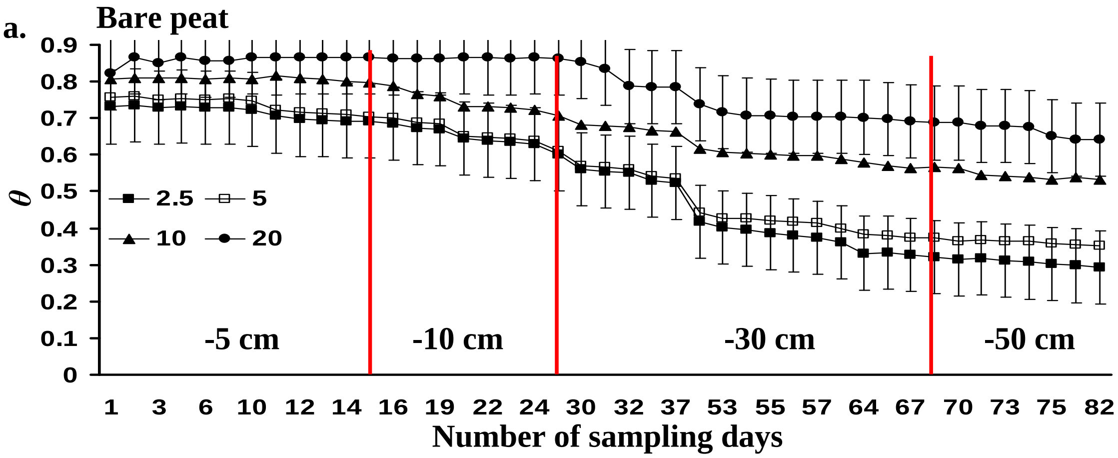
ψ reaches -100 cm at 2.5 cm below the surface in the bare peat by day 57 under a -30 cm *WT*, while the shrub never reached -100 cm over the sample period (Fig 5.4). *ψ* was progressively higher deeper in the profile for both monolith types (Fig 5.4), suggesting an upward flow from the bottom to the surface of the peat.

Table 5. 2. The decrease in soil water pressure (cm) at different depths in peat profile for different water table levels. (Parenthesis indicates the number of days the water table was set at a particular level)

Water table (cm)	**Change in soil water pressure (cm)**									
	Shrubs (tensiometer depth/cm)					**Bare peat (tensiometer depth/cm)**				
	2.5	**5**	**10**	**20**	**30**	**2.5**	**5**	**10**	**20**	**30**
-5 (17)	2	4	2	2	2	3	4	5	3	3
-10 (15)	7	9	8	8	7	9	10	10	8	10
-30 (36)	29	25.6	24	22	21	160	93	62	54	50
-50 (12)	28	17	13	12	10	92	36	18	9	16

Volumetric water content (*θ*) and diurnal water flux

Volumetric water content was consistently higher deeper in the peat profile and decreased at all levels within the peat monolith for both bare and shrub covered peat throughout the study period (Fig 5.5). The percentage loss in *θ* from all samples decreased from the surface to the base of the monolith (Table 5.3). However, the percentage loss of *θ* the through the profile was different for shrubs and bare peat. When the *WT* was high, (2.5 and 5 cm) losses were higher in bare peat (64 & 58%) than shrubs (39 & 39%), while at greater depths (10, 20 and 30 cm) losses were greater from the shrubs than from bare peat (Table 5.3).



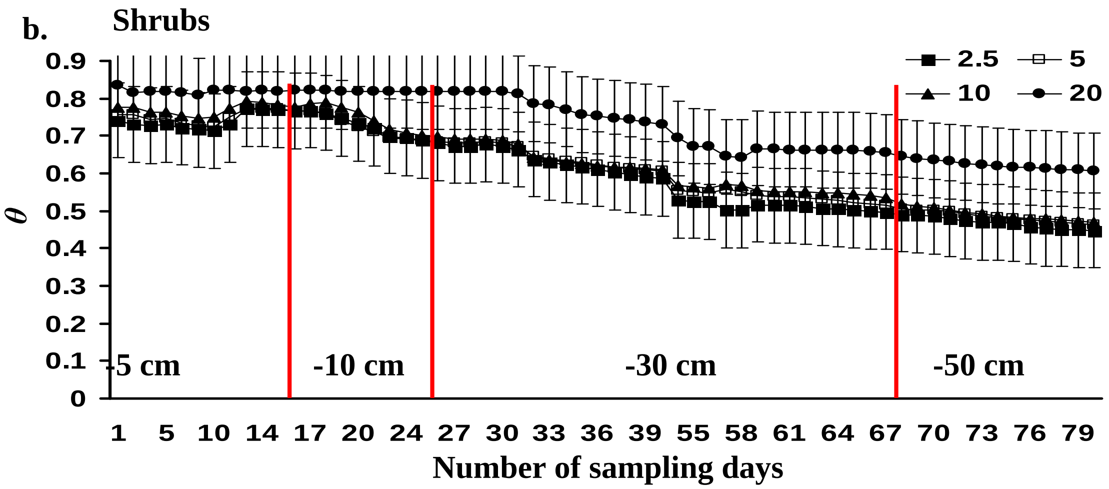


Figure 5. 5. Volumetric water content (*θ*) at 2.5 to 20 cm depths for a. bare peat and b. ericaceous shrub at different water table levels. (Standard error bars are for 2.5 and 20 cm depth profile)

Table 5. 3. Percentage loss in volumetric water content for bare and shrub covered peat at different depths in the peat profile from the start to the end of the study

Sampling depth (cm)	Percentage loss of volumetric water content	
	Bare peat	Ericaceous shrubs
2.5	45	35
5	40	37
10	28	35
20	25	37
30	5	11

The daily change in *θ* was observed for each sample throughout the peat monolith and was plotted as cumulative change (Fig 5.6). Cumulative change from the 2.5 (Fig 5.6 a) and 5 cm (not shown) layers were higher under the bare peat, while at 10, 20 (Fig 5.6 b & c) and 30 (not shown) cm water loss was higher for shrub covered peat. The greatest deviation in water loss between bare and shrub covered peat occurred after the water table was dropped to -30 cm (Fig 5.6).

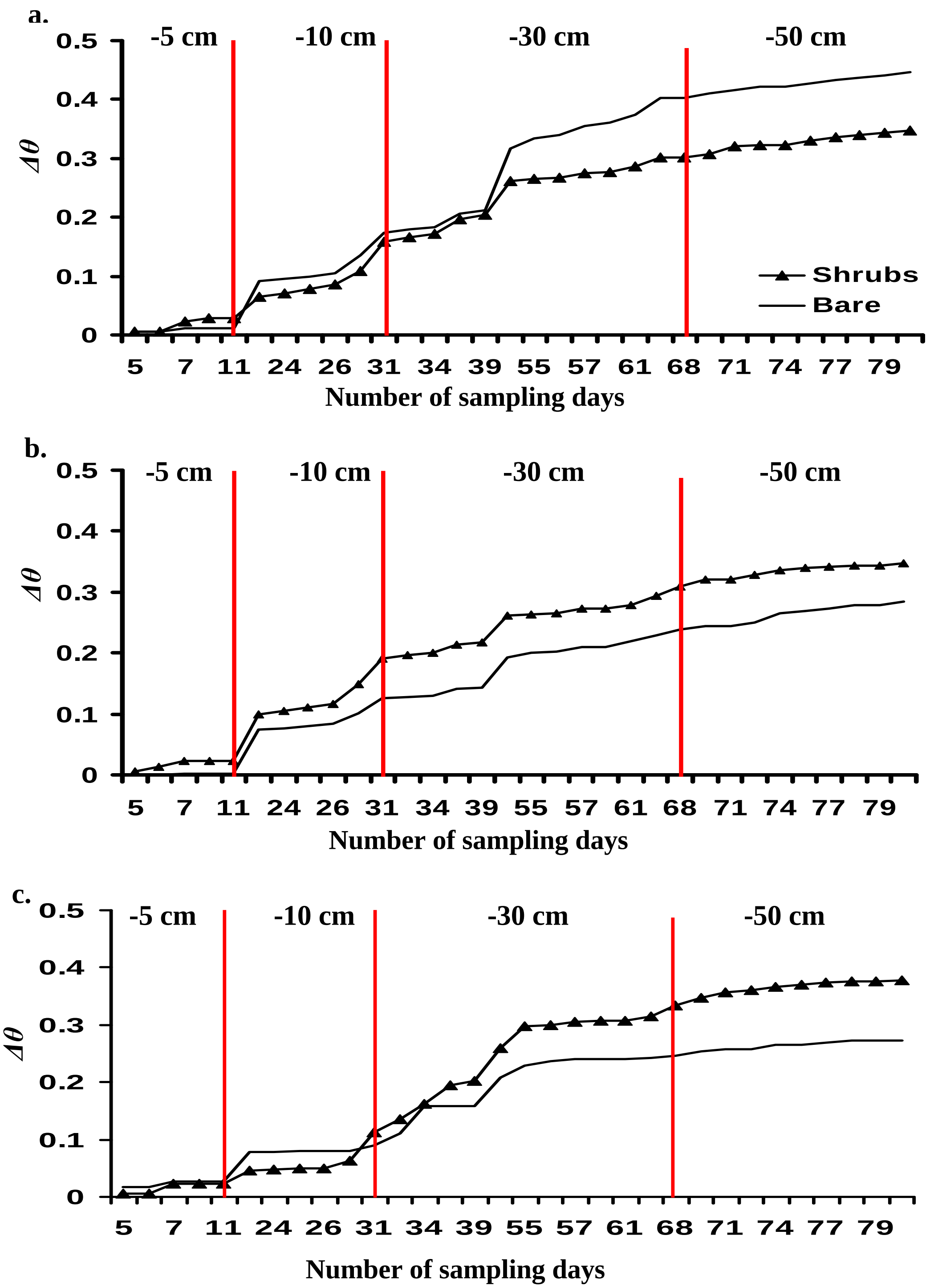
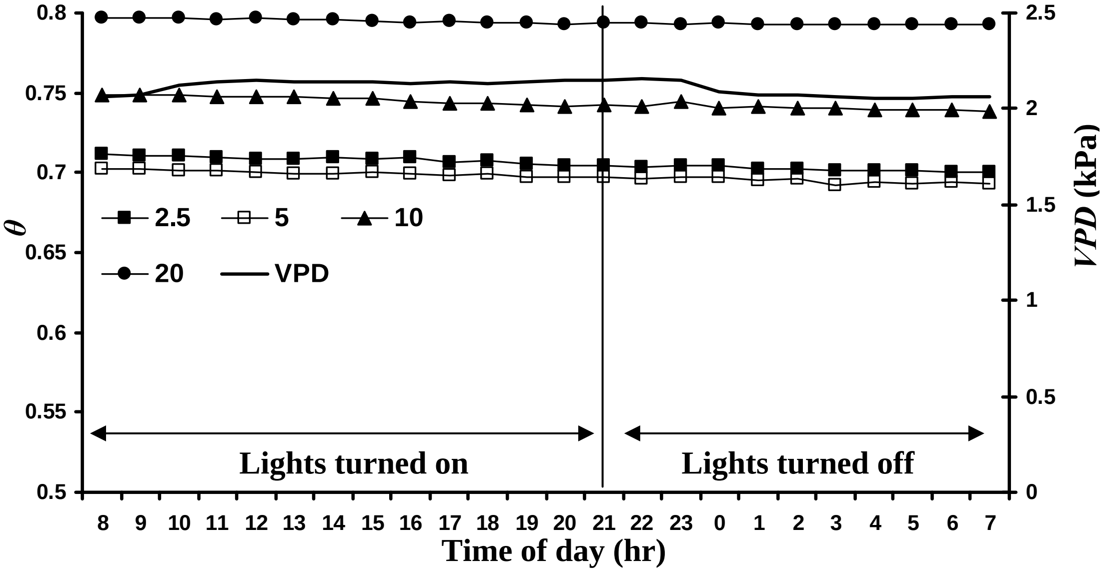


Figure 5. 6. Average cumulative change in volumetric water content at a. 2.5, b. 10 and c. 20 cm below the surface for bare (solid line) and shrub (triangle) over the study period. (Vertical lines represent lowering of water table to -10, -30 and -50 cm respectively)

The diurnal soil water flux was observed under the shrubs from 2.5 to 20 cm below the peat surface. Small (0.01) daily changes in θ were observed over the study (Fig 5.7). At *WT* between -5 and -10 cm water loss during the day was ca. 2 times that at night. The greatest difference in diurnal θ occurred at the 20 cm layer being 4 times higher in the day. When the *WT* was lowered between -30 and -50 cm daytime water use was twice that of night-time use and still greatest at the 20 cm layer (Fig 5.7). Daytime water use at the -10 cm depth doubled for *WT* between -30 and -50 cm. As the upper layers dries and the plant roots remain in contact with moist deeper layers hydraulic lift is typically observed. However, this was not recorded at $WT \geq -30$ cm, where θ declined throughout the day (Fig 5.7). Unlike θ, *VPD* increased between 8 – 22:00 hr but declined between 22 – 07:00 hr (Fig 5.7).

a.



b.

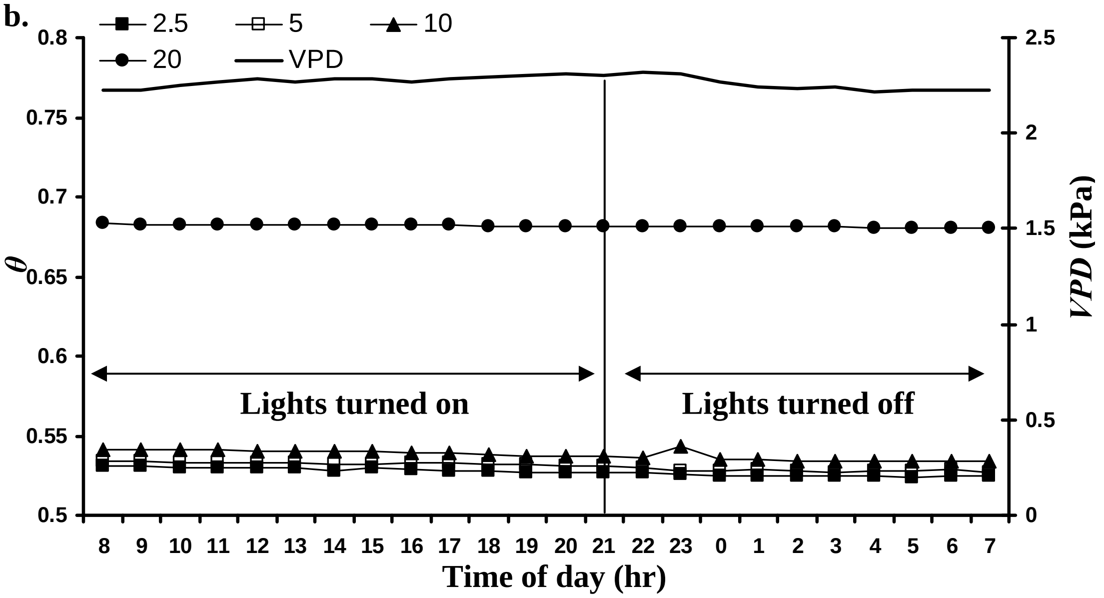


Figure 5. 7. Average daily diurnal changes in volumetric water content under shrubs at 2.5, 5, 10 and 20 cm below the surface and vapour pressure deficit of the air when the *WT* was between a. -5 and -10 cm and b. -30 and - 50 cm

5.4 Discussion

Et and *E* for shrubs and bare peat decreased as the *WT* was lowered (Fig 5.2). *θ* near the soil surface was greater a higher than low *WT* (Fig 5.5). High near-surface soil moisture increases the maximum rate that the soil-vegetation surface can supply water to the atmosphere. Eagleson (1978) defined this rate as the soil controlled *Et* rate. The reduced *E* and *Et* rates observed with falling *WT* is likely caused by the decreased rate of capillary rise associated with the lower *WT*. For natural peatlands a distinct decrease in the dynamic upward flow of water through capillary rise occurs when water tables fall beyond 30 cm from the surface (Romanov 1968; Schouwenaars 1993). This effect is further exaggerated in cutover peat (Price 1997) as low hydraulic conductivities reduce upward flow (Scholtzhauer and Price 1999). 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* increases until the *WT* falls below -30 cm (Table 5.1). Cumulative water loss from *E* and *T* are about the same (Fig 5.3), however, 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 and lost by *T*. At *WT* of -50 cm the ratio of *T/Et* decreases and may be a result of the water table occurring beyond the root zone or increased soil water deficit. The former is supported by Romanov (1968) who recorded a reduction in *Et* when water table fell below the rooting depth of shrubs (15 – 20 cm) and Lafleur *et al.* (2005) who recorded similar observations for natural peatlands. At high *θ* sufficient water can be supplied to plants to meet transpiration needs. As soil dries and θ decreases a larger water deficit is created in the soil. To conserve water the plants close stoma, reducing water loss by T (Dingman 2002). θ decreased through out the study (Fig 5.5) and the low T at -50 cm may therefore be more reasonably explained by stoma closure.

The greater cumulative water loss from shrub-peat monolith (Fig 5.3) suggests that subsequent drying of the soil would occur at a higher rate under shrubs than bare peat. However, in the upper soil layers θ and ψ were consistently higher for shrub-covered peat than bare peat and show that the bare peat dried at a faster rate (Fig 5.5 b). The presence of a thin litter layer (Chapter 4) and lower net radiation under the canopy (McNeil and Waddington 2003) reduces water loss from the surface of shrub covered peat. The greater cumulative daily change in θ at the 10, 20 and 30 cm depth below the shrub-peat surface (Fig 5.6, Table 5.3) indicate that the greatest water loss occurs from these levels. These values were between 55 and 65% of total losses from all samples. 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). Moore *et al*. (2002) recorded a maximum ericaceous shrub root depth up to 60 and 40 cm for hummocks and hollows respectively, while maximum densities between 20 and 40 cm and between 20 and 30 cm were observed, respectively. Lance (2008) recorded maximum root densities between 10 – 15 cm. Fine roots, which are more responsible for extracting water from the peat have a higher distribution between 10 – 25 cm (Moore *et al*. 2002; Lance 2008). The root distributions for these samples are unknown, but we assume that the higher percent water loss occurred as a result of greater root densities between 10 and 20 cm. 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 water from lower in the profile. In the experiment the water table was maintained at a set level and constantly fed by the mariotte bottle. Therefore water used by the roots can be quickly replaced by water from the mariotte bottle. The greater water use from these deeper layers coupled with the effects of the litter layer and canopy reduces water loss from the upper surface under a falling water table.

Consistent nightly diurnal increases in θ were not observed over the study (Fig 5.7). Hydraulic lift has been demonstrated under a number of deep (Richards and Caldwell 1987, 1989; Dawson 1993) and shallow rooted plants (Vetterlein and Marschner 1993; Wan *et al*. 1993). The previous studies have focused on hydraulic lift in arid regions, under drier soil conditions. The θ of the peat in this experiment remained above 50% and may not provide the critical pressure difference between the root and soil required for large water redistribution by hydraulic lift. *VPD* is important in controlling both transpiration (Wilson *et al*. 2001; Ray *et al*. 2002) and night-time evaporation (Iritz and Lindroth 1994). *VPD* (Fig 5.7) and air temperature (25±0.3°C) did not differ substantially when lights were on and off suggesting that *E* did not differ considerably during these cycles. Consequently there was little opportunity for diurnal hydraulic lift. The *VPD* observed in the lab was higher than what is typically observed in bogs. At sufficiently high *VPD* the atmospheric demand for water becomes too great and the stoma of the leaves close, reducing transpiration. It is unknown at what *VPD* stomatal closure in ericaceae occurs. If the *VPD* was too high and transpiration was reduced, the water loss observed under the shrubs may be underestimated over the study.To overcome the problems with *VPD* and temperature I suggest conducting a similar experiment in the field. Unlike the lab, *VPD* and temperature in the field is reduced at night resulting in lower *E*. Under these conditions and adjusting for increased θ by fog or rain, field validation will prove if hydraulic lift occurs under the cover of an ericaceous shrub.

Price and Whitehead (2001) suggest that θ and ψ of over 50% and -100 cm is necessary in the upper soil layer for the successful reestablishment of *Sphagnum* at the study site. This study indicates that soil covered by Sheep-laurel maintain θ and ψ of over 50% and -100 cm over a longer period than bare peat, and therefore assist in maintaining the hydrological conditions needed for successful regeneration and reestablishment of *Sphagnum*.

5.5 Conclusion

Under a falling water table, water loss from Sheep-laurel is higher than bare peat. Despite the greater water loss from the shrubs, the upper 5 cm of the bare peat dried at a faster rate. This is possibly a result of water loss reduction provided by a sparse litter layer (Price and Whitehead 2004; Chapter 4) and shading by the canopy (McNeil and Waddington 2003). The experiment shows that threshold values of ψ of -100 cm (Price and Whitehead 2001) in the upper 2.5 cm were not exceeded under an ericaceous shrub for most of the study and thus shrubs can be useful in the natural recolonisation of the moss. A water table above -25 cm is recommended to maintain suitable hydrological conditions at the surface (Price and Whithead 2001). At this *WT,* my data suggest the shrubs preferentially use the deeper water, and thus maintain higher θ in the upper 5 cm of the peat.

6.0 Conclusion and Recommendations

The Cacouna peatland is a harvested bog and receives most of its water from precipitation, and as such, interception from the canopy and the litter layer is particularly important, being the first and second source of water loss from the system, respectively. Interception from the canopy (33.7%) and litter (7%) were 40.7% or 120 mm of summer rainfall. This study suggests that rainfall intensity and duration were more important than gross rainfall in determining the amount of water intercepted. Other external factors such as temperature, humidity and frequency of events also influence rainfall interception, but to a lesser degree. Properties of the canopy (*LAI*) and litter (mass and thickness) also affect interception. The effect of these factors, excluding litter mass/thickness, were not observed over the study and provide future research opportunities in understanding the process of rainfall interception. It is important to note that interception values obtained are a feature of the annual rainfall regime. Therefore the overall depth of rainfall intercepted is applicable for the 2007 season and will change in subsequent years. However, the interception capacity of the canopy and litter is fixed and one can use these values to predict interception under changing rainfall regimes.

After interception the remaining precipitation arriving as throughfall, infiltrates the peat and is temporarily stored. This water is eventually lost primarily by evapotranspiration. Evapotranspiration from shrub covered areas was 2.5 mm day^{-1} (211 mm) over the season. Transpiration was 68% (142 mm) of total evapotranspiration losses, and represented the greatest water loss from the shrubs. Evaporation from the litter was lower than bare peat preventing 17 mm of water being lost to the atmosphere. The litter maintains higher water contents in the peat and is important in both short and long term water conservation. The study shows that the water loss through interception by litter is offset by reduced evaporation rates under it, and suggests litter is a more important tool for water storage at the peatland.

The laboratory experiments provided an interesting insight into soil water fluxes under an ericaceous shrub cover in a controlled environment. Evapotranspiration from the shrubs were higher than bare peat at all water table levels. However, most of this water loss occurred deeper in the profile as water uptake between 10 and 30 cm below the peat surface was greater under the shrubs. Higher water uptake at these levels matches up well with the maximum root densities recorded by Moore *et al*. (2002) and Lance (2008). Hydraulic lift is a useful ecosystem function as redistributed water may be used by plants unable to access deeper water. However, hydraulic lift was not observed in this study. This possibly due to: 1. the consistent vapour pressure deficit observed during the day and night suggests a steady evaporation rate. Even if there was an increase in moisture content the evaporation rates may have masked these changes. 2. Physiologically, ericaceous shrubs may not be able to redistribute water. This is possibly due to shrubs being found in a wet environment lacking substantial soil water deficits. Without such deficits hydraulic lift is not necessary.

The use of vascular plants in the reestablishment of *Sphagnum* has been observed in abandoned peatlands (Ferland and Rochefort 1997; Boudreau and Rochefort 1999). *Sphagnum* development is enhanced in the presence of plants, particular cotton grass

(*Eriophorum vaginatum*) (Lavoie *et al*. 2005). It has been suggested that the enhanced growth is due to the creation of suitable hydrological conditions caused by shading (Boudreau and Rochefort). Crum (1988) suggests that lower evaporation rates over moss surface are due to shading from shrubs, while Heijamns *et al*. (2001) attribute it to reduced wind velocities. Lower evaporation results in reduced soil water loss. Whatever the reason, observations in the field indicate that the moss becomes dry and brittle and eventually dies after the removal of ericaceous shrubs (McNeil and Waddington 2003). Price and Whitehead (2001) suggest that volumetric moisture content (θ) and soil water pressure (ψ) above threshold values of 50% and -100 cm respectively at the Cacouna peatland and ψ over -100 cm at other peatland types is needed for *Sphagnum* reestablishment. The lab experiments showed that shrubs maintained θ and ψ above the threshold. This was likely due to the presence of a fine litter layer, which reduced soil evaporation. These results are encouraging especially in abandoned harvested peatlands where no active restoration techniques are applied. In such situations the abundance of ericaceous shrubs will prove useful in *Sphagnum* development.

The major concern with using shrubs as companion species are the water losses through interception and transpiration. To overcome these losses it is recommended that the water table be raised within 20 cm of the surface. At this level water can be supplied to the peat surface by capillary rise, maintaining θ and ψ above 50% and -100 cm respectively (Whitehead 2001). At the higher water table, water is supplied to the most active layers of the root zone reducing the need of the roots to extract water from the surface. The litter layer also poses a problem as it acts as a barrier cutting off capillary flow between

Sphagnum and peat surface (Price and Whitehead 2004). However, it is possible for *Sphagnum* to establish itself over the litter in areas saturated at the surface (Price and Whitehead 2004). The results show that the evaporation retarding effects are not lost when the peat is saturated.

The main goal of peatland restoration is to return harvested sites to a naturally peat generating ecosystem. An active peat accumulating system is important as it becomes a sink of atmospheric carbon. To acquire the benefits of the shrubs such as shading and reduced wind speed one must ensure that the water table is sufficiently high to offset water losses from interception and supply enough water to meet daily transpiration rates. As such, ericaceous shrubs may be beneficial in the reestablishment of a *Sphagnum* cover at abandoned peatlands that have not undergone active restoration and, even at active restoration sites I suggest mixing of ericaceous seeds with *Sphagnum* diaspores, which would benefit the moss as it grows. The positive effects of the shrubs are not limited to the Cacouna field site. The research from this thesis will benefit restoration in other peatlands across North America and Europe where the application of ericaceous shrubs or similar plant types will be effective in the growth and regeneration of *Sphagnum*, the primary peat forming vegetation.

Future studies of Ericaceous shrub – *Sphagnum* – water interactions may include;

1. Interception of ericaceous shrubs in natural bogs. Including throughfall and stemflow and channelisation of rainfall along the roots.

2. Observations of diurnal fluctuations of volumetric water content in the field. This reduces the error brought about by consistent air temperatures observed in the laboratory experiments.
3. Analyses of maximum root depth and densities of ericaceous shrubs, which would allow us to link the zone of maximum water uptake with root distribution.
4. The influence of roots in the flow (hydraulic conductivity) and retention of water within the peat. This can be done using under a series of laboratory experiments (Price *et al*. 2008).

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Appendices

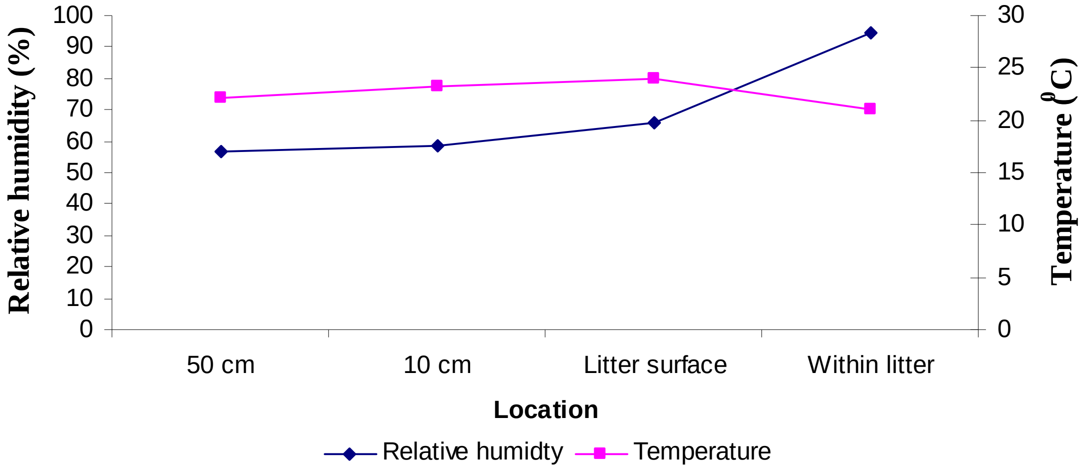
Appendix A1. Percent cover of Shrubs and mosses along baulks and trenches at the Cacouna peatland

Plant	**Percent cover (%)**			
	Baulk 1	**Baulk 2**	**Trench 1**	**Trench 2**
Kalmia angustifolia	43	45	27	24
Chamaedaphne calyculata	10	17	16	6
Ledum groenlandicum	13	4	6	3
Other shrubs	15	21	16	12
Total shrubs	81	87	65	45
Sphagnum	0	0	0	59
Other moss	10	2	0	1

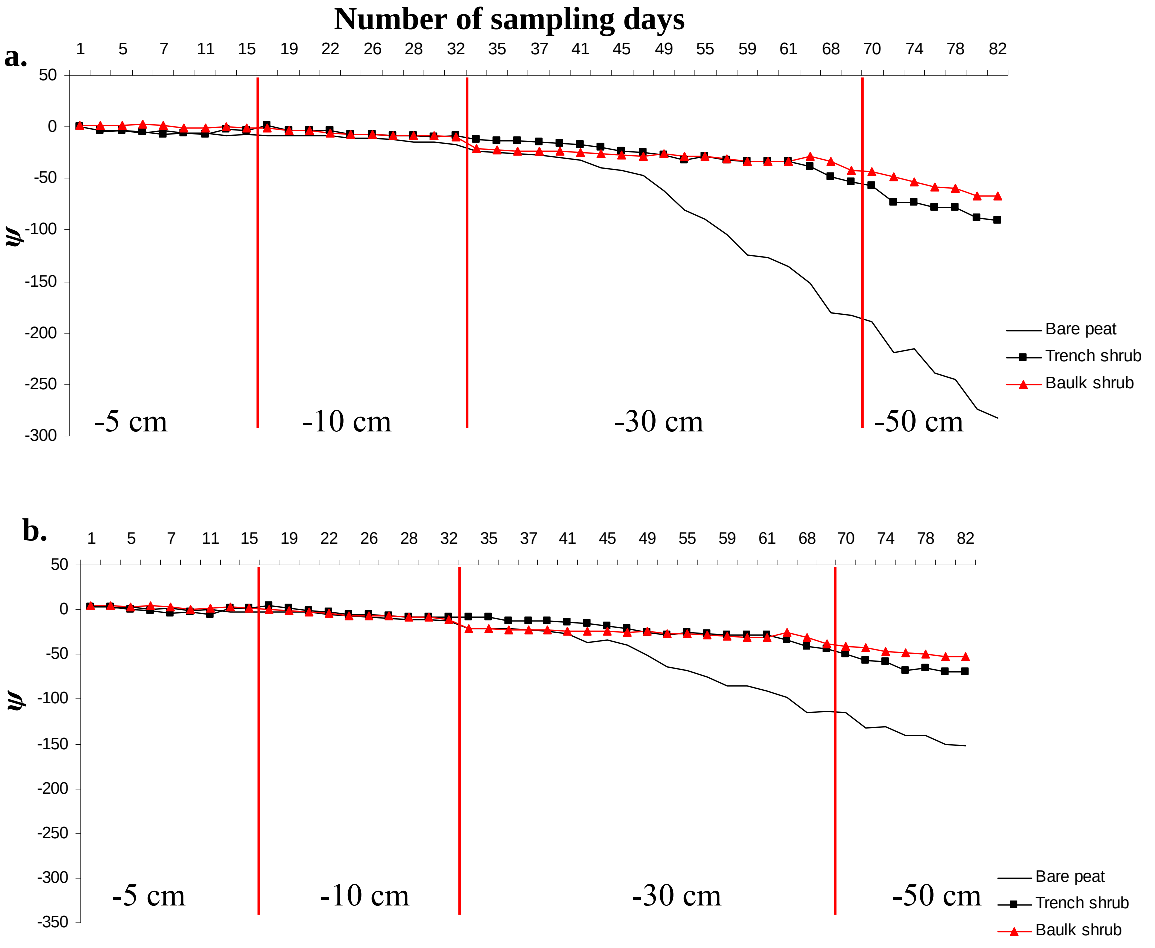
Appendix A2. Average height of ericaceous shrubs along baulks and trenches at the Cacouna peatland

Location	Average height (cm)	Maximum height (cm)	Minimum height (cm)
Baulk 1	47	83	23
Baulk 2	45	87	19
Trench 1	35	96	4
Trench 2	24	69	7

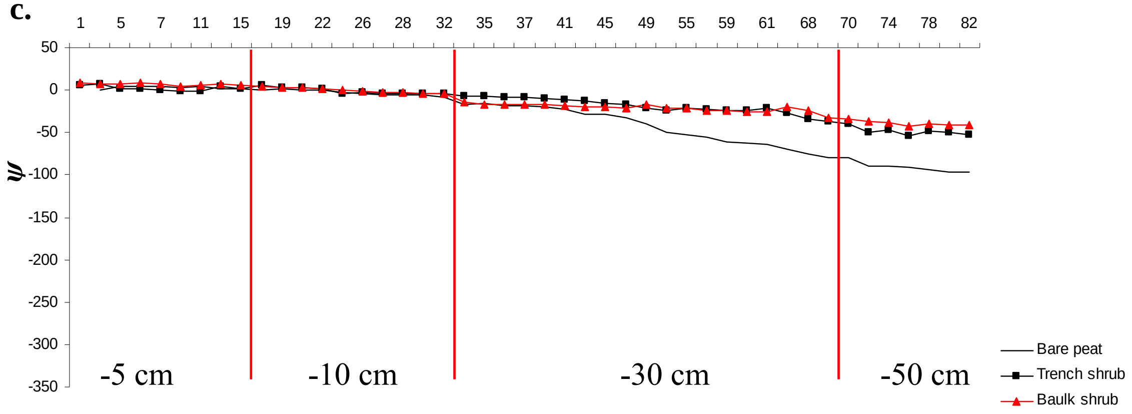
Appendix A3. Relative humidity (%) and Temperature (°C) at 50 and 10 cm above the peat surface, on the litter surface and within the litter layer



Appendix B. Soil water pressure (*ψ*) at a. 2.5, b. 5, c. 10, d. 20 and e. 30 cm below the surface for shrub covered and bare peat at different water table depths over the experimental period

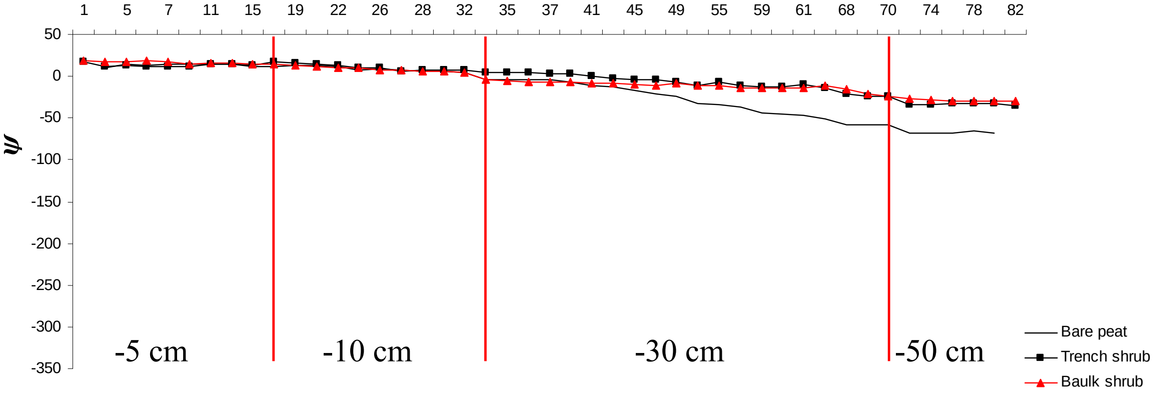


c.



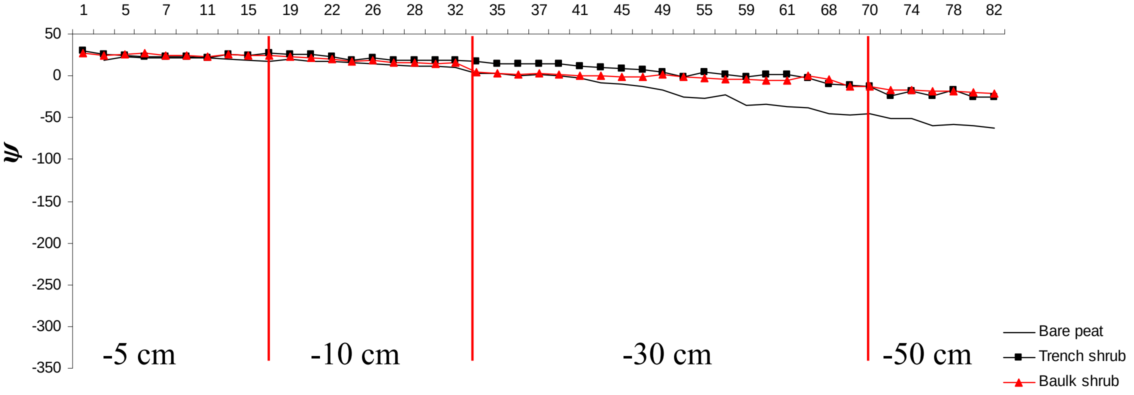
1 5 7 11 15 19 22 26 28 32 35 37 41 45 49 55 59 61 68 70 74 78 82
50 0 -50 -100 -150 -200 -250 -300 -350
ψ
-5 cm
-10 cm
-30 cm
-50 cm
Bare peat
Trench shrub
Baulk shrub

d.



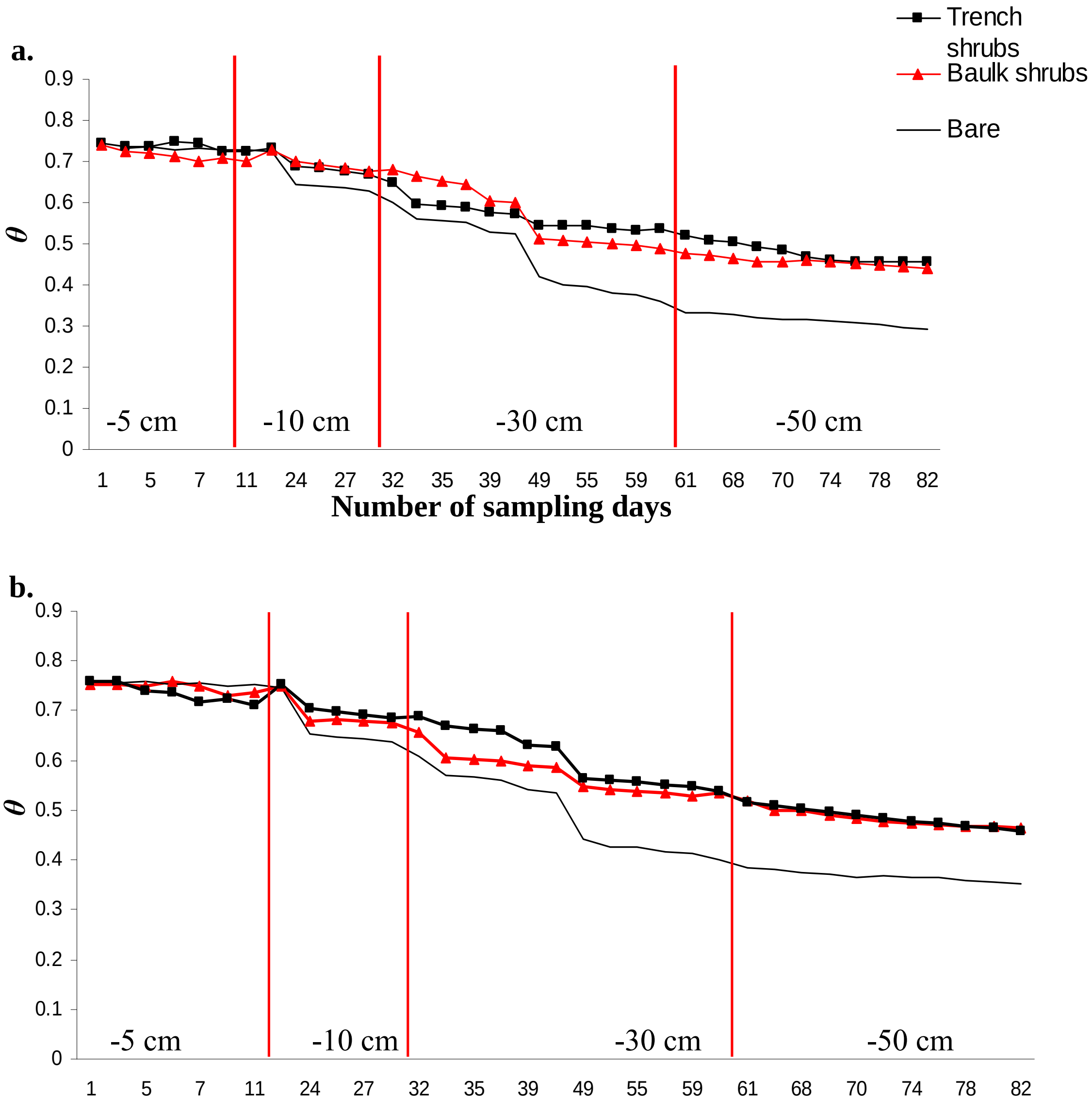
1 5 7 11 15 19 22 26 28 32 35 37 41 45 49 55 59 61 68 70 74 78 82
50 0 -50 -100 -150 -200 -250 -300 -350
ψ
-5 cm
-10 cm
-30 cm
-50 cm
Bare peat
Trench shrub
Baulk shrub

e.

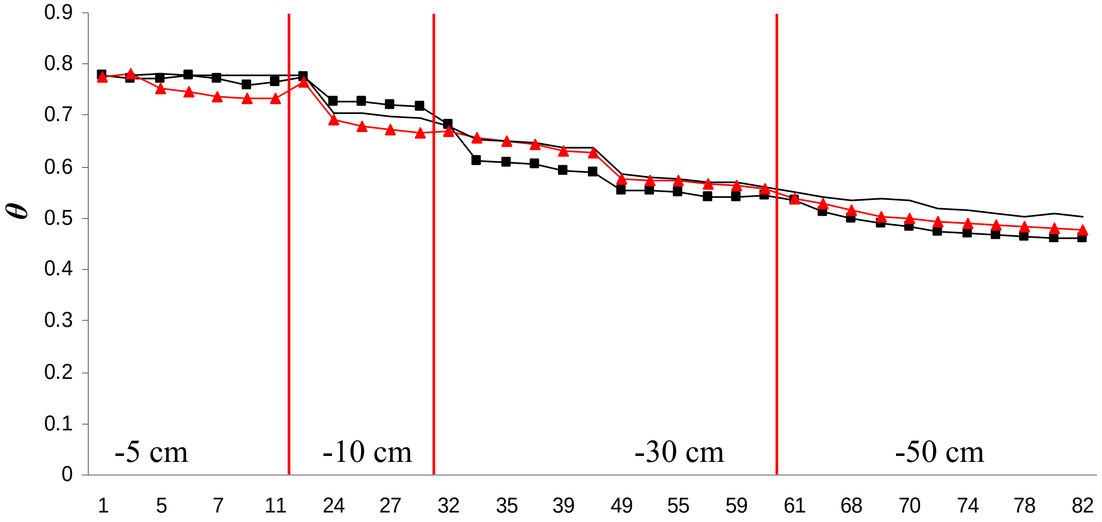


1 5 7 11 15 19 22 26 28 32 35 37 41 45 49 55 59 61 68 70 74 78 82
50 0 -50 -100 -150 -200 -250 -300 -350
ψ
-5 cm
-10 cm
-30 cm
-50 cm
Bare peat
Trench shrub
Baulk shrub

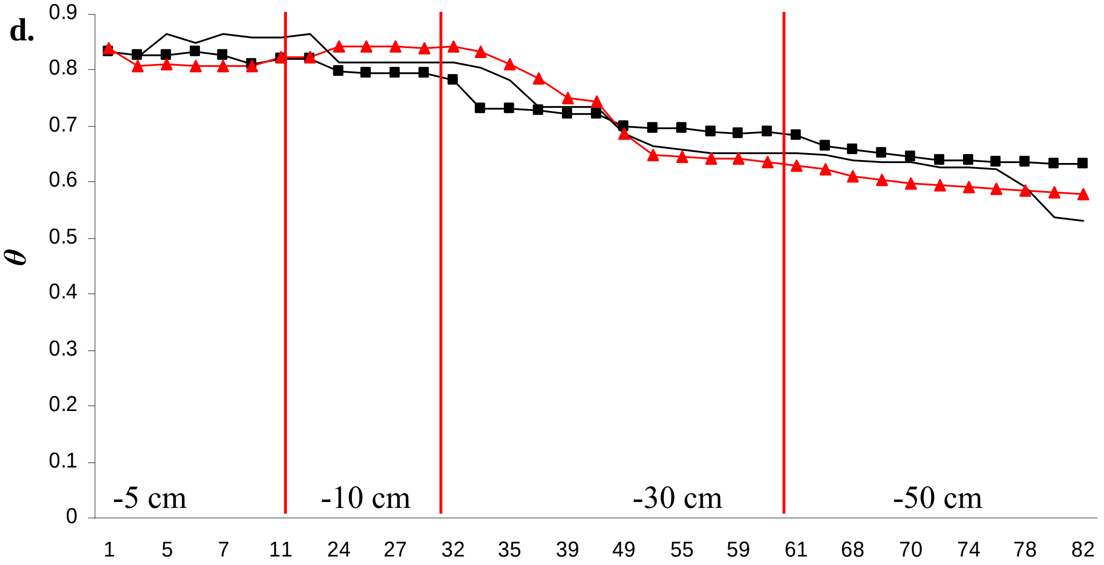
Appendix C. Volumetric water content at a. 2.5, b. 5, c. 10 and d. 20 cm below the peat surface for shrub covered and bare peat at different water table depths



c.


θ
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-5 cm
-10 cm
-30 cm
-50 cm
1
5
7
11
24
27
32
35
39
49
55
59
61
68
70
74
78
82

d.


θ
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-5 cm
-10 cm
-30 cm
-50 cm
1
5
7
11
24
27
32
35
39
49
55
59
61
68
70
74
78
82