RAINFALL INTERCEPTION: RESPONSES WITH LICHEN CANOPIES ALONG THE HUDSON BAY LOWLANDS OF CHURCHILL, MANITOBA

KATERINA SOFOS

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ABSTRACT

Interception is the proportion of a rainfall retained by the plant canopy that does not reach the ground and is subsequently evaporated. Despite their small size, lichens are exceptionally good at intercepting rain because of their fungal structure and therefore can have a profound impact on regional hydrology in the Subarctic. Four selected habitats were chosen to conduct an inventory of lichen biomass near Churchill, Manitoba to determine their differences in biomass and maximum storage capacity. A weather station was built with weighing lysimeters to analyze*in situ* interception of four lichen canopies. Measured evaporation is compared with the Penman-Monteith model to examine how the availability of canopy moisture controls evaporation through changes in canopy resistance, with the aim of quantifying antecedent storage capacity for interception during subsequent rainfalls.

ACKNOWLEDGMENTS

At a very young age I grew a passion in learning about physical geography and climate change. Due to the lack of guidance and proper teaching criteria, the process of learning more and more was not at a fast pace until my third year during my undergrad. I took a field studies course where my passion grew and I decided to not wait any longer and to follow my passion. The professor who guided me and helped me to reach my goals of where I am today is the same professor and now supervisor Dr. Richard Bello. I would like to thank him for being an incredible mentor, encourager, and inspiration throughout my academic career. I would also like to thank my partner during the research season Devin Ali who has also helped me significantly. Special thanks also go to the Churchill Northern Studies Center for accommodating me and who has only been supportive and welcoming through the three summers I have spent there. I would also like to thank the funding I received from York University, the Northern Scientific Training Program, and of course the CNSC. Finally, I would also like to thank my friends and family who have supported me throughout this thesis. It is all of those who are mentioned that have brought me closer to reaching this goal; my dream.

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CHAPTER ONE: INTRODUCTION

1.1

Interception is the proportion of a rainfall retained by the plant canopy that does not reach the ground and is subsequently evaporated (Thomas, 2016). Despite their small size, lichens are exceptionally good at intercepting rain because of their fungal structure. Their fungal structure has the ability to hold large amounts of water and therefore can have a profound impact on regional hydrology in the Subarctic where they can be locally abundant and where lichen canopies grow quite thick. As the climate warms and atmospheres become increasingly unstable, drizzles may be displaced by thunderstorms and potentially much more precipitation will evade interception and enter the groundwater system as a result of the deterioration in rainfall interception owing to this change in climate (Trenberth, 2008). If Subarctic lichens experience changes in rainfall interception in the future, this could lead to enhanced methane emissions due to increased soil moisture, as well as the potential of spreading infectious diseases (e.g particular mosquitoes are well knownvectors of infectious diseases worldwide) due to surface ponding of water. Interception by Arctic and Subarctic vegetation has received little attention overall, but deserves consideration especially since northern environments are being so profoundly affected by climate change. Discussions of climate change typically revolve around possible changes in future temperatures, which can pose a great challenge to ecosystems, but changes to climate in the form of hydrology and winds may be equally or more important.

To fully understand interception, a detailed knowledge of evaporation is required. Evaporation is the process of liquid water changing into water vapour (Ward and Robinson 2000). It is the depletion of water in the plant canopy which enhances its capacity to intercept the

next rainfall. *Potential evaporation* defines the maximum rate water will evaporate under given energy and atmospheric conditions when moisture supply is non-limiting and is very similar for all surfaces within a given environment. *Real or actual evaporation* on the other hand, is also controlled by water availability which is very distinctive from one plant canopy to another. Pure water surfaces and canopies which are laden with water, evaporate much faster because water is freely available compared to only moist soil surfaces or canopies with few cavities to store rainwater as moisture supply is more restrictive. Real evaporation depends on atmospheric demand, energy supply, and moisture availability. Monitoring these three factors while real evaporation is also being recorded will not only permit better estimates of the plant canopy's ability to intercept rainfall during the proposed field season, but will also shed light on how interception might be affected in the future as climate change induces changes in atmospheric demand, energy supply and moisture availability in the Hudson Bay Lowlands.

CHAPTER TWO: LITERATURE REVIEW

2.0 The Hydrological Cycle and the Links of Climate Change

2.1 Hydrological Cycle

The hydrological cycle is known to be the largest and continuous movement of water on earth that moves from the oceans to the atmosphere (Barron et. al.,1989). The hydrological cycle also influences and shapes the Earth's climate. One of the most crucial roles the hydrological cycle playsis in the exchanges of moisture and heat between the atmosphere and the Earth's surface which affect the dynamics and thermodynamics of the climate system (Trenberth 1999). Main components of the hydrological system areclouds, humidity, precipitation, evaporation and the energy that drives the movement between the atmosphere, ocean, and land.

Water plays vital roles in heating and cooling the environment in forms of vapour, liquid, and solids. Water vapour defined as the gaseous phase of water (Bengtsson 2010)in the atmosphere, plays a significant role and nearly doubles the effects of greenhouse warming caused by carbon dioxide and methane. As well, the oceans hold 97% of the world's water, far exceeding the atmosphere which only holds 0.001%. The remainder is locked up by ice caps, snow, and underground storage (Trenberth, 1999). A high percentage ~50% of surface energy usage results from evaporation while clouds influence the Earth's radiation budget and thereby control climate. Condensation that is released from latent heat provides 30% of the thermal energy inputs to the atmosphere which controls the Earth's atmospheric circulation (Trenberth 1999). On land, 35% of precipitation occurs from humidity from marine evaporation which is usually driven by winds, whereas 65% of precipitation is from evaporation over land. Precipitation that exceeds evaporation over land returns to the oceans as runoff (Trenberth 1999).

The hydrological cycle has many important roles and complex exchanges including how water reaches the surface, and the influence of further movement such as the exchange of organic and inorganic matter (Dodorico 2010). Given the importance of the hydrological cycle and its influence, it is important to take into account possible changes in precipitation. One of the many gaps in understanding the hydrological cycle is the degree to which the mechanisms governing the distribution of water influence interactions with the climate system. The atmosphere, upper ocean layers, and land surface determines the regional patterns of climate change. Regimes, such as the slower ones consisting of the bulk of the ocean, land glaciers, and ice caps, alter the responses of the climate system. Therefore, one of the most obvious gaps is the lack of quantitative knowledge.

Precipitation is highly variable globally (two thirds occurs between latitudes of 30 degrees north and south). It highly influences the distribution of vegetation, droughts, floods, and large-scale circulation of the atmosphere and oceans. Latent heat of vaporization (or condensation) influences the dynamics of the interactions between the atmosphere, oceans, and land (Chahine 1992). The global hydrological cycle is influenced by evaporation and precipitation over land. This energy mainly comes from radiation that is absorbed by the surface from the sun depending on surface factors such as albedo. Albedo, which is the measure of the reflectivity of a surface, is influenced by vegetation and bare soil conditions (Chahine 1992). Changes that occur in soil moisture and vegetation strongly influences evaporation and ultimately runoff which can influence and change surface conditions.

Land surfaces highly influence the hydrological cycle for several reasons. For instance, in higher latitudes with snow and land ice, the surface will accumulate precipitation it receives

during the winter which will eventually be released back into the atmosphere in the summer (Chahine, 1992). Vegetated surfaces also accumulate water on land surfaces that complicate representations of land surfaces in the hydrologic cycle. Shape and physiology of vegetation also influences radiation through absorption and reflection that also control the latent heat flux (Chahine, 1992). Improved understanding the hydrological cycle helps in forecasting the importance of precipitation as it relates to climate change.

2.2 Changes of the hydrological cycle due to Climate Change

One of the most pronounced examples of how climate change affects the hydrological cycle includes an increase in "heavy" precipitation events (Trenberth, 1998). An increase in extreme storm events is anticipated because surface heating will increase surface vapour pressure, air warming will increase the capacity of the atmosphere to carry more water, and surface heating will increase buoyant convection and atmospheric instability which provides the cooling mechanism for the formation of clouds.

This is further complicated by the possibility that the increase in rainfall mismatches the increase in the rateof evaporation depending on the future role of advected moisture from the oceans.(Trenberth 1998). Current models link the amplification of surface temperature in the north with the ice-albedo feedback, whereas northern atmospheres receive most of their energy through the poleward of energy from equatorial regions by winds and ocean currents. Ice-albedo feedback involves the process of melting glaciers, ice caps, and sea ice which decreasesthe reflectivity of the Earth's surface, amplifying warming, leading to further ice melt (Curry et. al., 1995).

Aside from the increase in extreme rain events, changes in the frequency of precipitation events are also important. Increasing the length of drought between rain events has the potential to increase plant stress, and the resulting surface dryness inhibits infiltration and enhances surface runoff further reducing the supply of soil water. These factors can contribute to a shift in vegetation composition in the longer term.

2.2.1 Climate Change Trends

Climate change models show that warming is more rapidin the north than elsewhere on Earth (Walsh 2009); though there has yet to be a clear indication of how much precipitation willchange as climate change progresses with models both showing increases and decreases in specific locations.With higher average temperatures in winter, more snow is likely to fall as the atmosphere's capacity to hold humidity increases (Trenberth, 1998). In addition, faster snow melt will occur which can cause flooding, and an increase in both soil moisture and runoff in spring and early summer. Churchill, Manitoba has faced severe flooding issues due to the snow melt in the spring of 2017 which generated floods which washed out the railway for the Hudson Bay Railway and has had a severe impact on the communities dependent on rail transport (Lambert, 2017). Changes to the hydrologic cycle can have both socio-economic consequences as well as environmental consequences.

2.3 Literature Review of Rainfall Interception and Canopy Water Balance

This portion of the thesis will introduce interception; examining its importance to the canopy water balance and the conceptual models that were first employed while it was being developed. Following this section, interception will be further discussed by examining its sensitivity to evaporation; its parameterization and the way interception is measured. In this

discussion, evaporation is differentiated from transpiration as the former originates as water residing *on* the canopy from rainfall or dew, not subject to physiological control by the plant. Transpiration describes water passing through the root, xylem, and stomatal continuum to the atmosphere, which *is* under physiological control by the plant through variations in stomatal resistance. These two streams are distinct because the leaf cuticle does not allow for passage of water from one stream to the other in vascular plants. Together, the two streams are often described as evapotranspiration from the plant canopy to the atmosphere. Lichens, it should be noted, have no vascular system and do not transpire.

Rainfall interception is a fundamental concept that is important to the forest hydrologic cycle and is also a critical parameter when estimating total ecosystem evapotranspiration, as well as for developing water balance models particularly atthe watershed scale (Zimmerman et. al., 2007) (Ward and Robinson 2000). When precipitation falls onto the vegetated surface, only a certain amount may reachthe soil surface directly (direct throughfall) depending on several factors such as the nature, and/or the density of the vegetation cover. The proportion not falling directly through the canopy, may be intercepted by leaves or stems of the vegetation canopy and may temporarily be stored onto its surfaces (Ward and Robinson, 2000). Some of the temporarily stored water can be evaporated back into the atmosphere, which is also sometimes termed interception loss (Ward and Robinson, 2000). The rest of the landing rainfall will be routed down stems, branches andtrunks of trees to the ground (stem flow)or drip off leaves (leaf drip) to the ground until the water in the canopy is depleted to the maximum storage capacity, where it can drain no more under the influence of gravity. From this point onwards, intercepted water residing in the canopy can only be depleted by evaporation. Direct throughfall, stemflow and leaf drip combined constitute total throughfall, sometimes referred to as net rainfall. Interception and

evaporation are thus equal in terms of hydrologic processes, though evaporative loss can only occur when the vegetated canopy is wet. Therefore, it is dependent upon short-term variation in rainfall, and intervening drought intervals.

Interception is important for several reasons. Firstly, the net rainfall that arrives beneath the vegetation is generally less than the gross rainfall falling on top of the vegetated surface. This is important because the spatial variability of rainfall is unpredictable, and if there are small rainfall events with little reaching the soil surface, this can have a significant impact on the water balance of a drainage basin. For example, throughfall and meltwater are typically concentrated at the edges of tree crowns while stemflow itself can cause high values of infiltration and soil moisture recharge at the base of the tree, as well as initiation of minor rills and channels in the surface and a change in water chemistry (Anderson et. al.,1976). Other impacts that are influential due to the passage of rainfall through the vegetation foliage can be the drop size which can have implications for soil erosion. (Anderson et. al.,1976).

When interception was first being examined, there were two opposing views on what controlled evaporation and transpiration from vegetation.Initially those interception losses were believed to have no effect on the catchment water balance, compared to current understanding that interception reduces net inputs along with diminishing soil water recharge and streamflow (Calder et. al.,1983). At that time, it was argued that the evaporation of intercepted water was balanced by water uptake by vegetation transpiration which is suppressed or ceases when the foliage is wet (Calder et. al.,1983). In other words, it was assumed that the overall effect of interception on the water balance would be so small or it would be considered neutral (Shuttleworth et. al.,1983).

The neutral hypothesis states that interception losses are essentially evaporative in any time period depending on the amount of energy available (Shuttleworth et. al., 1983). The available energy was used to transpire water from leaves, or to evaporate intercepted water. Further, interception is at least partly balanced by a reduction in transpiration that would occur if there was no rainfall.

Several experiments took place measuring interception during the 1960's. One of the examples focused on grasses which indicated there is no difference between the evaporation of wetted foliage and the transpiration of unwetted grass irrigated with water (McMillan and Burgy 1960).Factors such as vegetation density and canopy gaps were focused on to define differences between interception loss and transpiration. That experiment concluded that interception evaporative loss is balanced by an equivalent reduction to transpiration where interception losses are an alternative pathway for water loss to the atmosphere, not an addition to transpiration, with little, if any, net effect upon the water balance. Another experiment within a spruce forest included measurements of gross and net rainfall as well as surface drainage. Results based on this experiment using a small weighing lysimeter demonstrated annual water use was fifty percent greater than that recorded at either a grass covered percolation gauge or a nearby grass covered catchment (McMillan and Burgy 1960). The forest water loss appeared to be significantly greater than the net radiant energy available for evaporation due to interception. Interception was revealed not as alternative to transpiration, but as a net loss of water that would have otherwise been used to replenish soil moisture and groundwater. The debate that revolved around these experiments were if evaporation from wetted surfaces of vegetation could be at a significantly higher rate than transpiration from unwetted vegetation and whether or not significant evaporation of intercepted water could occur when transpiration rates would be small

(e.g. wetted dormant vegetation) (McMillan and Burgy 1960). These questions needed to be addressed in order to explain the sources of energy for enhanced evaporative losses. This is where the experiments of Howard Penman came to apply. He confirmed that, "*Whilst energy was being used up to get rid* of the intercepted *water*, the same *energy* could not be *used* to *get rid of the transpired water*" (Penman 1963).

It was the field experiments throughout the 1960's, that supported the conclusion that intercepted water indeed evaporated more easily and much faster than transpired water. Much of the evaporative losses of intercepted water thus result in additional losses within the water balance. Further theoretical analysis illustrates interception rates are influenced by meteorological conditions. Meteorological conditions include wind speed and the humidity deficit in the air, evaporation rate, rainfall rate and duration, as well as non-meteorological factors dependent on canopy structure (age and composition) (Murphy and Knoerr 1975).

Windspeed is one of the more influential components of evaporation especially when the air is unsaturated. Evaporation will vary with windspeed such that during longer periods of rainfall the interception loss will be greater under windy conditions (Murphy and Knoerr 1975). Duration of rainfall also helps influence interception by affecting the balance between how much water is held in on the vegetated surface on one hand, and increased evaporated losses on the other. The amount of water withheld on a vegetated surface after the losses due to drainage, is referred to interception storage capacity, or maximum storage capacity (Ward and Robinson 2000).

Net interception loss is understood to decrease as the proportion of night time rainfall increases due to reduced nocturnal evaporation due to decreased temperatures and net radiation. Evaporation requires energy (latent heat of vapourization) which is much more abundant during

the daytime. In high rainfall environments such as maritime climates, rainfallsmore commonly occur during the night where the impact of interception as an evaporative loss and the magnitude of the net loss may be reduced compared to areas of more day-time precipitation (Pearce et. al.,1980). Specific plant conditions may alter differences in net interception losses overall. This is because evaporation from the canopy may be limited due to the availability of water rather than energy. As such the loss of water through evaporation would initially be large immediately following the rainfall but progressively decline as the drought interval becomes longer, everything else being equal. Aside from the specific weather conditions, it is also the storage aspect of interception loss that plays a vital factor in affecting catchment water balance.

2.3.1 Maximum Storage Capacity

The maximum storage capacity is the minimum amount of water to completely saturate the canopy surface. This is a vital component as both the rate of evaporation from the wet canopy and the amount of interception depends on the storage deficit in the canopy (i.e. how depleted the actual canopy storage is compared to maximum storage capacity)(Gavazzi et.al., 2016). If the vegetation is dry prior to a rainfall, the interception is usually the greatest initially depending on the intensity of the rainfall event. During an extended rainfall event, the interception will reduce with time as the storage deficit approaches zero. How quickly this occurs, varies amongst the various plant communities making up the forest (Klassen, 1996). The larger the maximum storage capacity, the more precipitation is prevented from reaching the ground.

The amount and duration of rainfall influence interception losses. When there is a high intensity rainfall event, the canopy storage deficit is filled quickly. Intervening rain-free periods increase the storage deficit through evaporative losses, depending on their duration. In general, a

canopy will intercept more water during five distributed 1 mm rain events than during a single 5 mm rain event.

2.4 The Rutter Model

One of the original and most highly utilized interception models is the Rutter Model (Figure 1). Here C is the actual amount of water residing in the canopy and S is the maximum storage capacity of the entire canopy. C can temporarily exceed S during which time drainage occurs and the rate of drainage depends on C-S and decreases exponentially as C approaches S, when C=S, it ceases altogether. The term pP describes the proportion of rain that directly reaches the ground while p is the proportion of the canopy comprising gaps. The term (1-p)P reflects the proportion of rainfall interacting with the canopy. The Rutter Model was the first to provide a conceptual and physically based model representing interception processes by a running water balance of rainfall input, storage, and output in the form of drainage and evaporation (Muzylo et. al., 2009). Drainage and evaporation rates both depend on the amount of water storied in the canopy. Rutter (1975) also introduced the stemflow module that has been developed and incorporated into the Rutter Model. Stemflow represents a fraction of the rainfall that flows down a trunk or stem of a plant when canopy storage exceeds the maximum storage capacity (Muzylo et. al., 2009).

Spatial and temporal behaviour of evaporation is controlled by surface and atmospheric factors including radiant energy supply, atmospheric demand (wind speed and moisture deficit) and moisture availability (Ward and Robinson, 2000). In this simplified evaporation module, whenever the canopy is storing the same or more water than the maximum storage capacity (i.e. C>=S), evaporation proceeds at the potential evaporation rate. However, when C<S then the

evaporation rate is reduced by a factor C/S relative to the potential evaporation rate. With drainage and evaporation rates both depending on the amount of water stored in the canopy, they tend to vary throughout the drying event in such a way that drainage takes advantage of excess water while C is increasing during which time evaporation rates are insensitive to excess water because water is freely available as long as C>S. Once canopy storage declines to S, drainage stops completely and the sensitivity of evaporation to C/S is linear. (e.g. when C/S=0.7 actual evaporation is 70% of potential evaporation). When C=0 evaporation stops as the canopy is completely dried out. Note that the Rutter model describes intercepted water only and therefore evaporation. It does not describe transpiration.

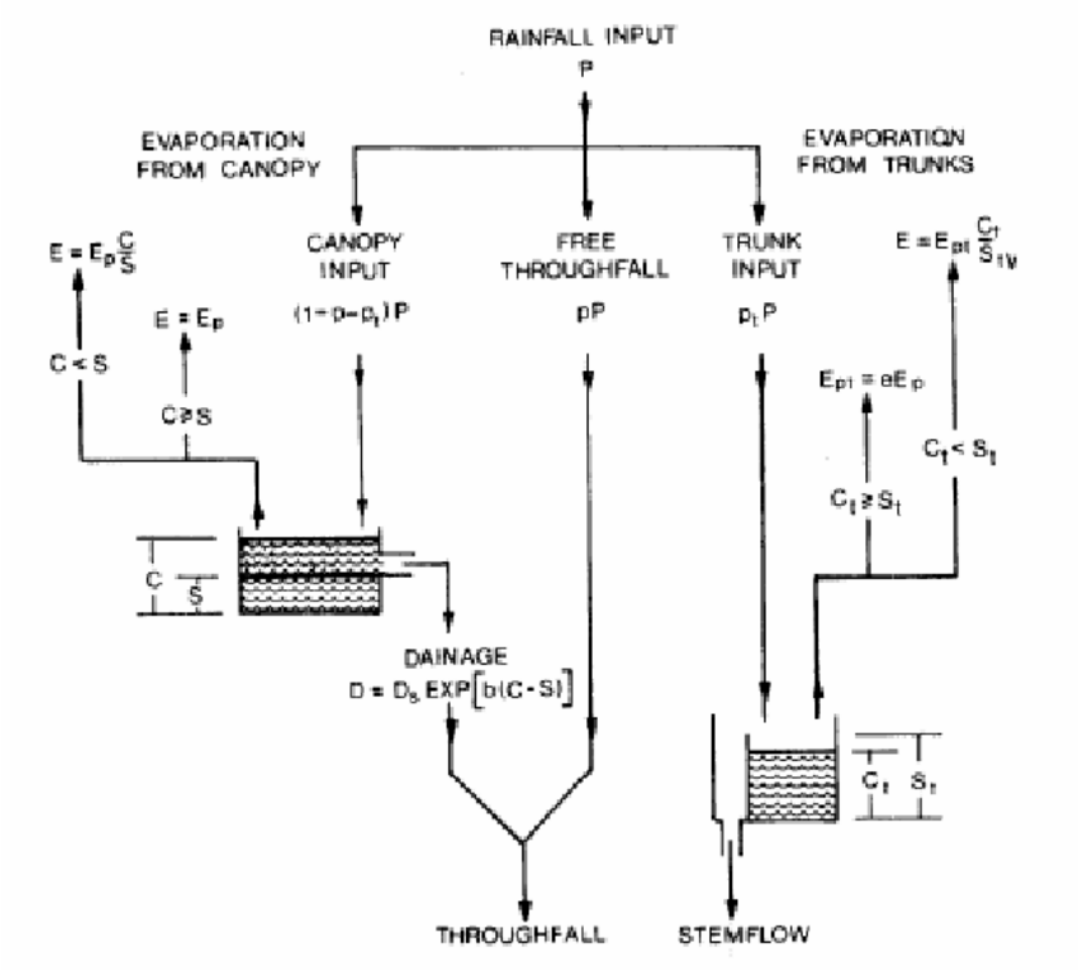

Figure 1 :Conceptual framework of the Rutter model (Gash and Morton, 1978).

The Rutter model calculates throughfall (Tf), stemflow (Sf) and interception loss ((1-p)P-Tf-Sf-E) from a running water balance in the canopy supplemented by meteorological data. The model was originally described by Rutter (1971) and elaborated and generalized as a result of research in hardwood and coniferous forests stands.Unlike other models, the model can continue after rainfall has ceased whereas some other models (e.g. Gash, 1979) assumes only one storm or one rainfall event can occur per day (Muzylo et. al., 2009). The model has been tested several times including, against observed interception losses for six forest types including both

deciduous broad leaved and evergreen coniferous species and gave a very satisfactory model performance (IH, 1998). The Rutter model does require a great deal of data and a very short data time step and can be considered complex to use (Ward and Robinson, 2000). Because it is based on keeping a running water balance, errors may accumulate over time.

For lichen mats in the Churchill area, Arama (1989) found that p=0 meaning that there were no gaps where droplets missed the canopy altogether and reached the ground directly as free throughflow. Arama (1989) discovered that not only are lichen canopies one of the most efficient at intercepting rainfall but that according to her sampling each dry kilogram of lichen biomass can store approximately 2.25 mm of rainfall (more than double their dry-weightmoisture-equivalent being intercepted).

The Rutter model assumes that drainage increases exponentially once the plant's maximum storage capacity has been exceeded and conversely stops when canopy storage has declined to the maximum storage capacity. While drainage can continue for several days in a tropical forest, Arama (1989) found that lichen drainage essentially stopped after approximately 70 minutes. It was suggested that this characteristic was related to the shorter travel distance of water from the canopy to the soil in lichens compared to forests.

As the Rutter model considers the plant canopy as a single entity, it ignores variations that might exist vertically within the canopy. This could be problematic in terms of how evaporation is modeled. After a rain, it is likely the case that the upper surface of the plant canopy dries first, both being directly exposed to the drying effects of the wind and receiving most of the energy supply. If the bulk of the intercepted rainfall resides in the top of the canopy, as it might in deciduous forests, then the single layer assumptions may prove valid. If on the

other hand, the total amount of C is distributed evenly in the vertical, then the availability of water (C/S) used to scale potential evaporation in the Rutter model, may be a poorer representation of actual moisture availability and hence evaporation, depending on the ease with which the wind and radiant energy can penetrate down into the canopy.

2.5 Evaporation Models

The model that is commonly employed to measure *actual evaporation* is the Penman-Monteith (P-M) model. The Penman-Monteith evaporation model has become well known as a physically-based method of quantifying evaporation as well as the basis for many of the conceptual advances in evaporation research that have taken place over many years and it forms the basis of current ecosystem-coupled Earth Systemmodels (Monteith and Unsworth, 1990; Bonan, 2018). The latent heat flux Q_E is related to the evaporation rate E ($kgm^{-2}s^{-1}$ =mms^{-1}) as l E = Q_E($Jm^{-2}s^{-1}$) where l (J kg^{-1}) is the latent heat of vaporization. The P-M model is given as,

$$Q_E = \frac{S\,(Q* - Q_G) + \frac{\rho C_p}{r_a}\,(e_T^* - e)}{S + \gamma + \gamma\frac{r_c}{r_a}} \quad (1)$$

Where S ($kPaC^{-1}$)) is the slope of the saturationvapour pressure versus temperature curve evaluated at mean air temperature, r (kgm^{-3}) and Cp ($Jkg^{-1}C^{-1}$) are the density and specific heat of the air,g($kPa\ C^{-1}$) is the psychrometric constant, e^*_T(kPa) is the saturation vapour pressure of the air at temperature, T (^{0}C), r_a(sm^{-1}) is the aerodynamic resistance and r_c(sm^{-1}) is the canopy resistance to moisture release from the interior of the vegetation. The term (e^*_T-e) is the vapour pressure deficit, or VPD (in kPa) which enhances evaporation when large. The aerodynamic

resistance is inversely related to wind speed and represents the difficulty of transporting humidity away from the surface and up into the atmosphere and is given by (Monteith and Unsworth, 1990) as,

$$r_a = \frac{\ln(\frac{z}{z_0})^2}{k^2 u_z} \qquad (2)$$

where k = 0.41 is the von Karman constant, z_0 is the surface roughness length (m), and u_z is the windspeed (ms^{-1}) measured at height, z (m).The important influence of water availability is represented by the single term r_c which expresses the difficulty in extracting water from the plant canopy.

Potential evaporation, Q_{EP} occurs over an open water surface or when moisture supply is otherwise non-limiting, (i.e. $r_c = 0$) and equation (1) reduces to,

$$Q_{EP} = \frac{S}{S+\gamma}(Q^* - Q_G) + \frac{\rho Cp}{r_a(S+\gamma)}(e_T^* - e) \qquad (3)$$

The second term $\frac{\rho Cp}{r_a(S+\gamma)}(e_T^* - e)$ represents *atmospheric demand* and shows the extent to which latent heat flux is enhanced by the drying power of the atmosphere. The term $\frac{S}{S+\gamma}(Q^* - Q_G)$represents the role of *energy supply* in driving evaporation. Under all other conditions of water availability, r_c assumes positive non-zero values which serve to reduce Q_E in the Penman-Monteith model (Equation 1) below potential evaporation (Equation 3). A great deal of focus is placed on specialized sensors to parameterize r_c in microclimate experiments as it is highly variable amongst different vegetated surfaces and soils, and because it exerts such a large

influence on the variability in *actual evapotranspiration*over time. By rearranging Equation (1), a solution for the canopy resistance is given by,

$$r_c = r_a \left\{ \left(\frac{s(Q_* - Q_G) + \frac{\rho C_p}{r_a}(e_T^* - e)}{Q_E \gamma} - \frac{s}{\gamma} \right) \right\} \quad (4)$$

provided the latent heat flux, Q_E is measured independently and all other terms on the right-hand-side are known or measured. The actual vapour pressure is given by, $e = e^*_T$ rh, whererh is the measured relative humidity at height z, andthe saturation vapour pressure dependence on air temperature, T (^{0}C) measured at height z is given by e* = a exp[bT/(c+T)] where a, b and c are empirical constants given by Buck (1981).

2.6 Arctic vegetation

Vegetation in the Arctichas a compressed growing season due to being largely controlled by temperature. As slower metabolic rates occur at lower temperatures, growth is rapid in the spring for vascular Arctic plants, where flowering and seeding is much faster compared to plants in warmer climates (Aiken et. al., 2007). Vegetation is usually more compact to keep vascular plants close to warm soils which also shield the roots (Aiken et. al., 2007). Plants in the Arctic have adapted to short and cold growing seasons. They have the ability to withstand extreme temperatures in the winter as well as the ability to function in the limited summer seasons (Aiken et. al., 2007). The heights of plants in the Arctic are also very short. Plants that extend above the snow are usually abraded due to strong winds, blowing snow, or because they are eaten by animals (e.g caribou, muskox, etc) (Aiken et. al., 2007). The number of plant species in the Arctic is very low compared to the south. The number of species varies depending where in the

Arctic, but along the Arctic Tundra there can be up to 1,700 vascular species (Aiken et. al., 2007). Aside from vascular plants, lichen and moss also exist in the Arctic and are quite common and highly abundant. They thrive in the ecosystem where they share abilities to stop growth during harsh conditions and resume growth with improved conditions, and they are able to be covered with ice and snow for long periods of time (Kershaw, 1985).

2.7 Lichen

Lichen is comprised of two organisms that coexist symbiotically; an algae and fungus. The algae are often cyanobacteria. Lichens are non-vascular, having no roots to extract soil water and have no cuticles or stomata. Lichens are poikilohydric, which means that they have no physiological way of controlling water loss to the atmosphere and are thus dependent on periods of rain, or dew, or high atmospheric humidity (Kershaw, 1985). Without these factors, it would be challenging to achieve a satisfactory level of thallus hydration as well as a vigorous rate of metabolic activity as lichens are also non-vascular, having no roots to extract soil water and have no cuticles or stomata, and therefore no physiological way of controlling water loss to the atmosphere.

As lichens are non-vascular their physiology differs and their “body” is referred to as a thallus as they have no leaves, stems, or roots (Oliveira et. al., 2005). Poikilohydric vegetation, including lichens, can tolerate extremely low levels of thallus hydration by temporarily shutting down their metabolisms without damage when desiccated. Lichens form a dominant component of the ground cover in many northern habitats yet the role of the lichen canopy in the water balance is poorly understood. Lichens come in different colors, sizes and forms which are sometimes plant-like, and they indeed produce their own carbohydrates (by algal photosynthesis

using sunlight) energy from CO_2, water and minerals in their environment to support fungal growth (Nimis et. al., 2002).

Lichens grow slowly and their lifespan is impressive especially in highly stressful environments including the Arctic tundra. Habitats with strong continuous daily levels of solar radiation and hence high rates of evaporation tend to have a sparse lichen cover (Kershaw, 1985). The relatively thin canopy of lichens covering the boreal forest floor and vast areas of open tundra is one of the most efficient at intercepting rainfall. The moisture storage capacity of lichens is double that reported for deciduous and coniferous forests (Arama, 1989). Lichens are known for their ability to absorb water vapour from both saturated and partially saturated air (Nash, 2008). At the same time, the absorption of liquid water by dry lichen thalli is a rapid process. It may or may not continue for several hours (Kershaw, 1985).The relationship between the rate of water uptake and the weight ratio may be of fundamental significance since it is also the central importance to the rate of evaporation of water from lichen thalli (Kershaw, 1985).What is important is the pattern of liquid water availability, the rate of water uptake, the amount of water that can be retained in the thallus, the rates of evaporative losses and the specific levels of adaptation in a lichen that will vary in a particular environment(Kershaw, 1985). The internal canopy resistance will vary depending on the lichen.

Lichens also have the adaptive strategy of forming clumps or mats, which impede evaporation from the canopies, lower layers and underlying soil (Arama, 1989). They can be regarded as “opportunistic”, actively metabolising during periods of thallus hydration and maintaining very low levels of activity when air-dry (Nash, 2008). Further, the lichen canopy has shown in the past to having a large maximum storage capacity, which is enhanced by the absence of direct throughfall, and the organism’s ability to draw water internally into the lichen

fungus. The measurement of the absolute thallus water capacity of lichen presents severe problems in two main areas: that of definition of the term and that of selection of the unit of measurement to be used (Kershaw, 1985). Arama (1989) found consistent relationships amongst many species of what are called fruticose lichens when expressing maximum storage capacity in terms of unit depth of water (mm) per unit biomass lichen per unit ground area (kg m^{-2}). Fruticose lichens are a form of lichen that are "shrub-like" and can grow quite large (Kershaw, 1985).

According to Kershaw (1985), at an ecological level, the rate of evaporation from a wet lichen surface depends on four factors: an external source of energy, usually solar radiation; the ambient temperature and the temperature at the lichen surface; the atmospheric humidity both at the lichen surface and in the air; and finally the wind speed. The effects of these four environmental parameters are inextricably linked. Apparently, higher wind speeds canreduce evaporation which means lichens may take more time to dry out if the rate of water removal exceeds the capacity of the thallus to supply water. Climate change also provideschanging characteristics of the atmosphere, which could result in a change in the extent of lichen ground cover. While the dependence of lichen extent on changing climate is not the focus of this study it would potentially have effects on moisture relationships in future high latitude environments.

2.8 Impacts of Soil Moisture

2.8.1 Soil Moisture

Churchill, Manitoba is known for being in the continuous permafrost zone with an average thickness of 60 meters (Morison et. al., 2017). On dry upland peat plateaus the active

layer (which thaws and refreezes seasonally) ranges from 40cm to 1m in saturated vegetated fen channels. Fen channels are a type of wetland that is part of the Hudson Bay lowlands (White et. al., 2014). Temperature regimes of the soil are found to be influenced by peat, snow cover, vegetation and soil or rock type (Bjors, 1959). Soil moisture is fundamental when analyzing biomass as soil absorbs, stores, and releases water depending on field capacity and pore size that is generally classified by the depth of the soil, structure, organic matter content, and texture. With continuous active permafrost in the north, there is an abundant amount of soil water in topographically lower sites from seasonal snow melt and soil thawing. The thawing of permafrost is not a rapid process and therefore cannot drain sufficiently. Permafrost soils thus provide moisture for tree growth even though in many instances the deeper soil may still be frozen where the roots cannot absorb water.

The significance of thawing permafrost to soil water availability emphasizes that northern environments are vulnerable to climate change. As such, changes in climate therefore affect hydrology and biogeochemistry in the north. Increased permafrost thaw and changes in precipitation patterns cancontributeto runoff into surface water bodies (Morison et. al., 2017). Runoff would not only occur from snowmelt but during the post-snowmeltseason will travel through pathways into deeper frozen soil profiles. These changes may influence different seasonal dynamics regarding hydrologic connectivity among landscapes during the ice-free season. The Hudson Bay Lowlands are also known for having wet surfaces (92%) with evapotranspiration being influenced by vegetation forms. Higher evaporation takes place where there is standing water or freely-available water such as on the wet tundra or in shallow lakes (Bonan, 1989). Wetter tundra landscapes also contribute to climate change due to the release of greenhouse gasses. The Hudson Bay Lowlands are the second largest global peatland dominated

area that contains organic matter (peat) in the forms of organic carbon, nitrogen, and phosphorus. It is organic carbon that is of concern in the peat as it is recycled to the atmosphere as both methane and carbon dioxide depending on the state of soil saturation. Tundra ecosystems are typified by low regional topographic gradients of 1-1.5 m km^{-1} containing features such as polygonized peat plateaus (up to 1-2m high).

Along with the important peatlands across the Hudson Bay Lowlands, the Boreal Forest also plays a significant role with soil moisture. A strong correlation exists between the seasonal dynamics of atmospheric carbon dioxide and, "the greenness of the Earth" (Bonan, 1989). In particular, the boreal forest is important in climate due to carbon dioxide sequestration. The boreal forest contains different soil moisture regimes depending on vegetation, as well as existing forest bogs. Forest bogs are common throughout the boreal forest that can contain high water contents, low organic matter decomposition, and high organic matter accumulation which influence the water budget and carbon cycle (Bonan, 1989).

Evaporation however, is not necessarily high from these forests even though there is available water. Evapotranspiration is influenced by varying vegetation forms including moss and lichen. Moss and lichen are abundant among the Hudson Bay Lowland landscapes with extensive canopies. For moss, wetter conditions promote their growth and can alsolimit nutrients available to trees which also enhance moss growth and promote greater peat accumulation. Also, soil moisture can be consistently high under lichen surfaces indicating how soil evaporation can be suppressed despite having saturated, poorly drained soils.

2.8.2 Role of Lichen in Soil Moisture

Lichens have a significant role in moisture and thermal regimes of forest soils (Porada et. al., 2016). Lichens which come in many different sizes have the ability to maintain soil moisture at or near field capacity throughout the growing season which reduces moisture stress in forests. They also have high albedo and low thermal conductivity which means that a lichen mat can be a great insulator that impedes the flux of heat into the underlying soil (Porada et. al., 2016). For example, a sampled lichen mat 12 cm deep has been shown to reduce soil heat flux by 50% which lowers the temperature through the soil profile (Bonan, 1989). Even during the driest periods with dry lichen mats, the soils underneath can remain saturated which inhibit moisture loss. The lichen canopy provides an effective barrier to the diffusion of moisture upwards from the soil surface to the atmosphere. At the same time, they effectively limit the supply of radiant energy to the soil thereby depriving soil water the energy required to evaporate. If lichens were to be removed, thaw depth would increase 2-3 times (Bonan, 1989). It is said that lichens can influence and hinder tree growthbut at the same time removing a lichen mat can also significantly reduce tree growth. Tree growth will vary depending on specifics in the soil profile such as temperature and nutrient supply. Despite the varied soil temperatures, nutrient availability is strongly influenced by lichens which inhibit decomposition so that great proportions of nutrients are tied up in organic soil matter (Porada et. al., 2016).

2.9 Research Objectives

The objectives of my research is to first, in Section A, perform a preliminary assessment using historicalEnvironment Canada rainfall data, to examine how lichen biomass in differing habitats can potentially affect interception in the Hudson Bay Lowlands near Churchill Manitoba. Second, in Section B, describe actual interception in these habitats based on the

results of a field experiment designed to measure actual evaporation from the lichen *Cladinastellaris*, using direct *insitu* weighing lysimeter measurements. Then the Penman-Monteith model is used to solve forlichen canopy resistance (Equation 4), and then relate the influence of canopy moisture storage on moisture availability by controlling canopy resistance, r_c and finally, test model estimates using parameterized estimates of r_c against measurements of r_c.

CHAPTER THREE:

Sites and Methods

3.1 Potential Importance of Rainfall Interception in Lichen Dominated Systems: Exploratory Findings

In this section I examine historical patterns in seasonal rainfall in Churchill, MB and link this to a simplified model of rainfall interception by the lichen canopy. Lichens comprise a dominant component of the tundra inthe Hudson Bay Lowlands in northern Manitoba. This is facilitated by lichen biomass field surveys conducted earlier by other authors and during my first field season while working on this project.

3.2 Methods

Daily rainfall data from the airport in Churchill, Manitoba (Environment Canada, 2016)was extracted from Environment Canada for the 35-year period 1980-2015 for the months of April to September to see if there has been any significant trend of summer precipitation. From this rainfall data,*potentialinterception*was modelled with assumed 1-10 mm maximum storage capacity lichen mats. These values of maximum storage capacity, S (mm) were previously found in different habitats in Churchill (Arama, 1987; 1989; Verratti, 2003). Potential interception $I_p$is the maximum interception a given plant canopy can achieve, as the canopy is assumed to be completely dry prior to each rainfall and is assumed to have no direct throughfall passing through the canopy to the ground. Throughfall is entirely comprised of drainage which occurs while the actual amount of water in the canopy temporarily exceeds the maximum storage capacity. A trend in precipitation (e.g whether increasing or decreasing) would support the premise of likely changes in future precipitation regimes. The exploratory findings suggest that

historically, more rain has been arriving in drizzles each year which suggests a potential increase in interception. This is contrary to the hypothesis that increases in large rain events should accompany increasing surface and air temperatures. The data analysis also allows us to evaluate the magnitude of potential interception in the past with historical rainfall patterns. These estimates used a model with the simple assumption that the canopies were completely dry prior to each rainfall. This is a *critical assumption* which will be the subject of experimental testing with summer field measurements.

Research was conducted in the Hudson Bay Lowlands (HBL) near Churchill, Manitoba (58.8°N, 94.2°W) from July 5th to August 20th of 2016. This region is a poorly drained area underlain by Palaeozoic and Precambrian rocks blanketed by deposits of marine silt and glacial till (Arama 1987). Lichen dominated systems make up ~12,000 km^2 of the HBL in northern Manitoba(Bello and Smith,1990).

3.4 Field Determination of Lichen Biomass

Lichen Biomass is the strongest determinant of maximum water storage capacity (Asplund et. al., 2017). To examine actual lichen biomass and the differences amongst habitats, an inventory of above-ground lichen biomass was conductedin distinct habitats in a portion of the Hudson Bay Lowlands coastal environment near Churchill accessible by road, from the coast to 15 km inland.

Lichen biomass was collected in four different dry-land habitats. For each habitat, two sites were sampled.These are; open beach ridge/glacial deposits, open canopy spruce-lichen woodland, high centred ice-wedge polygon habitats, and upland treeless peat bogs. There has never been an inventory of lichen biomass in the Churchill region. Since the critical interception parameter of maximum storage capacity was shown by Arama (1987) to be directly related to

lichen canopy biomass, the present or future capacity of lichens to intercept water is strongly dependent on biomass per unit ground area.

To do this, in each habitat eight 10 m x 10 m plots were selected. Each of the plots was subdivided into 100, 1x1m grid cells that were numbered using x,y coordinates and 20 pairs of random numbers were used to select 20 grid cells. Within each of the random grid cells chosen, a 25x25 cm quadrat was physically tossed and within that quadrat,alllichen biomass was collected down to the peat surface (see Figure2). Samples were sealed and labelled and returned to the laboratory in the Churchill Northern Studies Centre, CNSC where they were put in the oven to be dried at 40^0C until there was no further weight change, to determine the lichen biomass (kg m^{-2}). The 20 values from each site were averaged and compared to the 20 values from each of the other eight sites within a given habitat to determine the range and variability in lichen cover within and between habitats.

Figure 2: Photograph on the top is an example of a site being sampled. Red and pink flags denote the areas of sampling within the 10x10m plots. Bottom left photograph is of the quadrat being used to sample lichen within, followed by bottom right picture with an example of an extracted sample.

3.5 Physical characteristics of Habitats

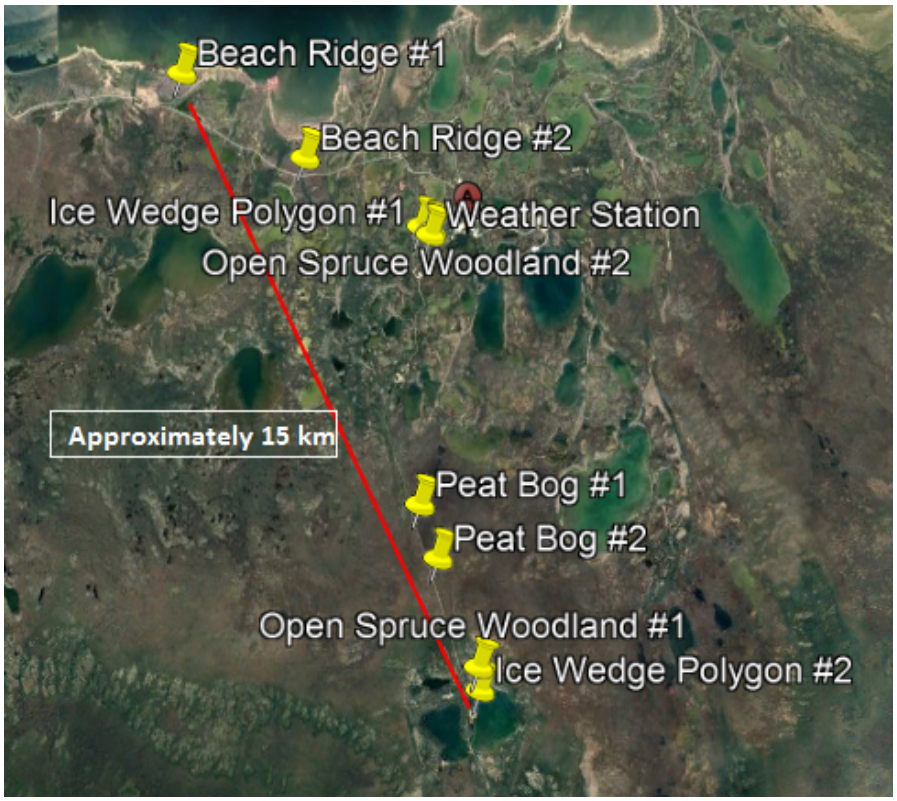

Figure 3: Google Earth image of sampling locations of different habitats that cover approximately 15 km within HBL.

3.5.1 Ice Wedge Polygons

Ice-wedge polygons are fairly common in the Arctic and sub-Arctic. Their formation is caused from the very cold winters that are below -15 °C where the soil is brittle to the point where it cracks. Then once the spring comes there is meltwater that fills the cracks and then refreezes, expanding the size of the crack. As years go by with the seasonal cycles, the cracks increase and enlarge in depth and diameter, as well as the ice wedges that occupy them. These processes create geometric appearance formations such as polygons that range in size between 5-50 meters across (see Figure 4). These polygons are active, and are very visible from afar.

Figure 4: A Google Earth image showing ice-wedge polygons near the Hudson Bay Lowlands.

Two ice-wedge polygon sites were sampled. The first site(58°43’38”N 93°50’10”W) was near the weather station along the peatlands. The second site (58°37’57”N 93°49’01”W) was near the boreal forest. The range in thickness and extent of the lichens sampled were remarkable.

Figure 5: On the top shows the first ice-wedge polygon site near the peatlands. The picture on the bottom is the second site near the boreal forest.

3.5.2 Beach ridge

Beach ridges consist of mineral soils that cover much of the areas with finely textured silt and clay that has been deposited by marine and glacial processes. During the last ice age the weight of three kilometre thick glaciers depressed the Earth's crust of the Hudson Bay region. After the glaciers retreated, the depressed landwas submerged inglacial melt-water and then ocean waters of the Tyrell Sea, flooding areas up to 300 kilometres inland from the current coast line. When the retreat of the continental ice sheets occurred, drainageout of Hudson Bay was

blocked which helped form expansive lakes Agassiz and Ojibway along the margins of retreating ice (Jeglum et. al., 1979). Thousands of years later, the area continues to rise at a rate of approximately one meter per century as a result of isostatic uplift. Beach ridge complexes as seen in Figure 6, have the appearance of strip-like features which mark successions of beach ridges. The beach ridge lines contain sandy material that radiate like ripples from the present-day coast that mark different stages of rebound (Jeglum et. al., 1979).

Figure 6: Google Earth imagery of beach ridges along the coast of the Hudson Bay near Bird Cove, Churchill Manitoba.

The soils along the beach ridges are typically warmer and drier, due to the thin, decayed organic soils (Chapin et. al., 2012) and do not have as much lichen in comparison to the other habitats. Topography of the beach ridges isfairly flat, with little to no vegetation and thin soils as seen in Figure 6. The two sites that were surveyed were located at, 58°45’37”N 93°56’09”W, and 58°44’34”N 93°53’12”W.

Figure 7: Close-up view of beach ridge lichen biomass.

3.5.3 Open Spruce-Lichen Woodland

Churchill is situated in the transitional zone between Arctic tundra and boreal forest. There is a great distribution of lichen woodlands along the boreal forest. Lichens make up extensive cover in these open-crown spruce woodland areas that also helps insulate the underlying soil from heating as well as conserving moisture. Lichens are important in the boreal forest that are usually long-lived and they tend to have higher lichen biomass compared to closed canopy stands (Chapin et. al., 2012).

Figure 8: Google Earth image of open spruce-lichen woodland within the boreal forest.

Two sites were chosen for open spruce lichen woodland habitats. One was locatedwithin the boreal forest adjacent to Twin Lakes (58°38’15”N 93°49’03”W), and the second site was

locatednear the peatlandsin an area between two ponds (58°43’43”N 93°50’25”W). The area contained moraines with a thinner peat surface (~5 cm). Both sites had large lichen mats. The site within the boreal forest had a greater variety of vegetation including more moss, cushion plants, shrubs, and Labrador tea. The second site had more moss and vascular species (Figure 9).

Figure 9: Top: One site sampled of open spruce-lichen habitat near the peatland. Bottom: The second site within the boreal forest. Green mounds are *Ledumdecumbens*, (dwarf*marsh*Labrador Tea).

As pictured in Figure 9, lichens are abundant and continuous lichen mats are quite large in size within these environments. Maturespruce trees surround the habitats that are quite old which support lichen growth through the reduction of evaporation by shading (Nascimbene et. al., 2009).

3.5.4 Peat bog

The Hudson Bay Lowlands are the second-largest continuous wetland-peatland system in the world (Kline, 2014). The development of wetlands is due to the impervious soil and poor drainage that helps generate large shallow pools, and lateral seepages (Kline, 2014). Dominant wetlands are bog and are also defined as peatland with the water table at or below the surface. These are very wet areas that contain moss and lichen. Two locations that were sampled forlichen biomass were within an extensive fen that contains several peat bogs near the forestedge approximately 11 to 13 km inland(58°40’16”N 93°50’27”W, 58°39’36”N 93°50’01”W).

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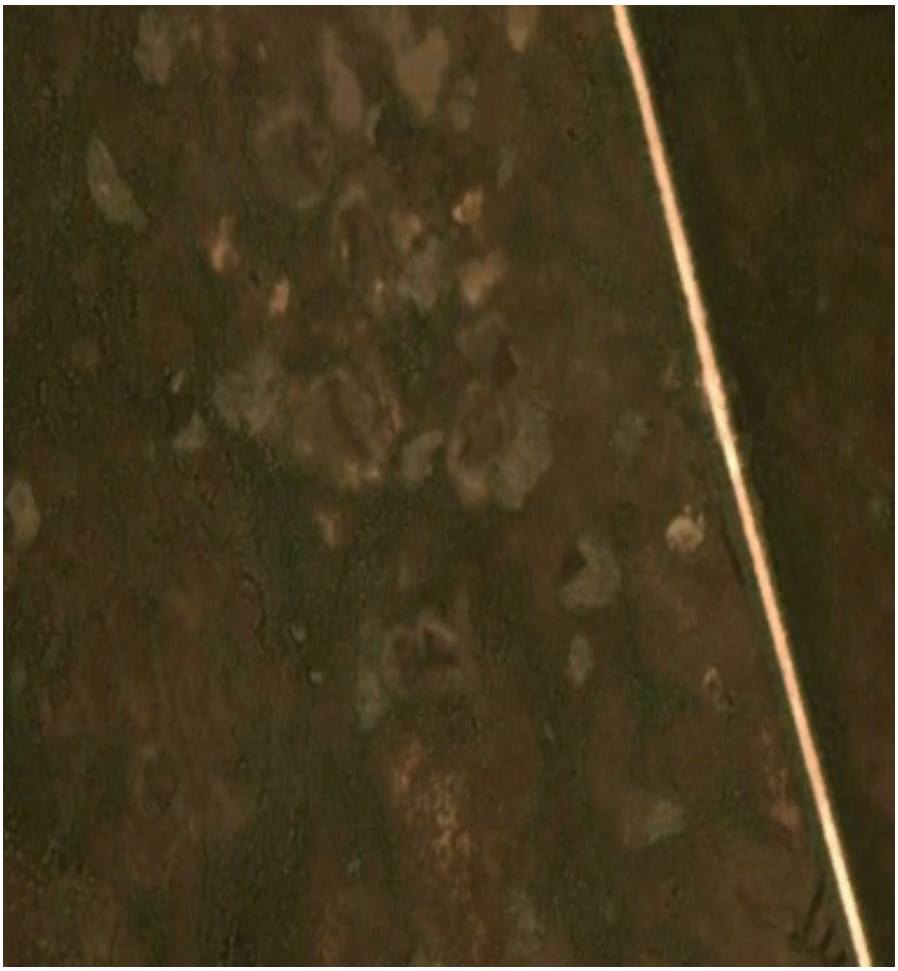

Figure 10: Google Earth images of peat bogs located by the Twin Lakes Rd**.**

The spread of lichens along the wetland depend on the surface of the bog. Because the bog is very wet, the water levels may influence peat erosion which can affect the amount of lichen present. Also, lichens are prone to dying when submerged for any length of time, as the CO_2 supply becomes restricted. These conditions are not favourable for lichen growth. There is also high competition with moss in this area, where many parts of the bog sampled contained much more moss than lichen.

Figure 11: Both photographs reveal the settings of both sites of bogs along the fen.

Figure 1 illustrates the potential competition for resources that lichen has with moss canopies. The lichen mats present are not as thick compared to the moss in the woodland habitat. Moss is more abundant in wetter habitats. There were several pools and ponds in the boggy areas as well that are not visible in Figure 11. All the bogs contain sedges (*Carex spp*.), as well.

3.6 Interception Methodology

Four separate lichen mats of varying thickness were extracted from the peat surfaceon the polygonised peat plateau and placed in weighing lysimeters to determine the increase of water storage during rain and condensation events and loss of water storage during evaporation intervals. A companion weather station provided data to analyze atmospheric factors influencing evaporation and canopy resistance. A further lab experiment to determine the moisture retention characteristics of the four lichen mats took place after the research season, in the laboratory at York University, which will be discussed further in this chapter.

3.6.1 Weather Station

The first step after equipment set-up was identifying and collecting suitable lichen mat samples. A classification system was developed of lichen mats being small, medium, and/or large (thickness). The larger lichen samples will be assumed to having the larger storage capacities than the smaller samples. A total of four lichen samples were collected to weigh consistently throughout the summer using the four weighing lysimeters. Lichen mats were placed within metal mesh baskets that were weighed half-hourly using temperature-compensated strain gauges (Omega Engineering) supported by an aluminum base plate with a resolution of 0.025 mm of water using Campbell CR23x datalogger. Ten second readings of net radiation (Middleton CN1), soil heat flux (Middleton SF1 x 3), windspeed (Davis Inc.), shielded air temperature and relative humidity (Newberg Inc.) were also sampled using a Campbell CR23x datalogger, to produce half-hourly averages. The recorded weight changes of these weighing lysimeters at night (gains from condensation) or during the day (gains from intercepted rain) and weight losses during the day (from evaporation) were used to inventory the summer water budget and modelled within the Penman-Monteith framework (Equation 1) using the meteorological measurements. A surface roughness length of 0.024 m (Verratti, 2003) was used in the

determination of aerodynamic resistance using Equation 3. The actual evaporation rate was measured as the weight loss in each of the four weighing lysimeters and this was converted to the equivalent latent heat flux, Q_E using the latent heat of vaporization (l_v= ~2.45 MJ kg^{-1}).

The weather station collected the data for the entire field season and was locatednear the first sampled polygon biomass plot. The peatland is an area of existing ice-wedge polygons that also contain extensive lichen canopies. The weather station was centered between the four weighing lysimeters containing pure samples of *Cladinastellaris* but the polygons also contained moss, vascular vegetation, and dwarf larch and white spruce trees.

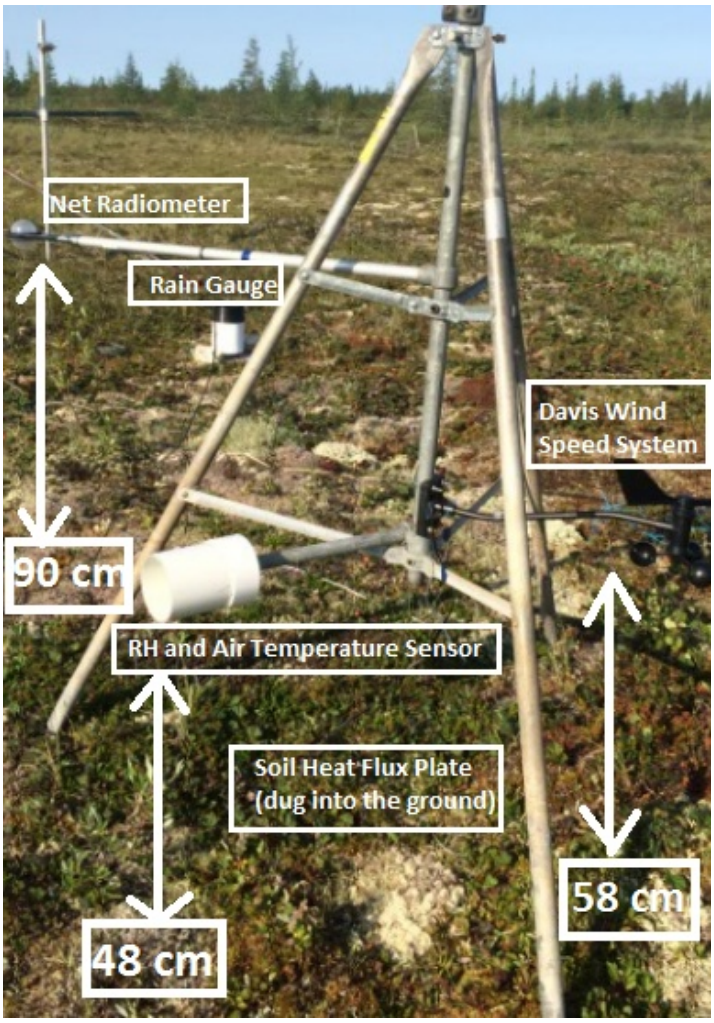

Figure 12: Weather station consisting of all equipment needed for measured parameters.

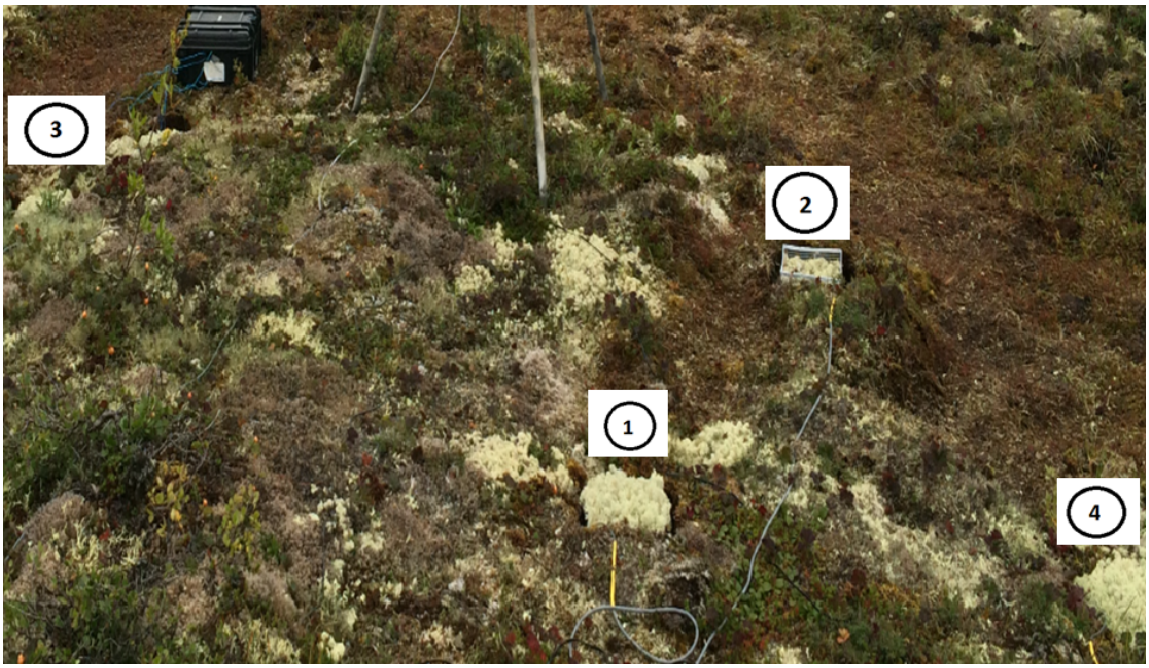

Figure 13: Location of the four lichen mats situated in weighing lysimeter baskets.

Preparation of the strain gauges and lysimeters were very important and they were carefully calibrated in the lab with known weights beforehand. The accurate conversions of the fluctuating voltages from the lichen strain gauge assemblies are dependent on these calibrations. To accurately measure lichen weight changes due to moisture changes consistently, the lichen baskets had to be protected. They were placed in the soil so they would not be disturbed (as seen in Figure13). It was important todig the holes in the ground suited for the base plates. Once the holes were dug, the baskets placed had to be levelled, even with the surrounding surfaceand it was vital to make sure nothing was touching the basket, whatsoever. The importance of this was so the displacement of the baskets would not be influenced byanything other than changes in canopy water storage. Obstacles include adjacent living vegetation as well as twigswhich might perhaps bridge the surfaces or the corners of the basket. Wind speed especially can trigger fluctuations in weight. Errors are reduced by the large sample sizes (n=180) per time

interval.Each time the site was visited to download data, the baskets would be checked to make sure they were level, and untouched by any foreign matter.

Figure 14: Top: An empty ¼" galvanized wire mesh basket, strain gauge and aluminum base plate prior to lichen placement. Bottom: Image with the lichen inside and installed in the peat.

3.6.2 Selection of Lichen Samples

The selections of lichen samples were random. Specific areas that were visited to abstract these samples were at the ice-wedge polygon habitats, as well as the boreal forest. These areas were chosen as they contained the most variety of lichen species and sizes. A selection of thin, medium, and thick lichens were collected using a spare 20x20cm basket to cut out the lichen canopies. A range of lichen thicknesses were deliberately chosen to span a range of moisture holding capacities and therefore moisture availability in order to better understand how

evaporation may influence interception. The four ultimately chosen ranged in mean thicknesses from 9.5-10.3cm.

3.7 Laboratory Drainage Experiments

These experiments were conducted in the lab at the end of the field season to determine the maximum storage capacity and the rate of drainage for the four lichen mats. Each lichen mat was submerged individually for 45 minutesin an aluminum tray filled with water with a light weight on top.After 45 minutes each lichen mat was placed in clear, air-tight plastic chamberto prevent evaporative water loss. The chamber included pre-soaked sponges to support the lichen samples just above the water surface and enable drainage at the base of the lichens. The lichen mats were then weighed periodically (±0.1 g). at intervals of: every two minutes for the first six minutes; every three minutes for the next fifteen minutes; every ten minutes for the next fifty minutes; every thirty minutes for the next hour; and then finally once every forty-five minutes until drainage ceased. The entire procedure took approximately 9-10 hours for each lichen mat. The maximum storage capacity was reached once drainage ceased. The chamber was always weighed before and after each experiment to make sure that no moisture was escaping the system. This methodology was used by Arama (1987), whoshowed valid and reproducible values of maximum storage capacities in this manner.Earlier drainage experiments were doneby Arama, (1987) using plastic bags instead of chamber systems which proved to be inadequate due to moisture escaping the system. After drainage experiments were concluded, average canopy heights were determined by inserting a pin through the mat to a solid surface at 22 locations which were then averaged. Then lichen mats were dried by putting them into a drying oven until there was no further weight loss and then weighed to determine their dry biomass.

CHAPTER FOUR: RESULTS

4.1Preliminary Findings (Precipitation Review)

Results show that there are not any significant trends in total summer precipitation between 1980 and 2015. There is however, a significant increase in April precipitation ($p<0.05$) over the same period (not shown). There has also been a significant decrease in drought days (Figure 15,-0.75 days per year, $p<0.05$), as well as a corresponding increase in light-rainfall days of between1 and5 mm d^{-1}(Figure 16, +0.76 days per year, $p<0.05$) since 1980. This suggests that more rain is arriving on days with light rain each year, at the expense of rain-free days, which suggests a possible increase in annual rainfall interception.

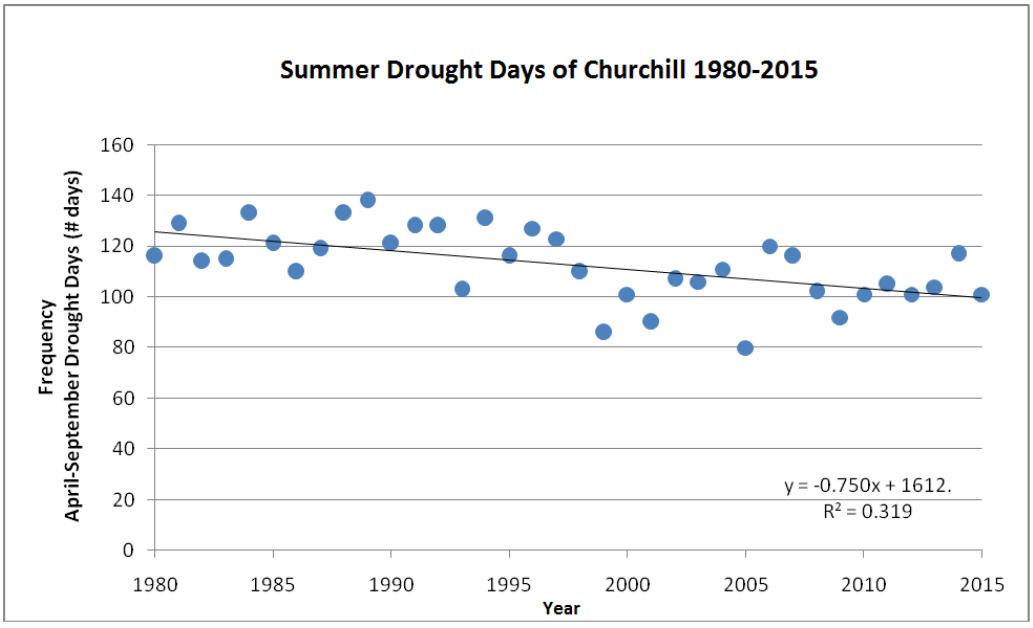

Figure 15. Historical trend in summer drought days for Churchill MB from 1980 to 2015. (n=36, $p<0.05$) A Shapiro-Wilk test indicates the residuals are normally distributed.

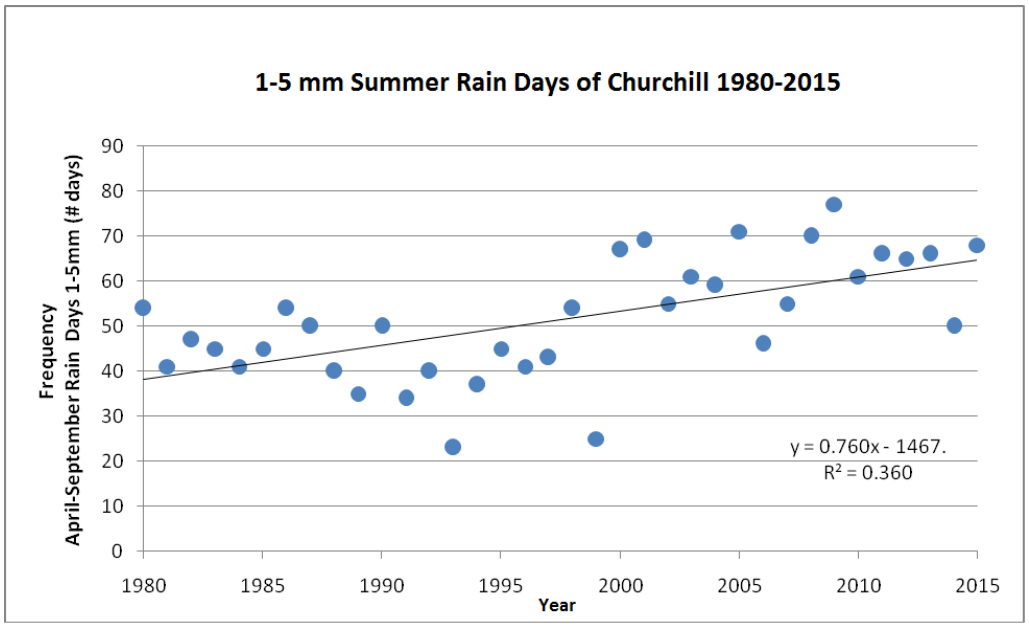

Figure16.Historical trend in summer rain days between 1-5mm for Churchill MB from 1980-2015.(n=36, $p<0.05$) A Shapiro-Wilk test indicates the residuals are normally distributed.

From these rainfall data,*potential interception*was estimated for lichen mats with specified maximum storage capacities ranging from 1 to 10 mm. These values of maximum storage capacity were previously found in different habitats of Churchill (Arama, 1987; 1989). Potential interception is the maximum interception a given plant canopy can achieve corresponding to the canopy being completely dry prior to each rainfall with the added assumption of no *direct* throughfall. Potential throughfall under these conditions comprises only gravity drainage of intercepted water which only occurs when a rain event exceeds the maximum storage capacity. This is a *critical assumption* which will be the subject of experimental testing in later

chapters.

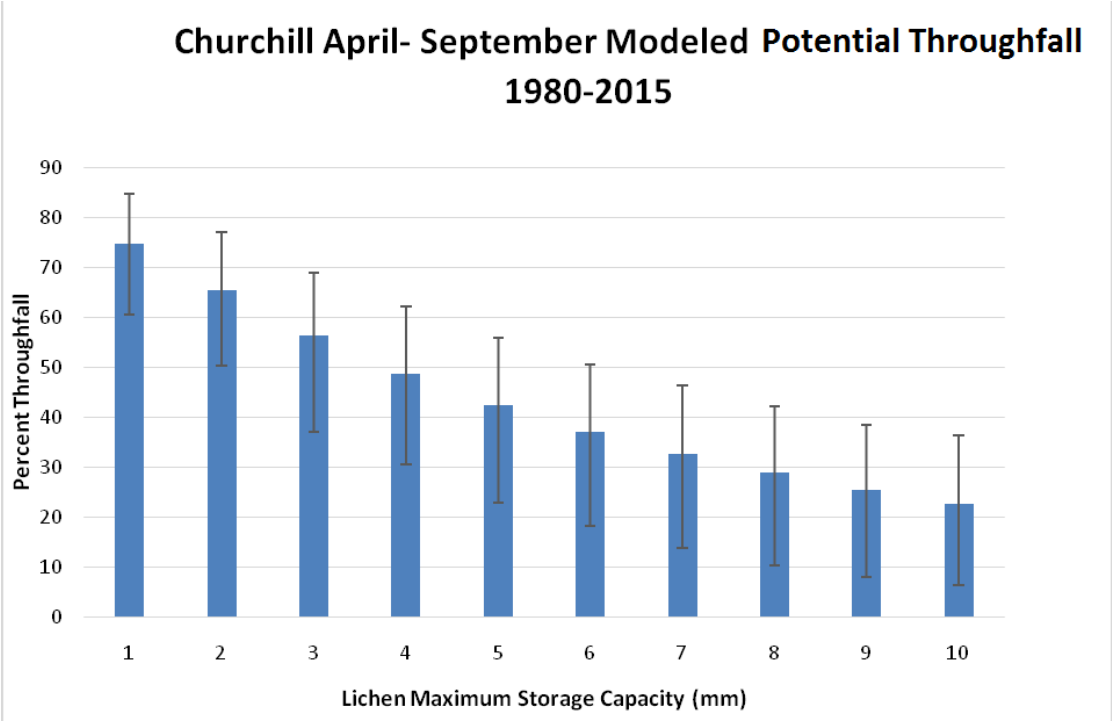

Figure 17. Modeled potentialthroughfall for lichens of varying maximum storage capacities. Error bars show annual maxima and minima from individual years.

In Figure 17, the y-axis represents modeled percent throughfall (100-S/P x 100) from gravity drainage averaged for each rain event over the historical period, where the x-axis corresponds to a range of lichen habitats of varying thickness. These resultsshow that potentially as much as 73% and as little as 22% of summer rainfall reaches the soil depending on habitat. This range corresponds to 27% to 78% interception, respectively. Furthermore, the variability is very large (± 15% throughfall) from year to year.

4.2 Lichen Biomass Inventory

An inventory of biomass was carried outin the summer of 2016to assess biomass differences in four habitats. Each habitat was different in terms of different settings, different locations, and different abundances of lichen. As expected from the preliminary model, large biomasses differences did exist. In some cases, one sample filled two large zip-lock sample bags because of how deep the lichen was. In other cases, some plots would have less than 10 samples because there was no lichen in many locations. Note, canopy depth measurements were not collected during thebiomass inventory. Through visual observations however, density could be a strong factor influencing lichen biomass in different habitats.

4.2.1Mean Lichen Biomass

There is a significant difference ($n=160$; $p<0.001$) in lichen biomass (using two-tailed t-tests) between all pairs of habitats that were inventoried. The habitat that contained the least biomass was the beach ridge habitat, followed by the peat bog. The highest biomass was collected from the openspruce-lichen woodland habitat, followed by the ice-wedge polygon habitat. The plots at the ice-wedge polygon and the open spruce-lichen woodland both contained large ranges in biomass. Openspruce-lichen woodlands overall carry exceptionally thicker lichen canopies.

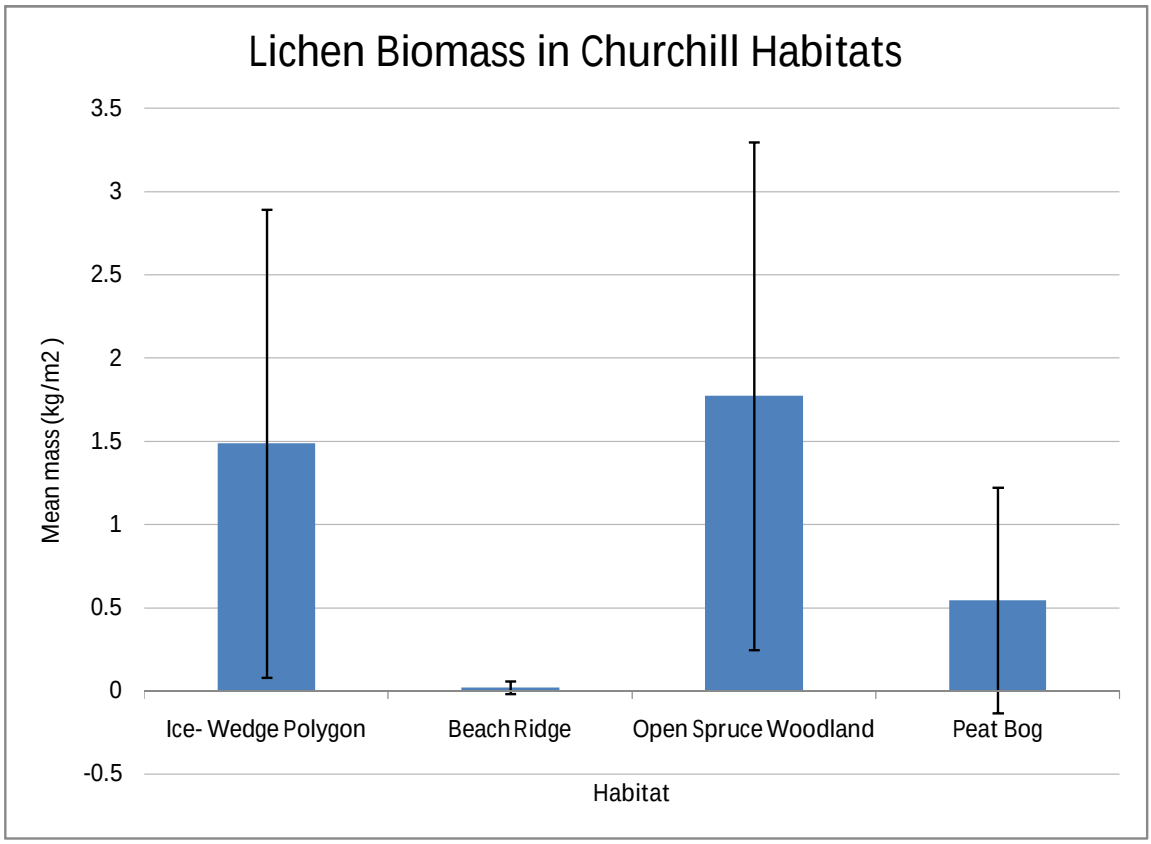

Figure 18 : Mean lichen biomass in different habitats. Error bars indicate standard deviations.

The range in values were somewhat anticipated as each habitat has their differences in soils, and coverage by other vegetation. Beach ridge habitats are elevated and exposed and drier. Theydo not typically containwell developed soils and hold water poorly as there is a lot of gravel. Lichen coverage was patchy andcollected samples were very small. Peat-bogs are very wet and contained some lichen but more so large moss canopies which can be competitive for lichen growth (Turetsky et. al., 2012). Open spruce-lichen woodlands have moist soils but also typically supported moist lichen canopies owing to decreased wind speeds and shade offered by trees. The ice-wedge polygons sampled along the peatland had abundant lichen cover intermixed with dwarf ericaceous shrubs.

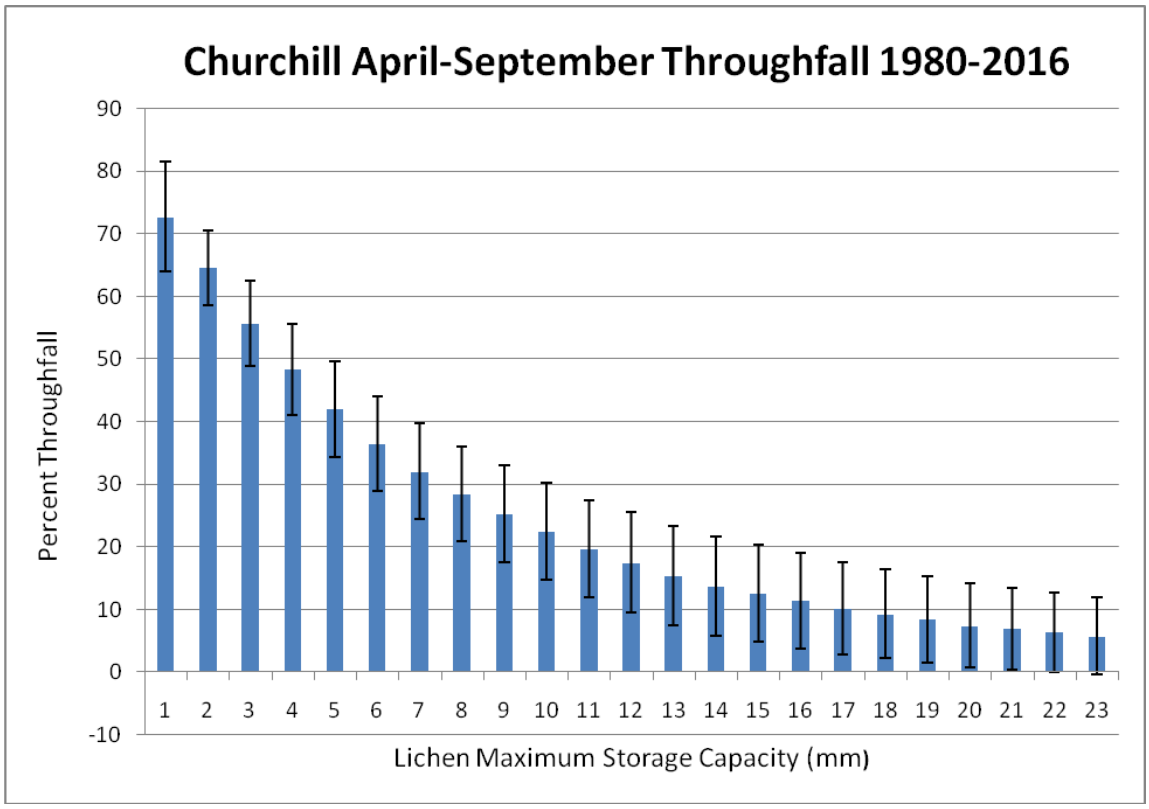

Figure 19: Modeled potential throughfall for lichens of varying maximum storage capacities for a range in maximum storage capacity in actual habitats sampled. Error bars show annual maxima and minima.

4.3 Estimated Habitat Throughfall Between April- September from 1980-2016

When potential throughfall was introducedearlier, it was applied to canopies corresponding to a range of maximum storage capacities previously described by Arama (1987;1989). Actual results, through the biomass inventory, provide exceptionally larger maximum storage capacities ranging between 1-23mm (Figure 19).This reduces the seasonal

potential throughfall in the deepest lichen mats to approximately 7% averaged over the historical period, with driest years' yielding no throughfall at all, which corresponds to 100% interception. The spatial variability in the historical potential drainage suggested by these results presents interesting challenges for hydrologic modelling.

4.3.1 Modelled Potential Throughfall of Each Habitat

To gain a better understanding of how lichens could potentially affect interception and infiltration of water into the soil in tundra habitats near Churchill MB., I apply the measured frequency distribution of lichen biomass of each site sampled, to calculate their aggregated effects. These results are for the lichen-only component of interception of rainfall for the historical period. Typically, vascular plants exhibit poor capacities to intercept rain while mosses exhibit excellent capacities to intercept rain (Arama, 1987)As well, lichen biomass is fixed to the current values over the entire historical period, so possible changes in growth which affect biomass and coverage are not considered. The following calculations are based on the annual average summerrainfall of 263 mm from 1980 to 2016. The annual average of 263mm was calculated from the total rainfall of each April to September (1980-2016). The rainfall events of varying magnitudes in each year were averaged andused to calculate throughfall using assumed maximum storage capacities and frequencies distributions of rainfall (e.g rainfall occurrences between 1-2mm and/or >10mm,etc.).

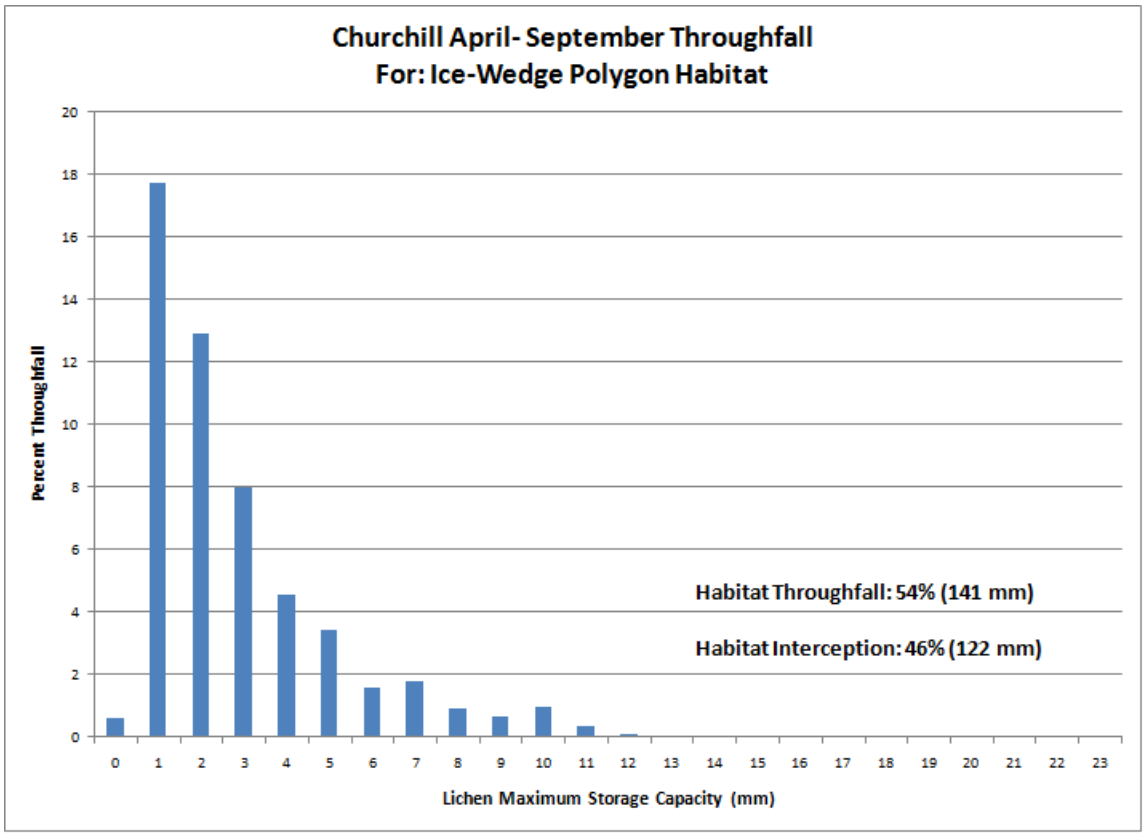

Figure 20: Modelled potential throughfall in the ice-wedge polygon habitat (averages of 20 samples in each plot, n=160 per habitat).

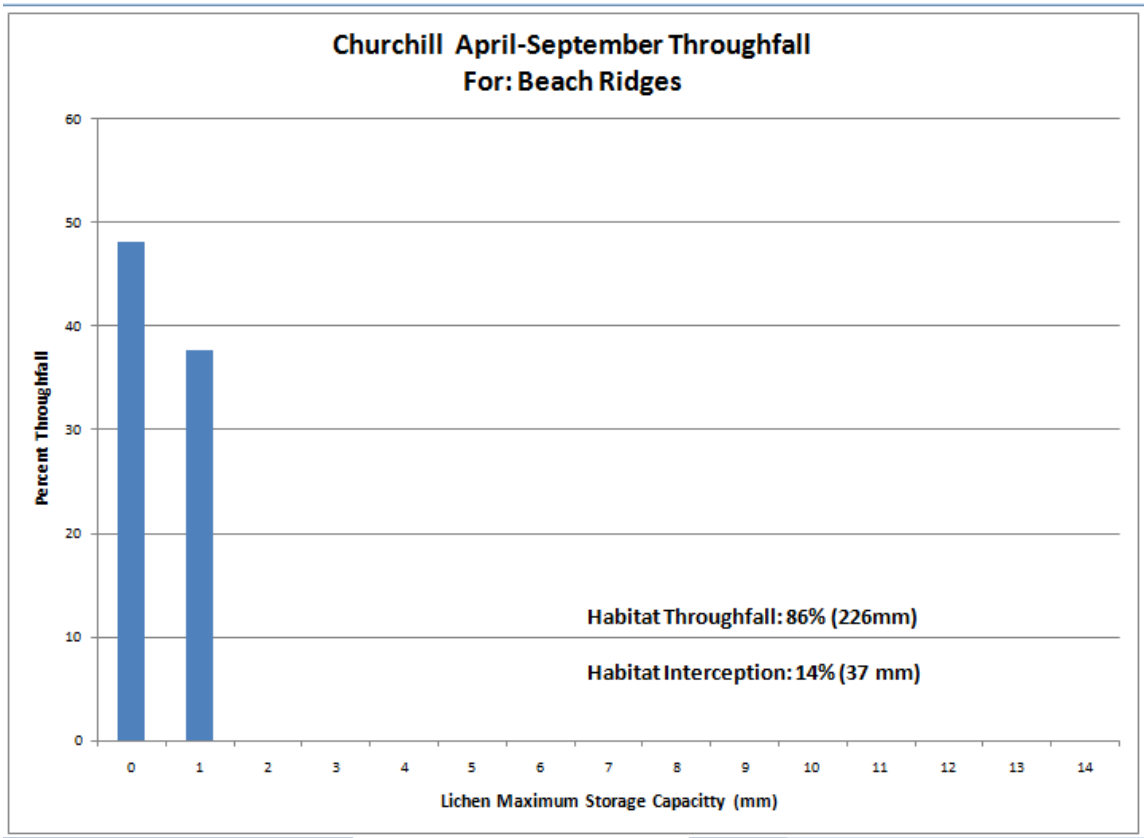

Figure 21: Modelled potential throughfall in the beach ridge habitat (average of 20 samples in each plot, n=160 per habitat).

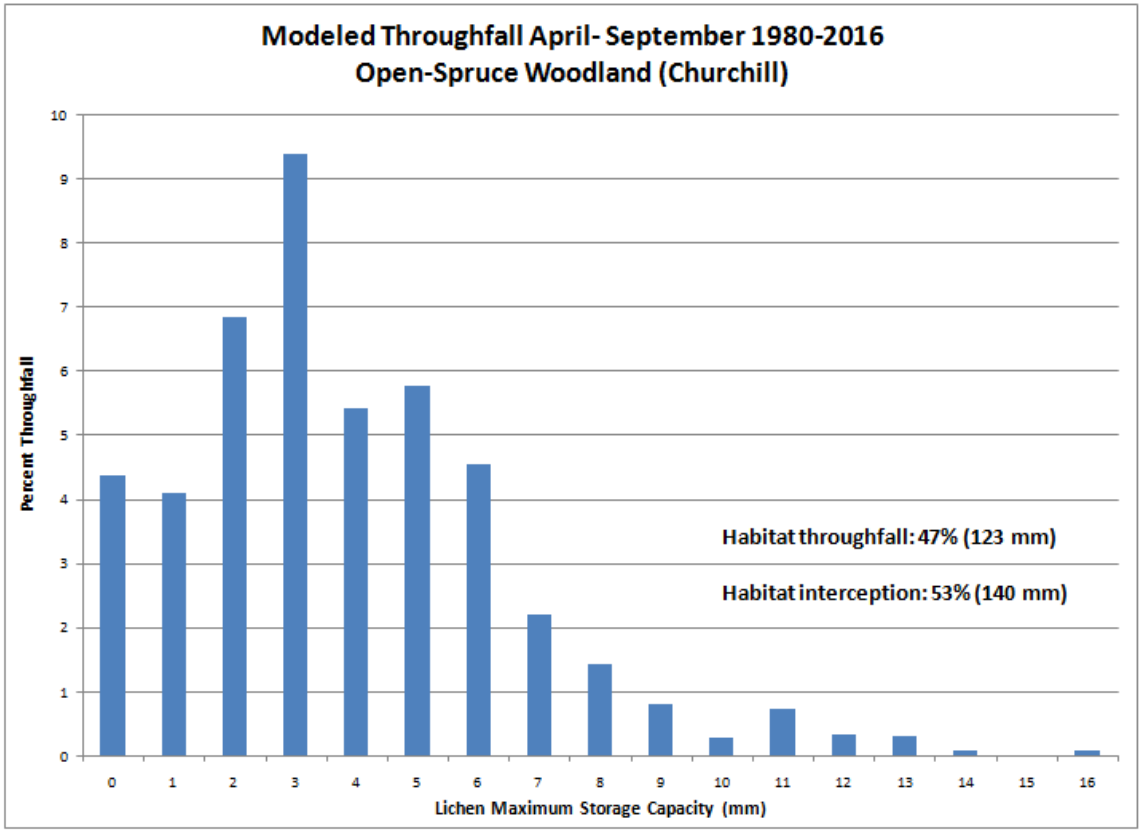

Figure 22: Modelled potential throughfall in the openspruce-lichen woodland habitat (average of20 samples in each plot,n=160 per

habitat)

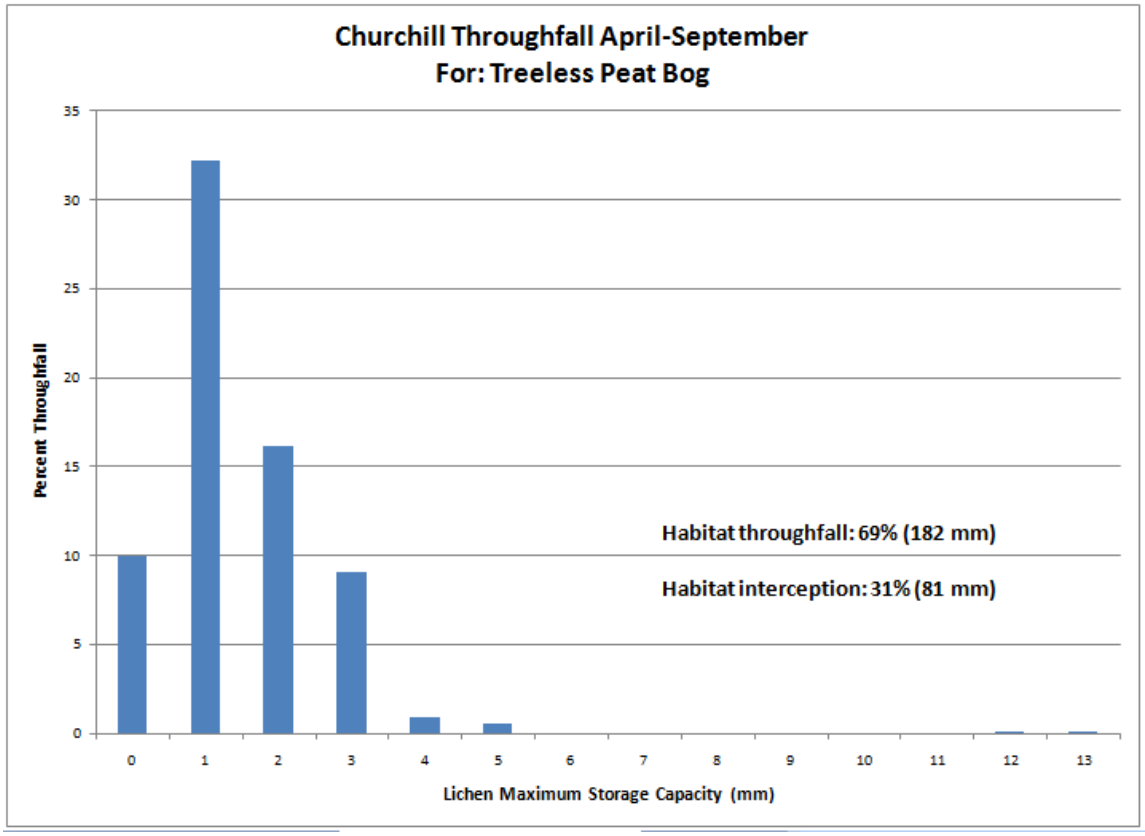

Figure 23: Modelled potential throughfall in the peat bog habitat (average of 20 samples in each plot, n=160 per habitat).

The figures show the proportion of annual rainfall for the period 1980-2016 that hasbeen intercepted, or drained (throughfall) in each habitat. The habitat that exhibits the largest maximum storage capacities is the open spruce-lichen woodland, followed by the ice-wedge polygon habitat, peat bog, and finally the beach ridges. Interception is very high within the open spruce lichen woodland habitat, as well as the ice-wedge polygon habitat. Due to low biomass in the beach ridge habitat, throughfall is very high.

4.3.2 Drainage Experiment results for Determining Maximum Storage Capacities

Drainage experiments were conducted in the lab to determine how quickly water would drain from lichen canopies due to gravity. This process only occurs if the water in the canopy exceeds the maximum storage capacity. By also noting the water content when drainage ceases, the critical value for maximum storage capacity is determined. Expressing this equivalent depth of water (mm) in relation to canopy biomass (kgm^{-2}) provides a generalized relationship for estimating maximum storage capacity when only the morphological characteristics of the canopy are known.

It is the following relationships between biomass and maximum storage capacity that provided the values for maximum storage capacity for different lichen compartments of each habitat listed in the previous section. The drainage experiments were conducted on four of the selected lichen mats from the field season that were returned to the lab at York University at the end of the field season. Results shown inTable 1are plotted in Figure 24. These indicate that about 80% of drainable wateris lost rapidly for all lichen mats within 30-45 minutes. Drainage started to slow down after approximately 50 minutes similarly with all lichen samples (An r^2=0.97 represents the correlation of drainage and time for all four lichen mats). Drainage effectively ceases after nearly 3 hours. Once drainage ceased, maximum storage capacity was determined. Maximum storage capacities ranged between 3.67 and 6.52 mm for lichen #2 and lichen #4, respectively (Table2).

Table 1**:** Lichen Drainable Water Experimental Results

Interval (min)	S (min)	Amount of water in canopy L1 (mm)	Amount of water in canopy L2 (mm)	Amount of water in canopy L3 (mm)	Amount of water in canopy L4 (mm)	Drainable water L1 (%)	Drainable water L2 (%)	Drainable water L3 (%)	Drainable water L4 (%)
2	2	11.59	6.60	12.92	13.10	1	1	1	1
2	4	11.33	6.46	12.06	12.47	0.92	0.88	0.75	0.79
2	6	11.10	6.36	11.60	12.13	0.84	0.81	0.62	0.69
3	9	10.86	6.22	11.24	11.90	0.76	0.70	0.51	0.61
3	12	10.65	6.15	11.07	11.71	0.70	0.65	0.46	0.55
3	15	10.49	6.08	10.88	11.55	0.64	0.59	0.41	0.50
3	18	10.39	6.02	10.76	11.43	0.61	0.54	0.37	0.46
3	21	10.27	5.97	10.65	11.29	0.57	0.51	0.34	0.41
5	26	10.08	5.91	10.52	11.20	0.51	0.45	0.30	0.38
5	31	9.92	5.85	10.41	11.09	0.46	0.41	0.27	0.35
10	41	9.80	5.79	10.32	11.00	0.42	0.36	0.24	0.32
10	51	9.53	5.72	10.18	10.83	0.34	0.31	0.20	0.26
10	61	9.43	5.67	10.07	10.73	0.30	0.27	0.17	0.23
10	71	9.31	5.63	9.99	10.61	0.26	0.24	0.15	0.19
10	81	9.22	5.60	9.92	10.57	0.23	0.21	0.13	0.18
30	111	9.00	5.57	9.78	10.49	0.16	0.19	0.09	0.15
30	141	8.88	5.49	9.64	10.21	0.12	0.13	0.04	0.06
45	186	8.76	5.46	9.58	10.18	0.09	0.10	0.03	0.05
45	231	8.69	5.43	9.55	10.13	0.06	0.08	0.02	0.04
45	276	8.63	5.41	9.54	10.10	0.05	0.07	0.02	0.03
45	321	8.60	5.38	9.54	10.08	0.03	0.04	0.01	0.02
45	366	8.57	5.38	9.53	10.06	0.03	0.04	0.01	0.01
45	411	8.54	5.35	9.53	10.05	0.02	0.01	0.01	0.01
45	456	8.52	5.34	9.49	10.04	0.01	0.01	0.00	0.01
45	501	8.51	5.34	9.51	10.04	0.01	0.01	0.01	0.01
45	546	8.50	5.33	9.49	10.02	0.00	0.00	0.00	0.00
45	591	8.49	5.33	9.49	10.02	0.00	0.00	0.00	0.00
45	636	8.49	5.33	9.49	10.02	0.00	0.00	0.00	0.00

Table 2**:**Lichen biomass, maximum storage capacity, density and mean depth of four lysimeter lichen samples.

Lichen Sample #	**Dry Biomass (kgm^{-2} or mm water equivalent)**	**Maximum Storage Capacity(mm)**	**Density (kg/m^3)**	**Mean Depth (cm)**
1	**2.99**	**5.5**	**31.44**	**9.5**
2	**1.66**	**3.67**	**23.13**	**7.2**
3	**3.03**	**6.46**	**31.57**	**9.6**
4	**3.49**	**6.52**	**34.03**	**10.3**

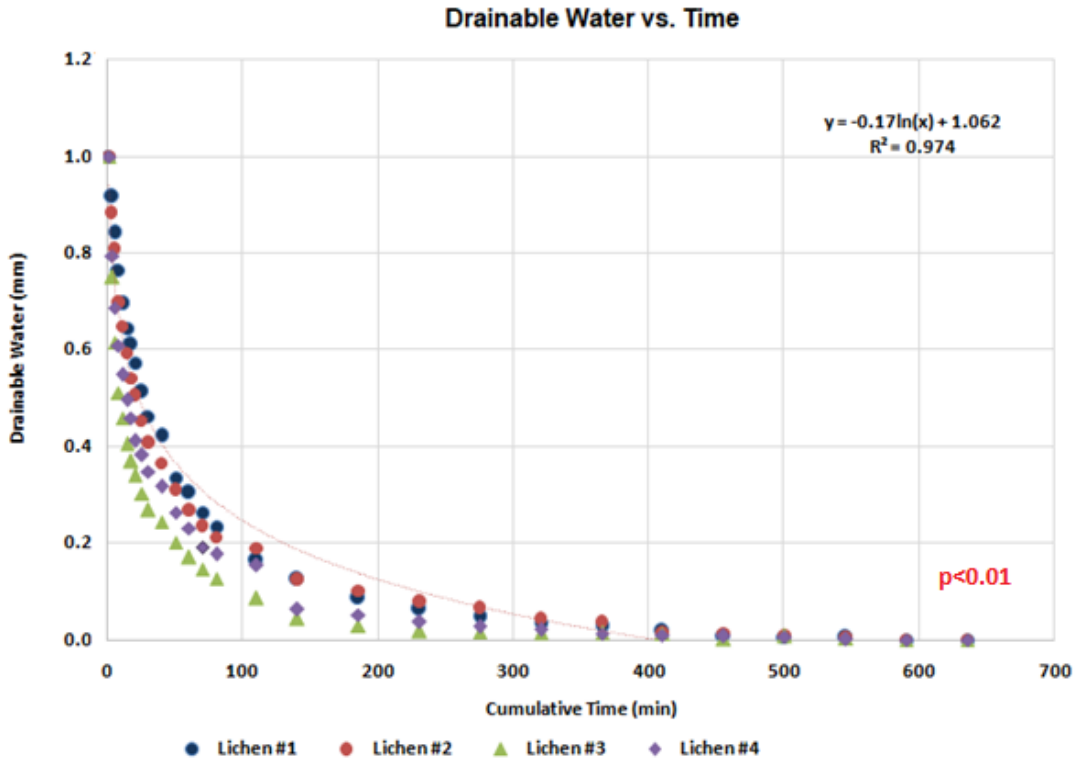

Figure 24: Decline of drainable water (C-S) from the four lichen canopieswithtime.

Despite different storage capacities, the drainable water rate is very similar and all lichen samples are strongly correlated. Each sample comprises entirely*Cladinastellaris* which can be one of the reasons why the drainage rate is similar. What is seen however is that lichen #3 drains the fastest, followed by lichen #4, lichen #2, and finally lichen #1.

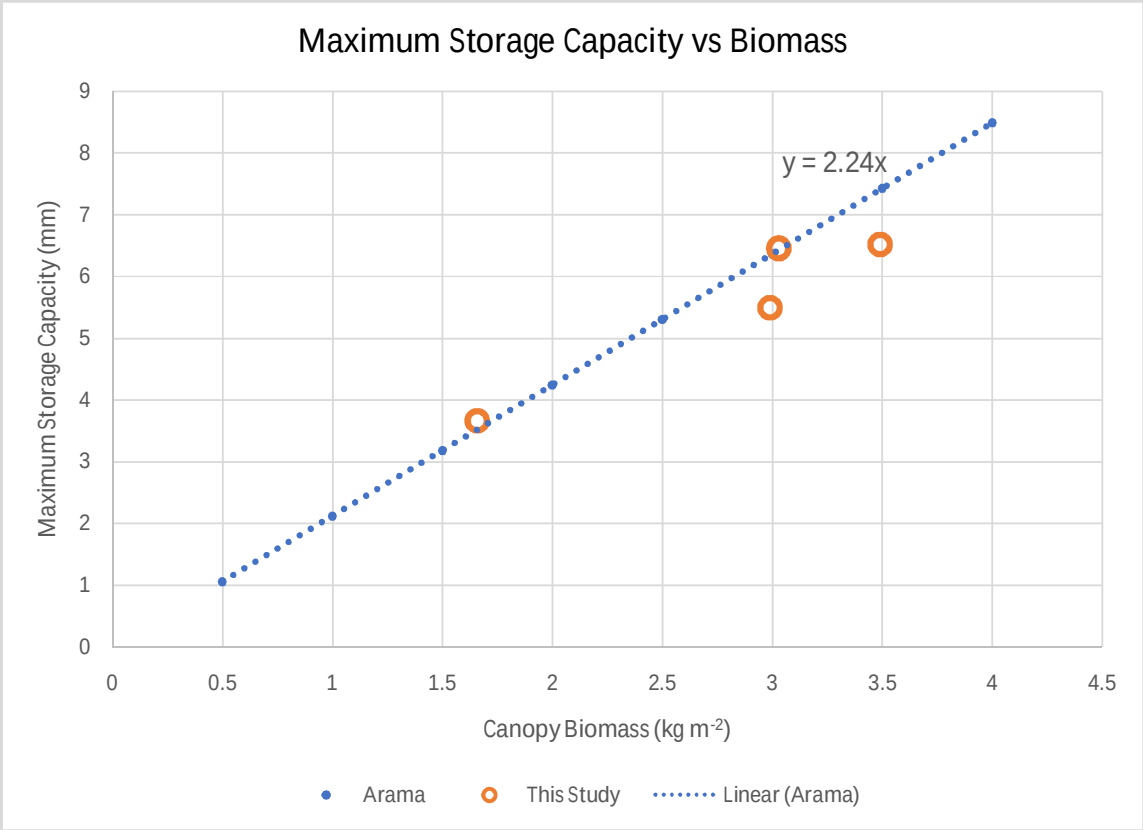

Figure 25: The relationship between measured maximum storage capacity and lichen biomass for the four lysimeter mats compared to the empirical regression model of Arama (1989).

The relationship between maximum storage capacity and dry weight (biomass) for all four lichens is plotted in Figure 25 along with the empirical relationship of Arama (1989) and indicates general agreement. Sample 4 which shows the largest departure from the empirical relationship, was also the deepest sample. However, sample 1 which also underestimates Arama's value of S is not notably deeper than sample 3 which is in perfect agreement. Density was not measured throughout the field biomass inventory. However, with the lichen samples that were continuously weighed by strain gauges, height measurements were taken. These data show (Table 2) that there may be a tendency for lichen samples to be compressed as

they increase in depth, though the sample size is much too small to draw general conclusions.Density, in addition to biomass,appears (Figure 26) to be linked to maximum storage capacity, although again, the sample size is much too small to draw inferences.

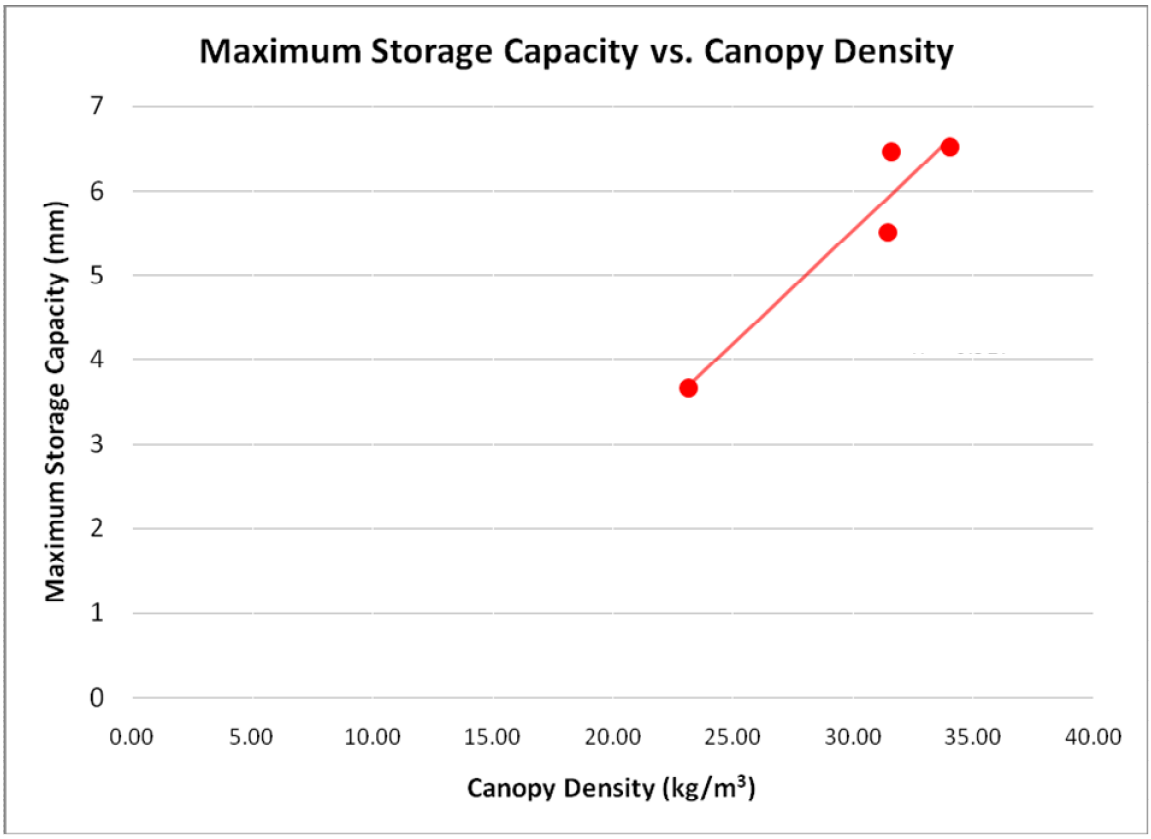

Figure 26: Maximum storage capacity plotted against canopy density for the four lysimeter lichen samples.

4.4 Field Determination of Summertime Lichen Water Budget from Weighing Lysimeters

The section includes the water budget estimates using weighing lysimeters. The length of the field season was 138 days (Day of Year 194-132) where the recorded weight data, measured half-hourly were collectedfor four lichen canopies described in the methods section.

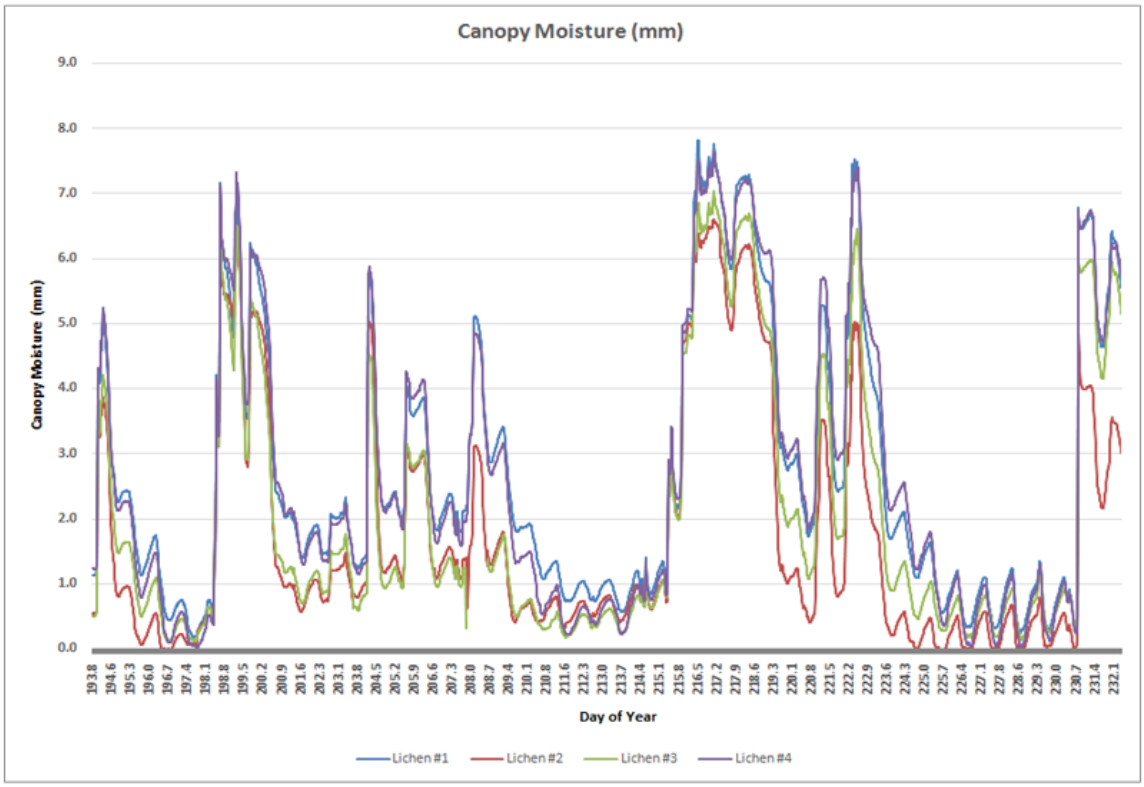

Figure 27: Progression of lichen canopy moisture storage (mm) throughout the measurement period.

Figure 27 shows the seasonal fluctuations in canopy storage through droughts and rainfalls. Compared to the maximum storage capacities (MSC) indicated in Table 2, there are numerous points in the graph that show more water than the MSC. This corresponds to a period of continuous rain from Day 215-218 in Figure 28. Soon after this interval ends, moisture in the canopies drained. Drainage after rainfall typically occurs rapidlyif canopy storage exceeds the MSC.During light drizzles, most is intercepted and subsequently evaporates over time. The only exception occurs when lichens arestillsaturated from aprior rainfall due to suppressed evaporation.

In general, canopiesgain and lose moisture synchronously. Lichen #2 typically has the lowest C (red) followed by lichen #3 with a few exceptions. Lichens #1 and #4 are nearly identical. At times of no rainfall, when the lichens are nearly or completely dry, they fluctuate from 0.5 -1 mm storage due to nocturnal condensation which evaporates the following morning. An example is seen on Figure 27 between DOY 224 and 230 during a drought. This process generates the *saw-tooth* pattern which is seen many times duringthe summer.

4.4.1 Precipitation Intensity

Tipping bucket rain gauges were used to collect rainfall data every half hour as well, to help determine rainfall magnitude and intensity. Figure 27 reveals frequent rainfall events during the summer. Some rainfall events were brief, some would last an entire day, and some were extended drizzles that would fluctuate on and off. The highest recorded rainfall event was 13.6 mm, and the second highest event was 10.6 mm.

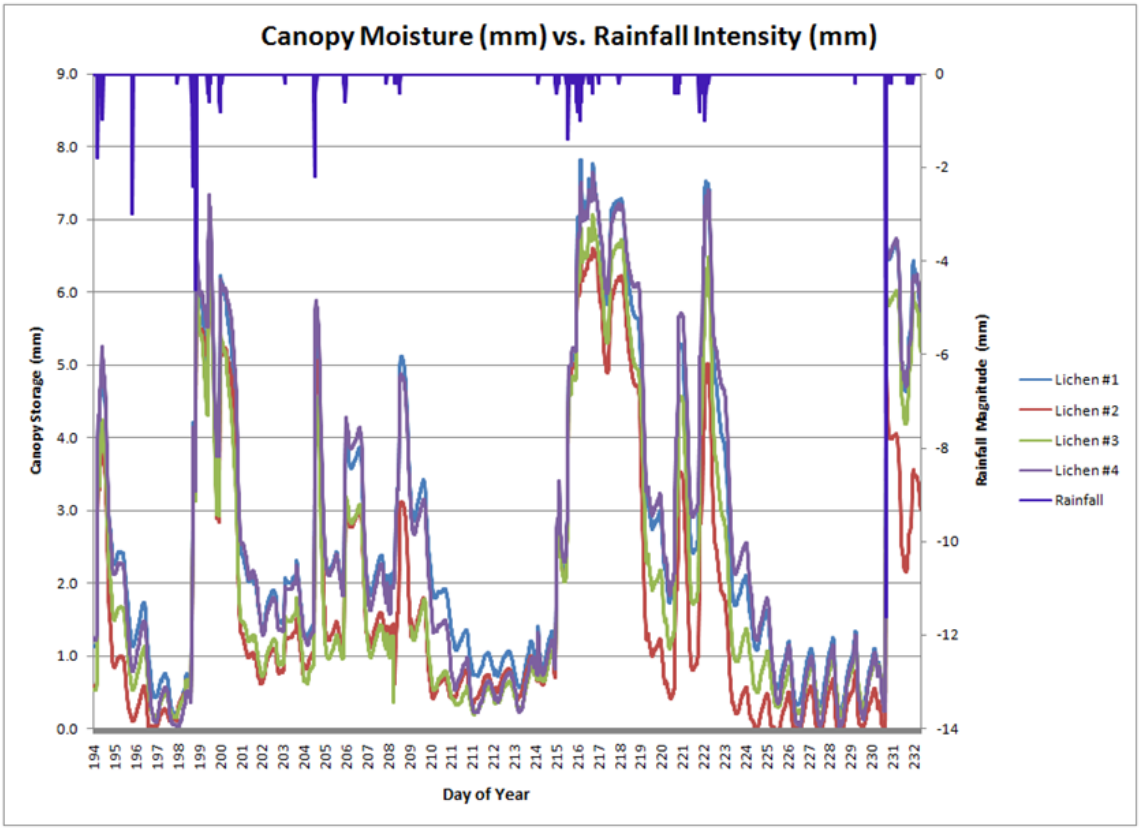

Figure 28: Progression of canopy moisture and rainfall intensity (mm per half-hour) during the field season.

Out of the thirty-eight days, there were nineteen days with rainfall events with some rainfall events lasting more than 24 hours. There was a period of intermittent rainfall that lasted for five days (Days 214-218) as seen in Figure28. This period of rainfall totalled 11.4 mm. The longest period with no rain was seven days from Days 223-229, followed by the second-longest drought period of five days between Days 209-213. A total of 60.7 mm of rainfall occurred during the measurement period. If there are frequent continuous drizzles that last for days, it can have similar effects to one high intensity rainfall event in extending the period of time the

canopies hold some moisture, in which case a smaller proportion of the following rain event can be intercepted.

4.5 Lichen evaporation: the roles of energy supply, atmospheric demand and moisture availability

Over nearly six weeks of the study period, a total of 60.7 mm of rain was collected by rain gauges from a total of nineteen rainfall events that ranged between 0.2-13.2 mm. Since there is no direct throughfall, falling rain water must interact with the canopy and either be interceptedor drained. Throughout the field season the total amount of rainfall intercepted ranged between 35.6 (59%)- 42.1mm (69%) as seen in Figure 32 for the four samples. In order, from the lowest amount of rainfall intercepted to the highest:lichen #2 with 35.6 mm (59%), lichen #3 with 37.5 mm (62%), lichen #4 with 41.7mm (69%), lichen #1 with 42.1 mm (69%). The total amount of throughfall from drainage ranged from 18.5mm- 25mm (31-41%).

The amount of rainfall intercepted depends on the canopy's maximum storage capacity as well as favourable meteorological variables. The weather station continuously measured wind speed, temperature, relative humidity, net radiation, as well as ground heat flux. With these variables, the rate of evaporation and drainage are also influenced.

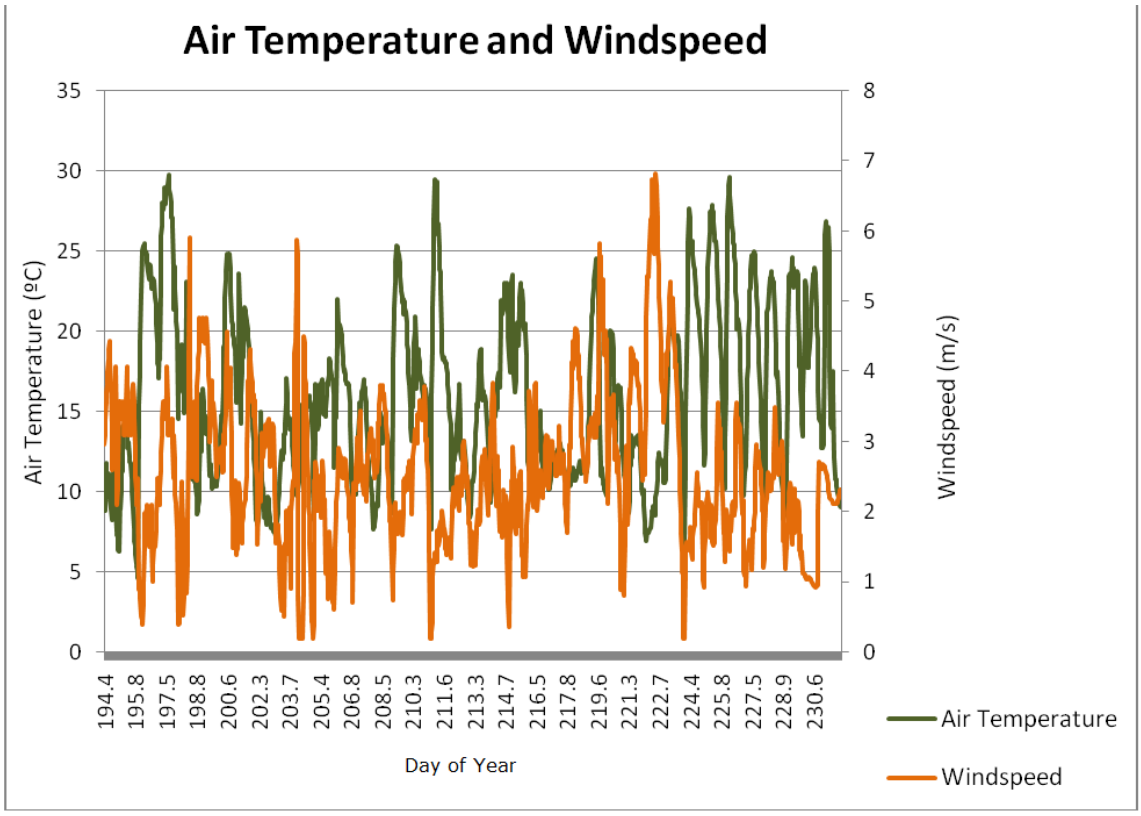

Figure 29: Wind speed and air temperature throughout the research season.

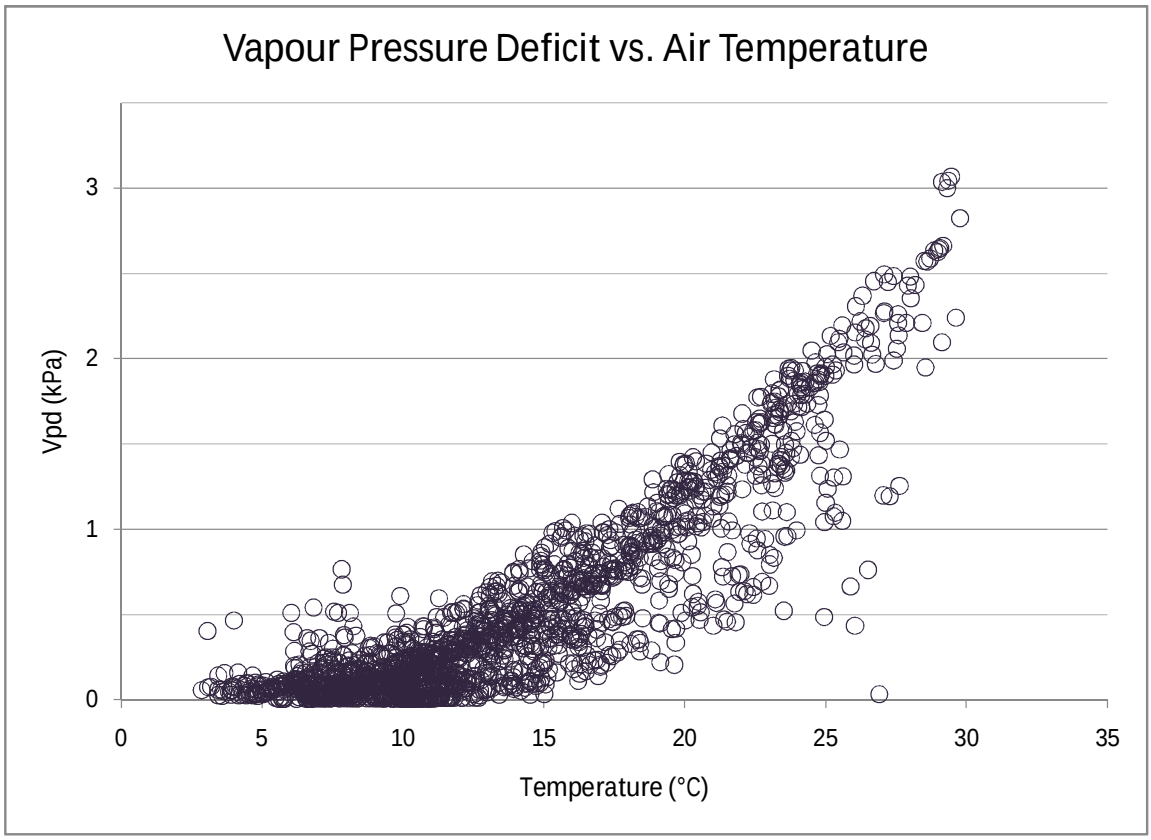

Figure 30: Half-hourly vapour pressure deficit and air temperature.

Vapour pressure deficit and temperature are positively correlated with higher temperatures corresponding to drier air conditions.

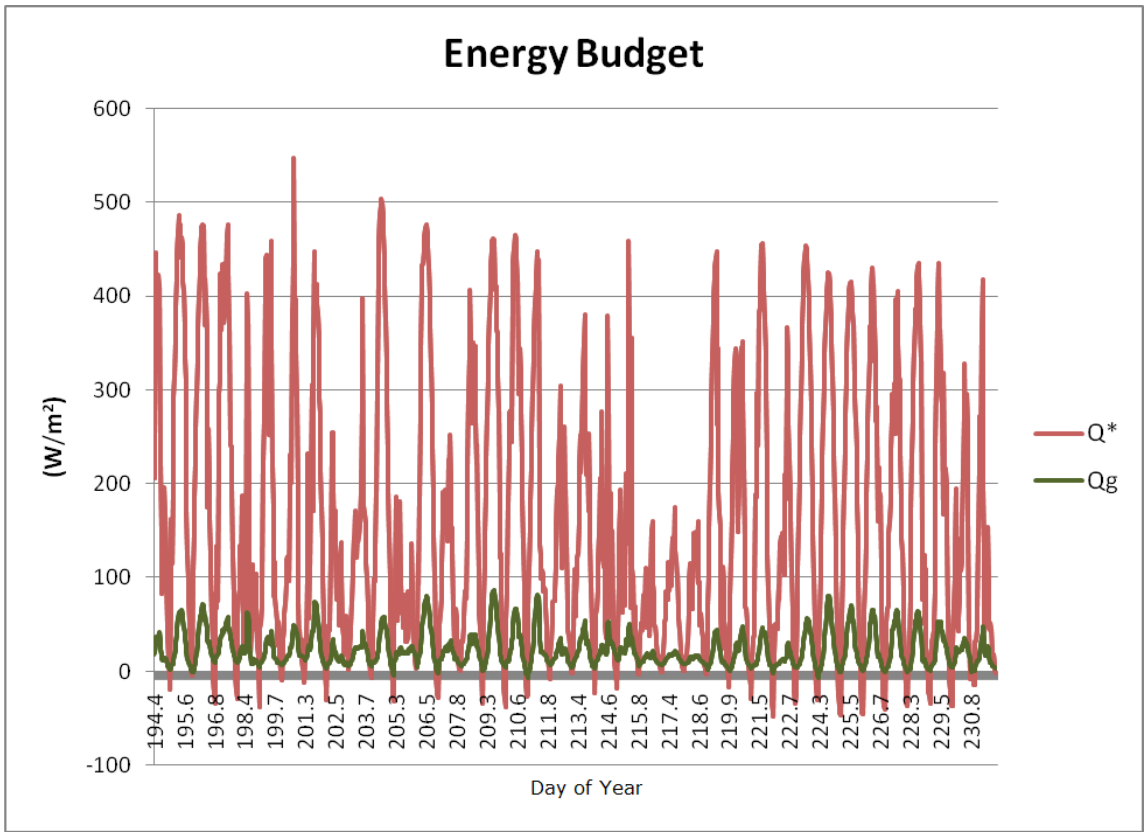

Figure 31: Energy budget components of net radiation, Q* and ground heat flux, Qg.

4.5.1 Interception through different precipitation events

When calculating interception and drainage, the positive and negative changes in canopy moisture were closely examined during, before, and after rainfall events. There is no time limit during an event.

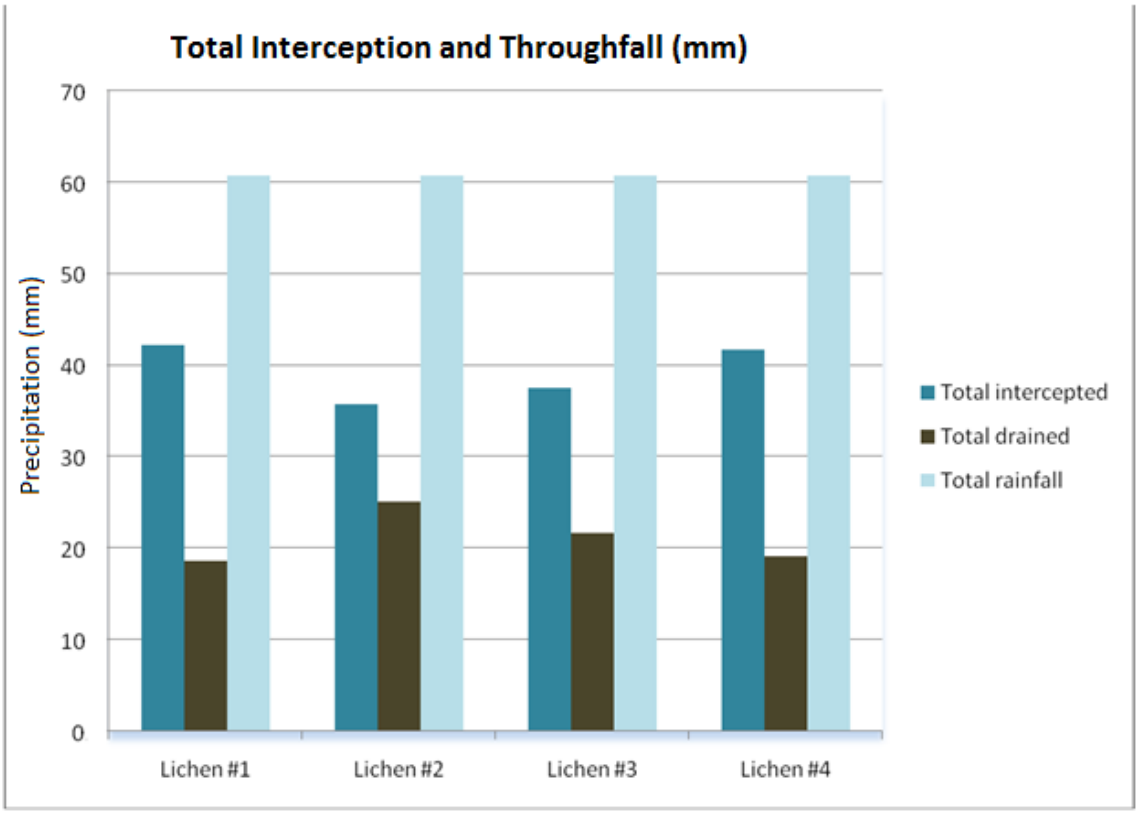

Figure 32: Total interception and throughfallfrom weighing lysimeters during the measurement season (including all half hours).

Several of the rainfall events were less than 2 mm, which were mostly intercepted. Based on Table 2, the maximum storage capacities ranged between 3.6-6.5 mm which also supports the premise that most rainfall events less than 3mm can potentially be intercepted.

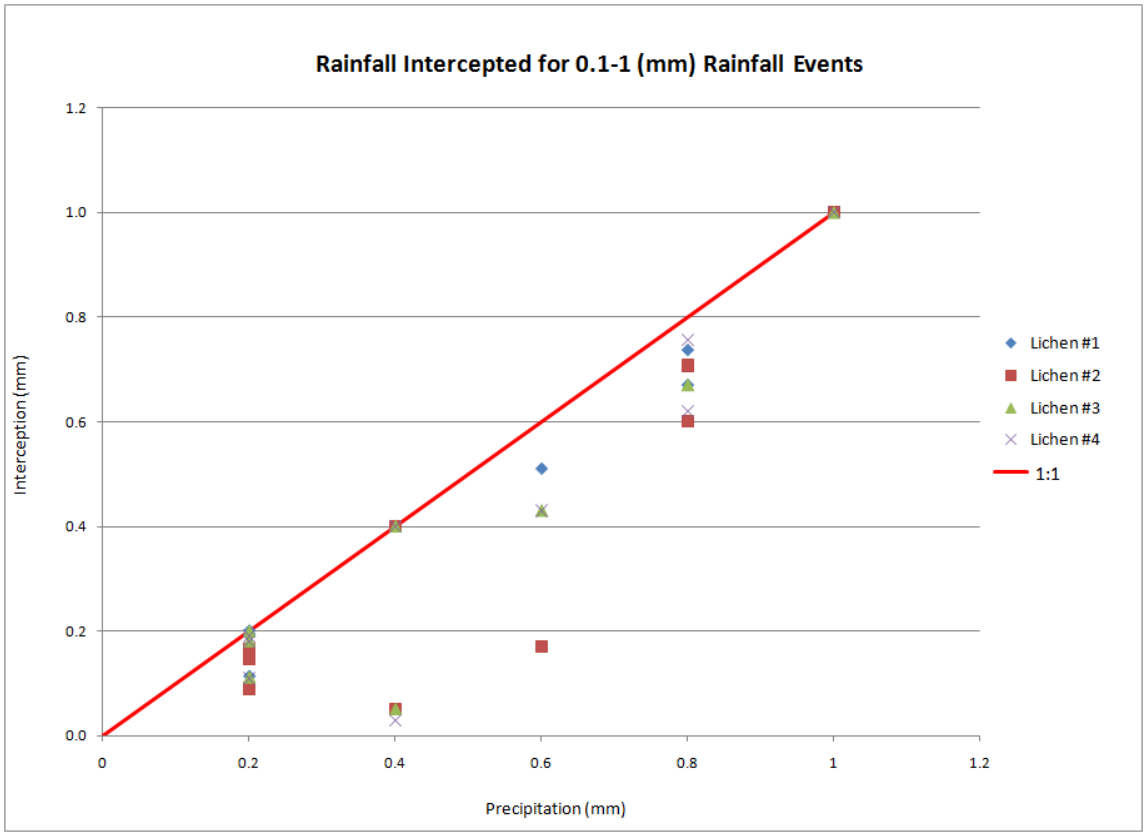

Figure 33: Rainfall intercepted forlight 0.1-1.0 mm rainfall events.

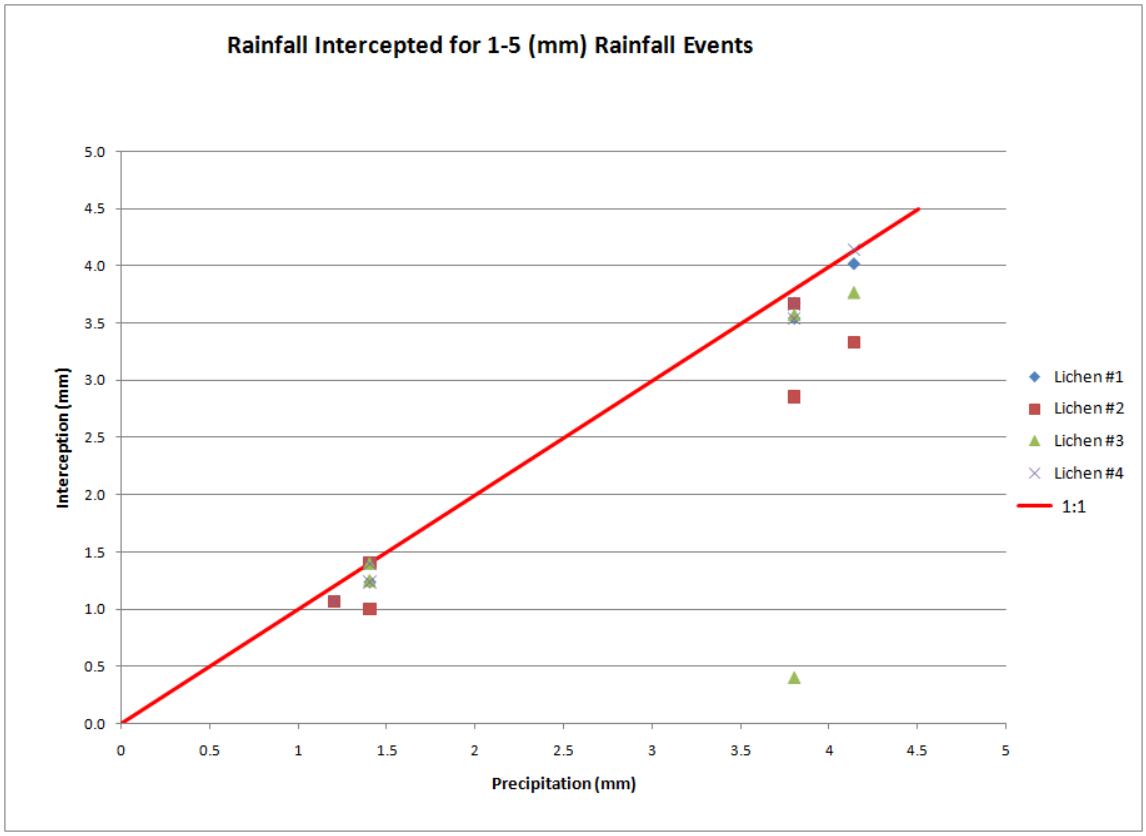

Figure 34: Rainfall intercepted for1-5 mmrain events.

There were rainfall events exceeding 5mm but most were not intercepted because the canopies already exceeded their MSC's,(not shown).

Overall throughout the season, the lichen mats did not often exceed their maximum storage capactiy. The difference between the actual moisture in the canopy (C) andMSCwas computed to demonstrate the potential for drainage by gravity. There were very few occasions when MSC was exceeded by C. When MSC was exceeded it was due to a heavy or extended rainfall event.

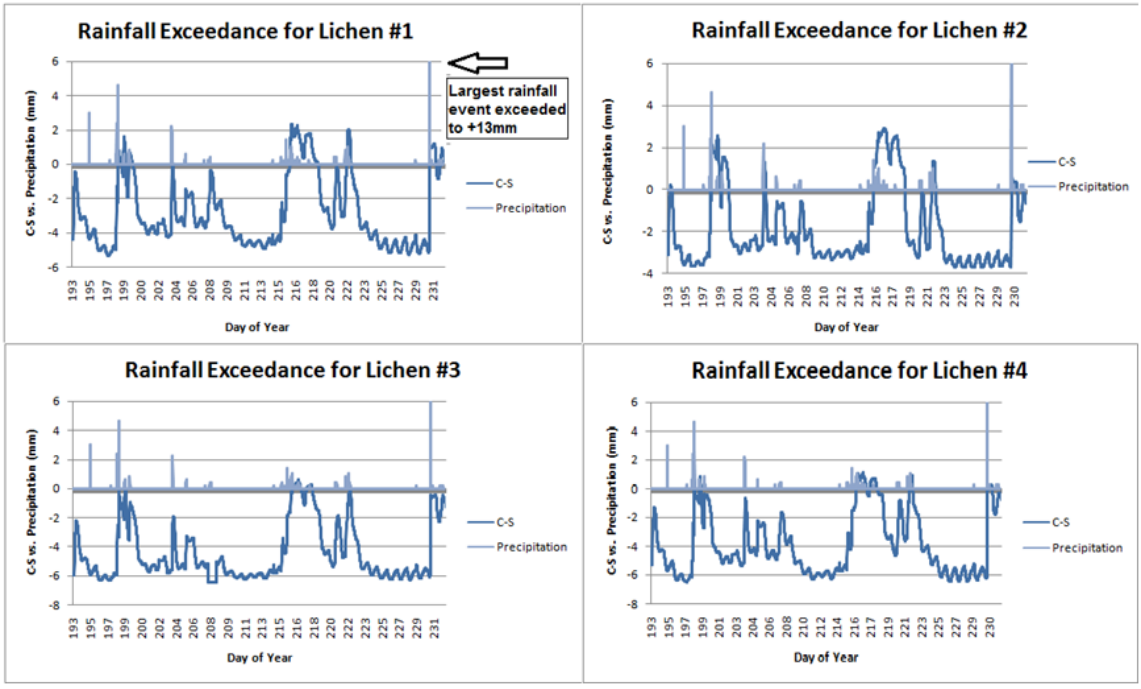

Figure 35 (A,B,C,D):The seasonal progression of rainfall magnitude versus residual canopy capacity (C-S)for the four lichen samples. Positive values indicate periods of drainage.

There were several rainfall events that had high intensities, and/or were on-going which would influence the time and amount of water drained. Most rainfall events that occured insufficient to raise C-S into the positive range and were therfore completely intercepted (Figure 35) Rainfall events which raised C-S into positive values, represent occasions when drainage did occur. For example, on Day 198 there was a rainfall event that was 10.6 mm. The water content of each lichen matt exceeded the MSC on this day due to the continous rainfall event that obviously did not allow enough time for the canopy to completely dry. Overall, the MSC was exceeded on 6-10 occasions (depending on the lichen mat) during a total of 19 rainfall events.

4.6 Condensation

As seen in Figure 27 there are periods during the field season where a noticeable *saw-tooth* pattern appears. The rise portion of the pattern exists between sunset and sunrise (~6:00 am). The pattern is seen each night, except when nocturnal rainfall occurred. The lichen mats lose water during the morningwhen net radiation begins going positive. This nocturnal gain iscondensation.

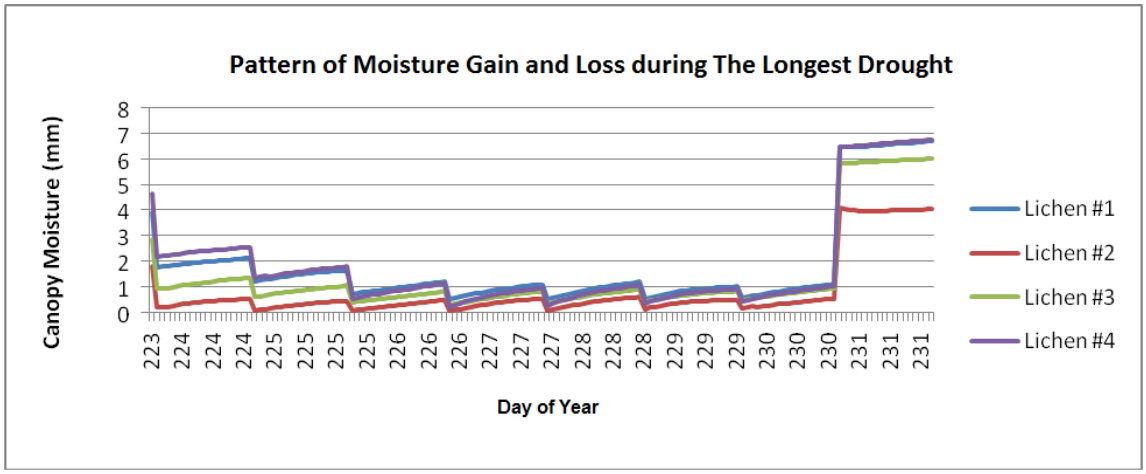

Figure 36. The characteristic *saw-tooth* pattern during the longest period with no nocturnal rainfall.

The y-axis represents the canopy moisture storage that flucuates between 0-2 mm (depending on the lichen mat). The x-axis shows the timing of that period. Lichens increase in water after 19:00 (standard time) and begin to decrease after 6:00 am. The flucuation is not large, but the average moisture gain when there is no rainfall ranges between 0.30-0.40 mm.

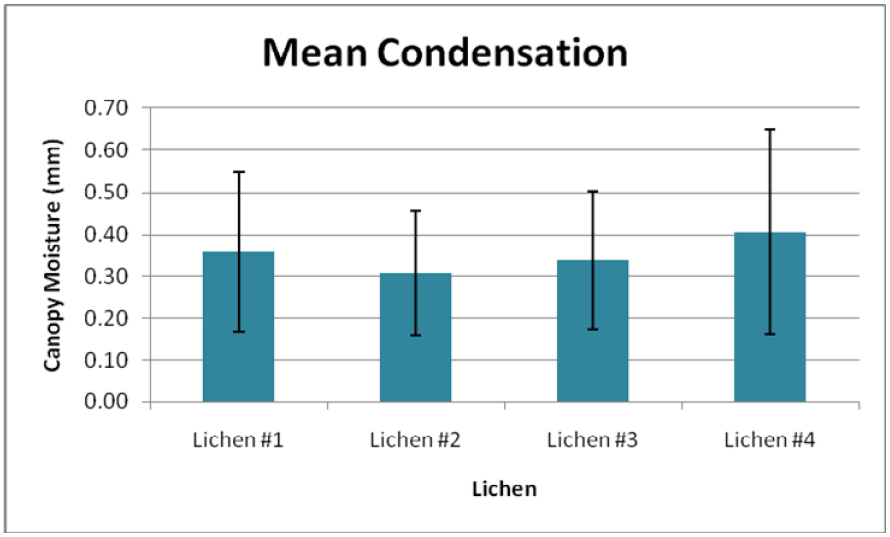

Figure 37: Mean canopy moisture gains during the night.

Condensation periods during the evening were defined by periods of negative net radiation (Q*<0). Since the duration of this period of radiative cooling varied every night, and was influenced by nocturnal cloud conditions and vapour pressure deficit, surface cooling and condensation varied from night to night, and therefore fluctuations were not always the same. Rainfall events during specific nights have been excluded from condensation totals since weight gains during these events are not considered condensation.

4.7 Canopy resistance

Canopy resistance, r_c(Equation 1) represents a measure ofthe difficulty of water escaping the thallus (in units of seconds per meter). The importance of this to an understanding of canopy evaporation is to quantify the role of moisture availability; how the amount of water in the canopy, will influence how quickly water will evaporate. Gravimetric moisture content describes the quantity of water in the canopy, measured in grams of water per gram of dry biomass. An x, y plot of the two variables describes the relationship between the two and provides an

independent means of parameterizing r_c from GMC alone, for incorporating into the evaporation formula of Penman-Monteith for the sampled lichens.

Figure 38 displays the semi-log relationship for data ranging from almost completely desiccated to the maximum storage capacity. Canopy resistance ranges from1 to 3000 ms^{-1} (ln(3)=1; ln(3000)=8). Gravimetric moisture content ranges from 0-2.5 g[H_2O]/g[biomass]. The higher the canopy resistance is, the more challenging it is for water to escape the lichen thallus. Each lichen mat displays similar patterns of canopy resistance. When drainage declines to the MSC after a rainfall, resistance is lowest but non-zero, indicating that there is still some residual resistance to moisture escape above what would be expected if there were no restrictions to moisture availability, say over a plane water surface of a lake. When lichens hold no water, atGMC =0, resistance to moisture loss is at least three orders of magnitude higher than when GMC = 2.0.

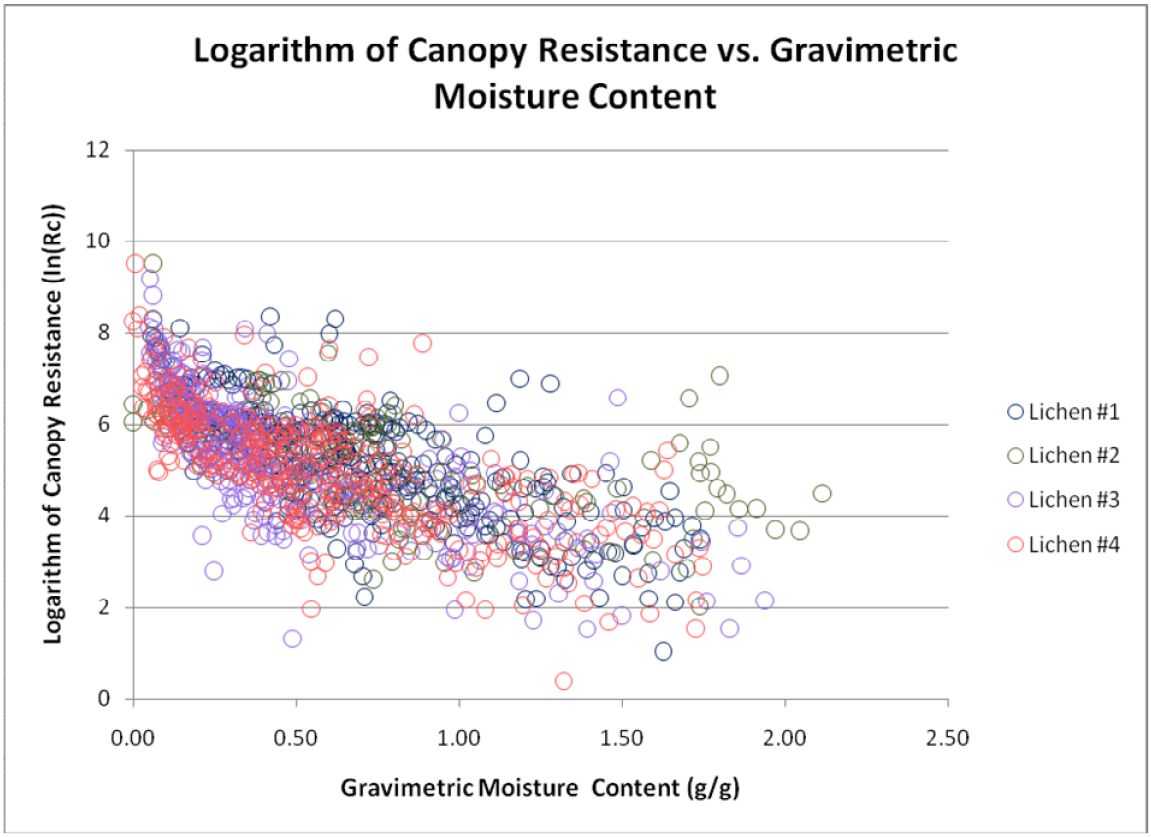

Figure 38: Canopy resistance versus gravimetric moisture content for half-hourly data over the measurement period. Rain events and night time data are excluded.

The pattern reveals that the canopy resistance of all lichens act in a similar manner with respect to moisture availability. The regression statistics for each lichen mat are shown in Figure 39.

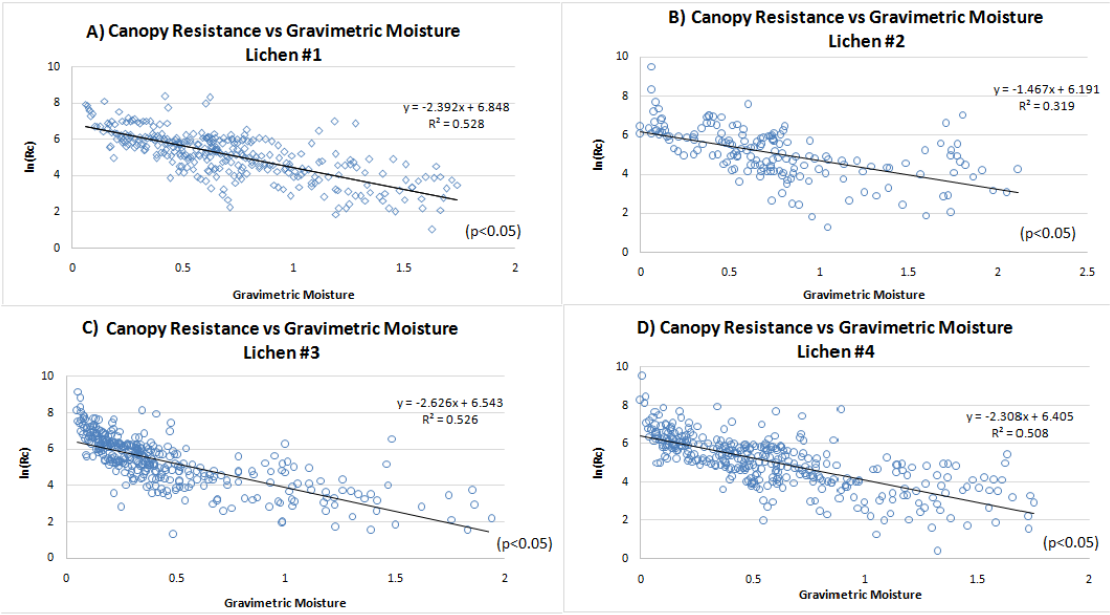

Figure 39a,b,c,d Regression equations of the daytime natural logarithm of half-hourly canopy resistance for each lichen canopy(1,2,3,4) versus gravimetric moisture content (dimensionless) throughout the measurement period excluding, rainfall events. A Shapiro-Wilk test on the regression residuals indicate they are normally distributed.

Regressions show a statistically significant and strong relationship. All except for lichen #2have similar slopes and coefficients of determination of at least 50% which demonstrates that at least half of the variability in half-hourly r_c determined from Equation 4 can be explained by the variability in GMC measured with the weighing lysimeters. One sample that hasR^2<0.50 shows a slightly different sensitivity. This may be due to an experimental error causedby a fox which dragged the weighing lysimeter out of its locationfor a short period of time.

4.8 Modelling Evaporation

Results of canopy resistance regressions show similarities between all lichen canopy samples suggesting a generalized relationship could be used to parameterize lichen canopy

resistance in this part of the Hudson Bay Lowlands. While this outcome is encouraging, when the parameterized values of r_c using the regression relationships are substituted into the Penman-Monteith (Equation 1) and half-hourly evaporation estimates are compared to measured evaporation from the lysimeters, much more scatterresults (R^2<0.50; Figure 40). It is apparent that the largest outliers in Figure 40 occur during numerous instances when half-hourly evaporation is particularly large. In part, the errors in the evaporation estimates have increased because the scatter in Figure 39 is for the natural logarithms of canopy resistance whereas the scatter in modelled P-M evaporation in Figure 40 incorporates the errors in the modelled canopy resistance itself. Nevertheless, it would be insightful to better understand the limitations of the approach used by conducting an error analysis.

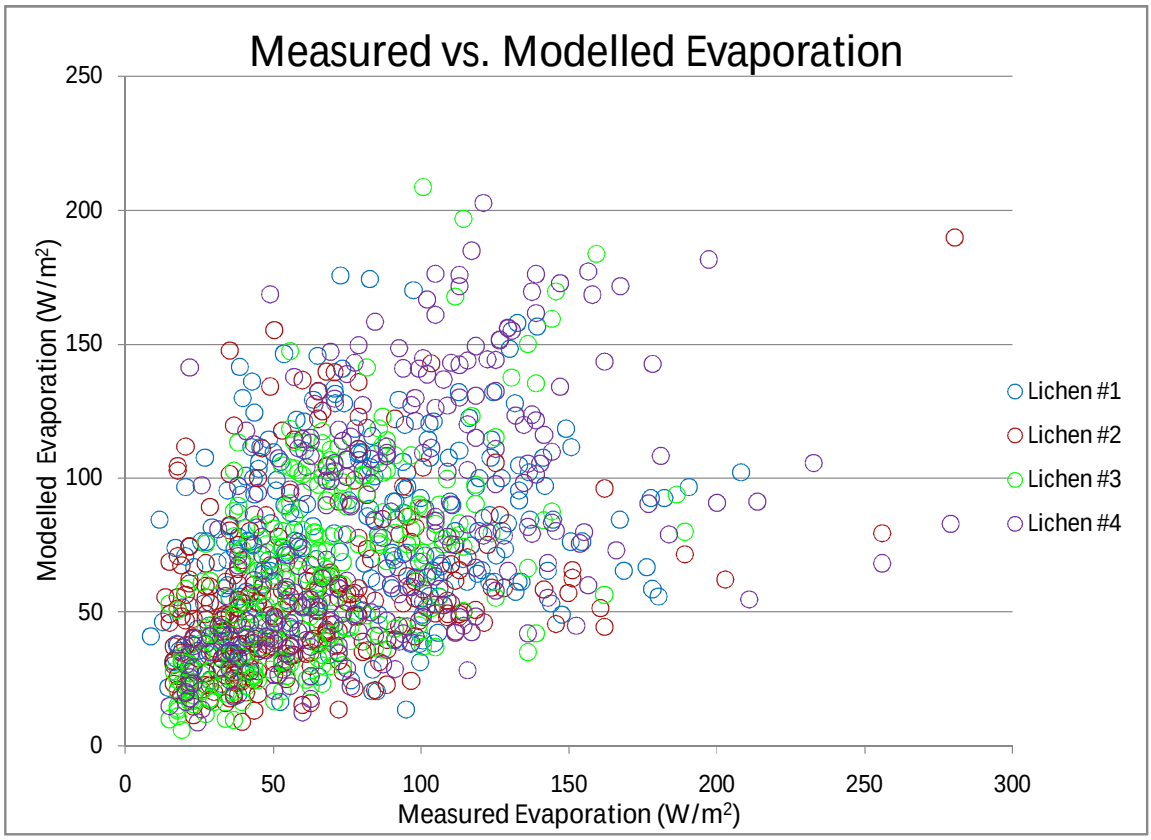

Figure 40: Measured versus. modelled evaporation for half-hourly estimates. Measured evaporation is from weighing lysimeters and modeled evaporation is from the P-M model using the parameterizations for canopy resistance based on gravimetric moisture contents.

4.9 Error Analysis

The variables measured for the P-M model estimates of evaporation include windspeed, net radiation, ground heat flux, air temperature and air humidity. These could all represent sources of error as well as the determination of gravimetric moisture content itself using the weighing lysimeters.Table 3shows the sensitivity of errors in canopy resistance to these environmental

measurements. The errors are computed as the deviations of measured r_c using Equation 4 from the regression estimates of r_c shown in Figure 39 a,b,c,d.

Table 3: Sensitivity of errors in canopy resistance Dln(rc) to changes in environmental measurements, Dx. Dln(rc)=0 represents the value of x for which there is null error.

	Temperature [$^0C^{-1}$]			Relative Humidity[RH^{-1}]			Net Radiation [$(Wm^{-2})^{-1}$]		
Lichen #	Dln(rc)/Dx	p	Dln(rc)=0	Dln(rc)/Dx	p	Dln(rc)=0	Dln(rc)/Dx	p	Dln(rc)=0
1	-0.075	<0.001	18.0	0.035	<0.001	62.2	-0.002	<0.001	245
2	-0.06	<0.001	17.6	0.025	<0.001	61.0	-0.001	<0.01	231
3	-0.074	<0.001	15.9	0.026	<0.001	66.7	-0.001	<0.001	81
4	-0.067	<0.001	18.5	0.029	<0.001	59.6	-0.001	<0.001	251
MEAN	-0.070		17.5	0.029		62.4	-0.001		202
STDEV	*0.007*		*1.2*	*0.005*		*3.1*	*0.001*		*81*
COVAR	*-0.106*		*0.1*	*0.157*		*0.0*	*-0.400*		*0.400*
	Ground Heat Flux[$(Wm^{-2})^{-1}$]			Windspeed[sm^{-1}]			Canopy Moisture (mm)		
Lichen #	Dln(rc)/Dx	p	Dln(rc)=0	Dln(rc)/Dx	p	Dln(rc)=0	Dln(rc)/Dx	p	Dln(rc)=0
1	-0.01	<0.001	17.7	0.009	>0.05	2.4	0.012	>0.05	1.4
2	-0.009	<0.01	16.2	0.106	<0.01	2.5	-0.007	>0.05	0.8
3	-0.004	<0.01	-35.6	0.077	<0.01	5.1	0.001	>0.05	194.5
4	-0.007	<0.001	18.8	0.122	<0.01	2.4	-0.002	>0.05	1.0
MEAN	-0.008		4.29	0.102		3.3	0.001		49.4
STDEV	*0.003*		*26.586*	*0.023*		*1.5*	*0.008*		*96.7*
COVAR	*-0.353*		*6.202*	*0.224*		*0.460*	*8.042*		*1.958*

The errors in $\ln(r_c)$were regressed against each variable x; represented by measured half-hourly temperature, relative humidity, net radiation, ground heat flux, windspeed and canopy moisture. The regression slope or sensitivity of the errors to each variable are shown in Table 3 as $\Delta \ln(rc)/\Delta x$.Examples of the regressions against measured air temperature and measured ground heat flux are shown in Figure 41a,b,c,d and Figure 42a,b,c,d respectively, for illustration.

Some interpretations drawn from this analysis and documented in Table 3 are as follows.The sensitivity of the error in canopy resistance to air temperature, $D\ln(r_c)/DT$ is highly

significant for all canopies and averages -0.070 indicating decreasing errors as temperature warms, with no net error ($D\ln(r_c)=0$) at 17.5 ^{0}C. There is very little difference between samples indicated by a coefficient of variation of ~0.1and as seen in Figure 42. With extreme air temperatures ranging from 5 to 30 ^{0}C over the measurement period, this corresponds to errors in canopy resistance between0.34 to 2.50 sm^{-1} respectively.

The sensitivity of canopy resistance errors to the relative humidity of the air is also highly significant for all canopies and averages 0.029, indicating increasing canopy resistance errors as humidity increases, with no mean error at RH=62.4%. Relative humidity ranges from 25% to 99% over the measurement period, with corresponding errors in canopy resistance between 0.28$sm^{-1}$and 3.57 sm^{-1} at the extreme limits of the measurement range.

Canopy resistance sensitivity to net radiation averages -0.001 with decreasing errors at higher radiation levels with no error at an average 202 Wm^{-2}. The point of null error however varies more between samples than do the null errors for temperature and humidity with sample#3 showing a distinctive difference compared to the other three. Lichen #2 shows slightly more scatter with a slightly larger p-value. With net radiation ranging over the measurement period between -30 and 500 Wm^{-2} the corresponding errors in canopy resistance ranges between 0.54 and 1.95 sm^{-1}.

Canopy resistance error sensitivity to changes in ground heat flux is about eight times larger than that to net radiation (c.f. Figure 42). However, because the range in values is more restricted over the measurement period (-100 to 60 Wm^{-2}) the corresponding range in errors in canopy resistance are also quite small between 0.63 $sm^{-1}$and 3.62 sm^{-1}.

Lichen #1 showed no sensitivity to windspeed and the three others were significant at $p<0.01$. Again, sample #3 showed a distinctly different null value from the other three samples. The increasing errors in canopy resistance to increasing windspeed were also weakest in Lichen #3 at 0.077 compared to the average of 0.102. Over the measurement period, windspeed ranged from 0.23 $ms^{-1}$to 6.2 ms^{-1} corresponding to r_c errors between 1.59 $sm^{-1}$and 0.68 sm^{-1}.

Lastly, canopy resistance showed no significant error sensitivity to canopy moisture in any of the samples over the range of 0 to 3.5 mm water storage over the measurement period.

Overall, errors in canopy resistance show a systematic and highly significant dependence on all the measured meteorological variables, with least sensitivity to windspeed. There is no apparent systematic error sensitivity to measured lichen moisture content. Despite these biases, the magnitude of the errors in canopy resistance is extremely small, even at the maximum and minimum limits of environmental conditions encountered over the measurement season, when compared to the range in canopy resistances found over the measurement period (1-3000 sm^{-1}). This suggests that improvements could be made to the estimates of canopy resistance by improving measurement accuracy, for example, but with marginal expected model improvement.

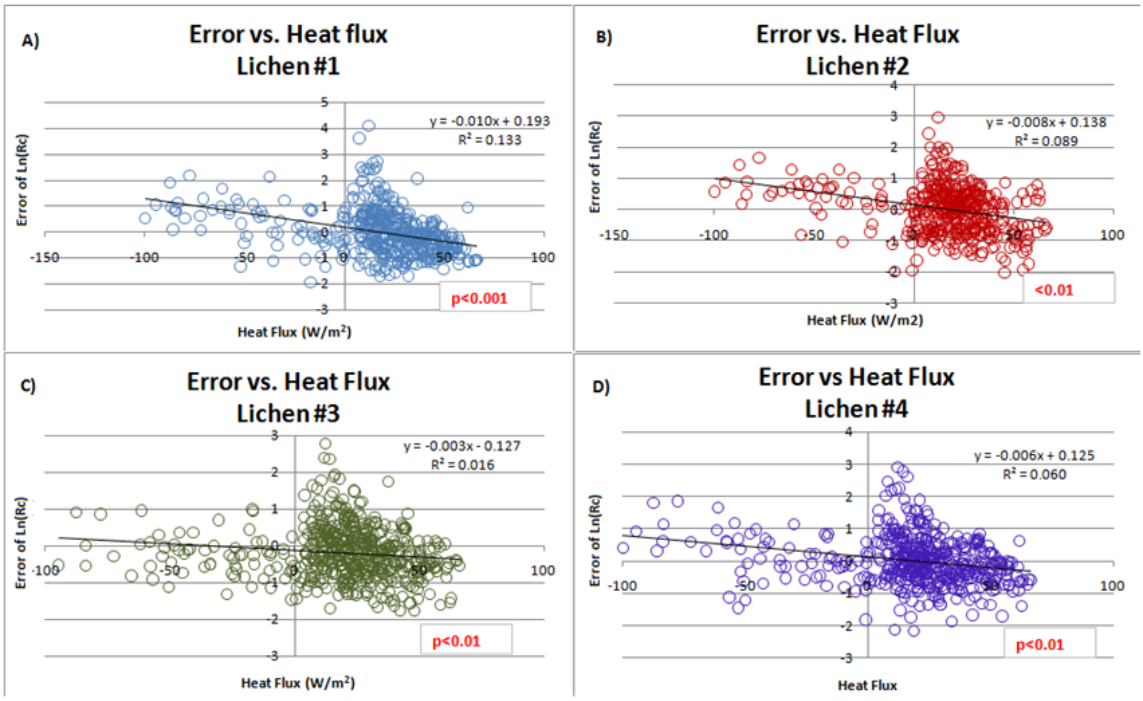

Figure 41 a,b,c,d: Canopy resistance error vs ground heat flux in all canopies.

The medians of canopy resistance (sm^{-1})over the entire measurement period for each lichen canopy are shown in Table 4. Here the errors in r_c at the seasonal extremes of each measured variable (from Table 3) are expressed as proportionsof the median. As a proportion of median canopy resistance, errors are all less than 1.9%, with the smallest proportional error being 0.1%. This leads to the same conclusion that errors in the resistance parameterization does not likely reside in measurement errors.

Table 4: Proportional errors of canopy resistance with respect to seasonal median r_c (sm^{-1}) for each environmental variable when at the seasonal minimum and seasonal maximum.

	Temperature			Relative Humidity			Net Radiation		
Lichen #	Median	Min	Max	Median	Min	Max	Median	Min	Max
1	194.4	0.014	0.002	194.4	0.00	0.68	194.4	0.010	0.003
2	160.8	0.013	0.003	160.8	0.00	0.51	160.8	0.009	0.004
3	225.9	0.010	0.001	225.9	0.00	0.43	225.9	0.005	0.003
4	172.4	0.015	0.003	172.4	0.00	0.60	172.4	0.008	0.004
	Ground Heat Flux			Windspeed			Canopy Moisture		
Lichen #	Median	Min	Max	Median	Min	Max	Median	Min	Max
1	194.4	0.019	0.003	194.4	0.005	0.005	194.4	0.005	0.005
2	160.8	0.017	0.004	160.8	0.005	0.009	160.8	0.006	0.006
3	225.9	0.006	0.003	225.9	0.003	0.005	225.9	0.004	0.004
4	172.4	0.013	0.004	172.4	0.004	0.009	172.4	0.006	0.006

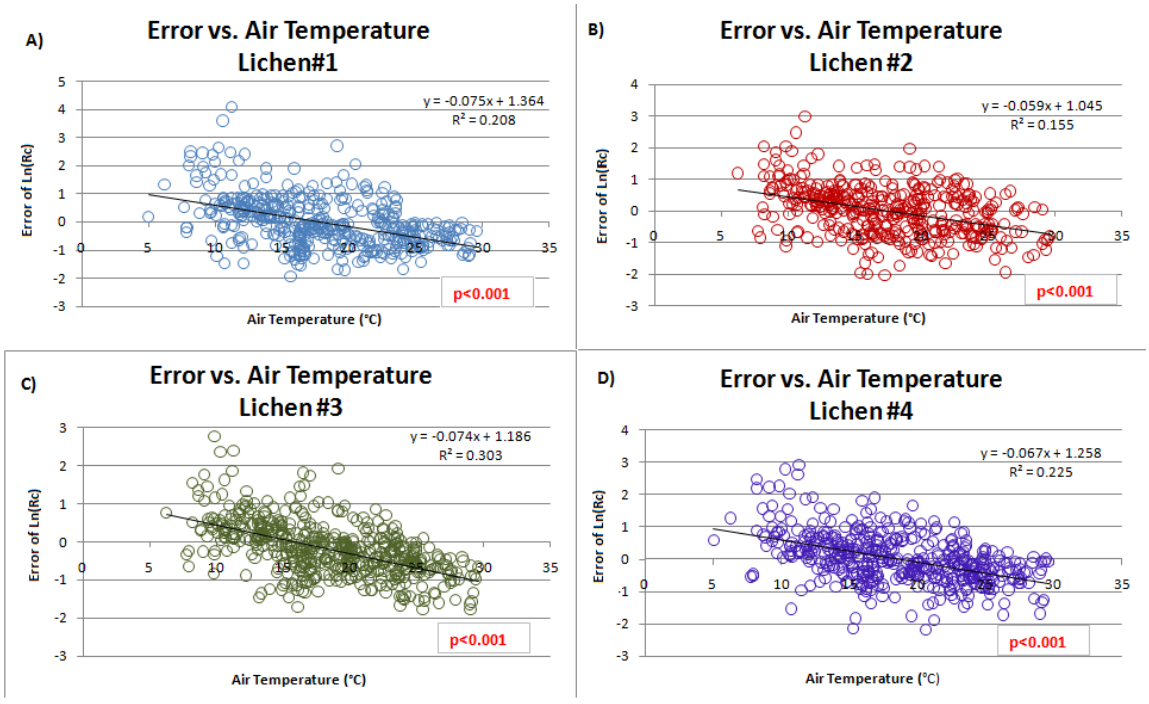

Figure 42 a,b,c,d: Error in canopy resistance versus measured air temperature for all canopies.

Another possible source of error in the parameterizations of canopy resistance may reside in the experimental design. The bulk change in weight of the entire canopy was used to describe interception gains and evaporative losses and these were measured with great precision by the weighing lysimeters. However, it was commonly observed that after rainfalls, the lichen canopy surface dried out first (lichens become stiff and crusty) and then the drying proceeds downwards until after a few days the entire canopy dries out. It would become progressively more difficult for water to escape as time proceeds. This exponential increase in the difficulty of water escaping to the atmosphere is reflected in the logarithmic dependence of r_c on the mass of water remaining in the canopy. However, the lysimeter cannot differentiate between a small amount of residual water at the base of the canopy after an extended period of drought and the same small amount of water residing in the top of the canopy after a drizzle. The newly arrived surface water could evaporate within a half-hour while it might take several hours for the same amount of water at the base of the canopy to evaporate under the same environmental conditions.

To rectify this problem and account for the vertical distribution of water within the lichen canopy would require a more sophisticated experimental design beyond the scope of this thesis and is therefore, a possibility I cannot explore at this time. It may however be needed to develop more accurate estimates of lichen canopy evaporation and therefore rainfall interception.

CHAPTER FIVE: DISCUSSION& CONCLUSIONS

5.1 Lichen Biomass

Much of the research conducted for this thesis is the first of its kind, and certainly for lichens of the Hudson Bay Lowlands. The exceptions are the seminal manual rainfall interception work of Arama (1987, 1989) and the habitat-scale evaporation estimates from lichens using Bowen ratio energy balance (BREB) system of Verratti (2003), in the same general area.

A survey of lichen biomass has never been recorded in the lichen-dominated Hudson Bay Lowlands region (~12,000 km^2 in Manitoba). The habitat with the largest lichen biomass was within the open spruce-lichen woodland. In a sheltered setting with reduced sunlight and moist conditions and moist soils, lichens grow for extended periods of timeand the closed coverage keeps lichens untouched and compact (Sales et. al., 2016). Moisture readings were not taken during biomass sampling. However, based on subjective observations, many lichens in the forest were damp to-the-touch. Asmentioned earlier, lichens are poikilohydric and shut down their metabolisms when dry. Enhanced moisture levels and delayed drying time provides longer periods for active growth and biomass accumulation. Lichens are also nonvascular, and without rootsdepend on the atmosphere for water in the form of rain and dew.A study on lichen biomass in the Sonaran Desert in Arizona (Nash and Moser; 1982) focuseson how dependant lichens are on precipitation. They found that lichen biomass communities near the Pacific coast in the western side of the desert are larger and can be explained based on precipitation alone (Figure 43).With more moisture, there is more biomass in comparison to different habitats.

In this study, the lowest lichen biomass was on the beach ridge habitats. Beach ridge habitats are not only in open elevated areas, they are mainly mineral based soils (sand containing rocks and very low vegetation) with a poor capacity to hold moisture. This observation supports how these lichens are rarelygrowing, remainingdesiccated for extended periods of time (aside from during rain events); fully exposed to sun and high winds with high rates of evaporation.

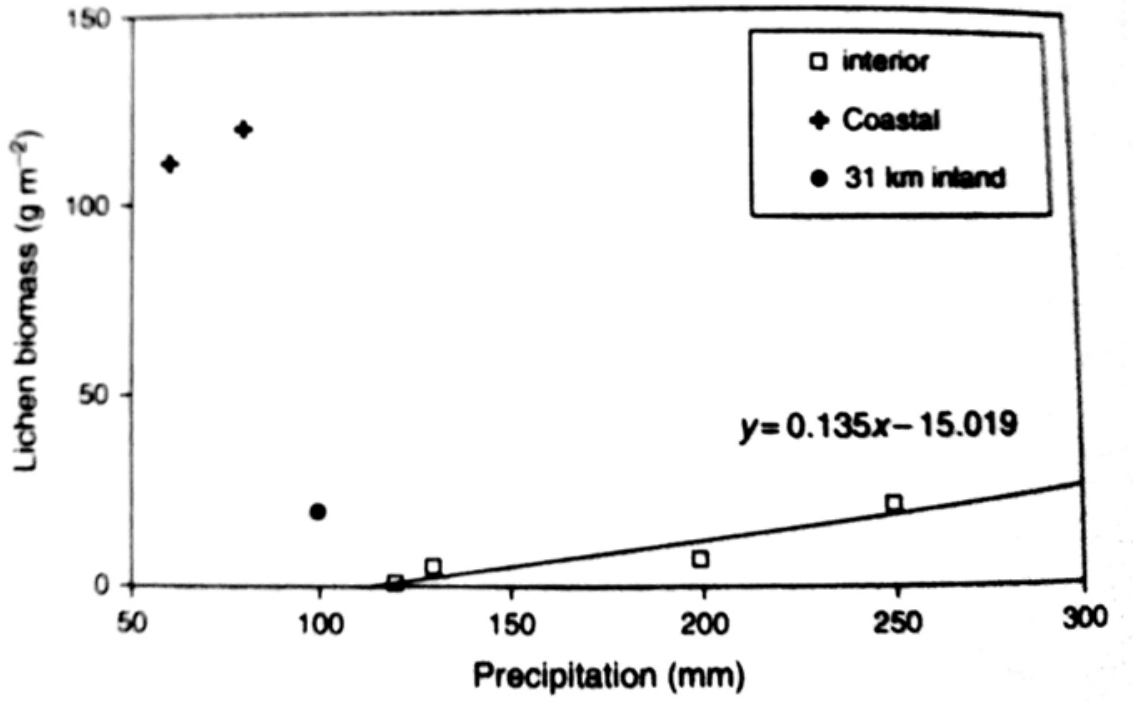

Figure 43 : Relationship of lichen biomass in the Sonaran Desert region to mean annual precipitation (Nash et. al., 1982).

5.2 Potential Interception and Maximum Storage Capacity

Laboratory experiments were conducted on samples of *Cladinastellaris* to relate biomass and density to their drainage characteristics. One key variable measured was maximum storage capacity, MSC and the relationship between biomass and MSC bore a close resemblance to those

of Arama (1987;1989) and (Verratti, 2003) collected from the same general area. Lichen maximum storage capacities ranged 0-23mm. Derived values of the MSC's were then used to determine the *potential* interception that would occur in various habitats in the Hudson Bay Lowlands. Using historical (1980-2015) rainfall data from Churchill MB, potential interception by lichens in each of four habitats was calculated under the assumption that lichens were dry prior to each rain event, and resulted in summertime interceptions ranging from 140 to 37 mm for the spruce lichen woodland and the beach ridge habitats, respectively, but with large interannual variability. These amply demonstrated the profound impact lichens could potentially have on reducing the amount of water entering the ground water and stream systems.

Another important variable measured in the lab experiments was the drainage rate. These showed rapid (60%) drainage of available water in the first 30 minutes after a rainfall with all drainage ending after approximately 3 hours.

> Drainage varies between different vegetation types and climatic regions (Levia et. al., 2003). A study of stemflow on 24 palm trees in the southwestern Amazon basin of Brazil (Germer et. al, 2010) with a tipping bucket rain gauges at 5 minute intervals, that from a total of 40 rainfall events, only two that did not generate any stemflow (rainfall depths at 0.5 mm). The mean resultant stemflow was 8.0 ± 1.8% and ranged from 0% to 23.3% for individual events (Germer et. al, 2010).

Another study by Domingoet. al.(1998) looked at three species of two shrubs and a grass in a semi-arid area of northern Spain to demonstrate the differences in interception loss. The three species included, *Stipatenacissima* (perennial tussock grass), *Anthyllis cytisoides* (drought-deciduous leguminous shrub), and *Retamasphaerocarpa* (woody leguminous shrub with ephemeral leaves). Field measurements of gross rainfall, throughfall, and stemflow were taken

for each rainfall event for only the two shrub species. For *Stipatenacissima*, measurements of canopy drainage were taken by being wetted and recorded every 0.125 seconds and averaged every 10 seconds (Domingo et. al., 1998) collected by a data logger. A weather station was also created that measured wind speed, wind direction, relative humidity, air temperature, and solar radiation that was recorded and averaged every 5 minutes.

Results revealed significant differences between each species including *R. sphaerocarpa* having the lowest interception due to having a low area index, with *S. tenacissima* having the largest interception due to higher biomass density (Domingo et. al., 1998). Species of *S. tenacissima* and *A. cytisoides*had low free throughfall and drainage rates. The authors concluded that structural differences were responsible for the distinctive drainage rates. These included*R. sphaerocarpa* and *A. cytisoides*having "funnel shaped" branches which contributed to smaller maximum storage capacities in comparison to *S. tenacissima* that has more of a firm mat of dead litter as a base (Domingo et. al, 1998). This role of canopy structure is consistent with the very fast drainage experienced for the dwarf lichen canopies.

5.3 Field determinations of the lichen water balance

Four precision weighing lysimeters measured water gain and loss during a 63-day summer period from pure *Cladinastellaris* canopies with biomass ranging from 1.66 kgm^{-2} to 3.49 $kgm^{-2}$and MSC's ranging from 3.67 to 6.52 mm. By isolating periods of rain from periods of evaporation and isolating nocturnal periods from the daytime periods, estimates of interception and drainage, estimates of evaporative loss and estimates of condensation gain were made possible.

Field measurements show that with a total of 60.7mm of rainfall, 18.54 to 25.07mm (30.5% to 41.3%) was drained and 35.7 to 42.2 mm of rainfall (58.8% to 69.5%) was intercepted and eventually evaporated. These values for interception are large and are somewhat largerthan the historical *potential* interception estimated for the ice-wedge polygon habitat of 46% (Figure 19) calculated using the assumption that the canopies were dry each time a rainfall occurred. This discrepancy could be attributable to the four samples used being, on average, thicker than is typically found in these habitats or due to the fact field season rainfall differed substantially from the long-term average. The seasonal interception averages are however, very similar to the seasonal interception of 61.2% found by Bello and Arama (1989) for similar ice-wedge polygon habitat nearby at Malcolm Ramsay Lake. The field values of interception are comparable to the long-term historical *potential* interception mean for lichen mats having a maximum storage capacity of 5 to 7 mm (Figure 20).

Condensation appeared every night throughout the summer when it didn't rain. Condensation was indicated by a *saw tooth* pattern that appeared each night, ending each morning with sudden decrease in canopy storage. On average, every evening the lichens would gain moisture between 0.31-0.41 mm and would decrease in moisture after sunrise as temperatures and net radiation increased. Condensation overall added 8.3-10.9 mm of moisture to the lichens over the summer period corresponding to a 13.7% to 18.0% increase in overall moisture inputs to the canopy (that did intercept and not drain). It increased seasonal totals of interception between 0.10 to 0.20 percent throughout the summer (varying by lichen sample).

5.4 Canopy Resistance

5.4.1 Canopy resistance vs. Gravimetric moisture content

It was hypothesized that canopy resistance (r_c) can be estimated or modelled if the amount of water stored in the lichen canopy is known, either as a fraction of maximum storage capacity (C/S) or as a proportion of lichen dry weight (GMC). The ability to improve upon *potential* interception estimates to get actual interception estimates rests entirely on modelling how dry the canopy is at time of rainfall which is equivalent to modelling the evaporation between rainfall events. To estimate and model canopy resistance, regression equations were developed to provide the best fit between half-hourly estimates of canopy resistance using the P-M model and gravimetric moisture content (GMC). Of the four lichen canopies, three of them had near identical results during the measurement period, excluding night times with coefficients of determination exceeding r^2=0.50, with the one that was less (r^2=0.32) The results are encouraging for employing in a lichen water balance model, as the GMC can be determined as a running total provided the evaporative losses from the previous time step are known. The lichen sample that resulted in an r^2=0.32 most likely had error due to the disturbance from a fox (fragmented data from fox was removed). As all four lichen canopies shared similar trends they also shared differences in density and maximum storage capacity. Interestingly, an experiment by Verratti (2003) using manually weighed lichen baskets over several hours on a peat plateau at Twin Lakes near the Churchill Northern Studies Centre, yielded a near identical relationship between $\ln(r_c)$ and C/S as that for sample #2 of $\ln(r_c)$=-1.421 (C/S)+5.47 (R^2=0.67) (Figure 44).

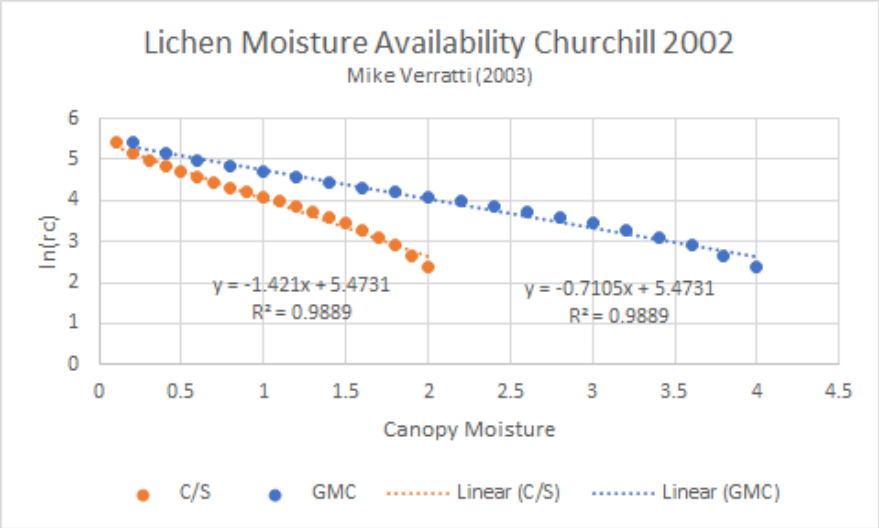

Figure 44: Lichens moisture availability and canopy resistance from a model after Verratti (2003).

5.4.1 Modelling Evaporation

Canopy resistance (r_c) is important and necessary in calculating and modeling evaporation using the Penman-Monteith approach (Beven 1979). Modeling evaporation using the Penman Monteith model with parameterized estimates of r_c, resulted in unexpectedly large errors compared to weighing lysimeter estimates, possibly deriving from poor r_c parameterization. Some of the potential reasons for this formed part of the Results chapter on *Error Analysis*. An error analysis suggested although there are statistically significant biases in canopy resistance related to the input variables, none are particularly large. Table 4 expresses these errors in proportional terms in a manner similar to the absolute values in Table 3.There remains the likely possibility that the experimental design which considered the entire lichen canopy to be uniformly moistened, contributed to most of the scatter.

5.4.2 Final conclusion

An inventory of lichen biomass has shown that biomass varies between habitats. Four chosen habitats showed a significant difference between all. The highest amount of biomass that was collected from was at the open-spruce lichen woodland habitat, and the lowest amount was collected at the beach ridge habitat. An inventory of lichen biomass has never been recorded near the Hudson Bay Lowlands. The differences in mean biomass ranged from 0.02 -1.78 kg m^{-2} in biomass ($p<0.001$) suggest rainfall interception will be habitat dependent.

For the historical period 1980-2016, estimates of potential interception ranged between 14-53% which is equivalent to 37-140 mm. Regional canopy storage therefore likely needs to take into consideration the regional distribution of lichen biomass, given the measured range in MSC.

Over the experimental field season there were a total of thirty-eight days with nineteen of them consisting of rainfall. The amount of rainfall intercepted ranged between 59% - 69%. Drainage was therefore less than interception which overall supports how strong a role lichen canopies play in the hydrological cycle the Hudson Bay Lowlands innorthern Manitoba. Notably, the measured interception from this field-season did not differ noticeably from an experiment from an earlier study and did not differ noticeably from the historical long-term modelled *potential* interception, which simply assumed that the canopies were completely dry when rain events occurred.

Lichen canopies are capable of intercepting large amounts of water and moisture that will have a large impact on the water budget and an even larger impact if they continue to grow thicker as the climate warms. With increasing small rainfall events this influence could get even stronger.

The Penman-Monteith model was used to compare with measured rates of evaporation. The results are encouraging though inconclusive as there were large resultant errors in the evaporation even though systematic errors have relatively small impacts on estimating canopy resistance. Despite these errors, all lichen canopies exponentially increase canopy resistance as moisture storage declines, which is distinctive and represents an important feature to consider in future water budget modelling.

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REFERENCES

Aalto, Juha, Peter C. le Roux and Miska Luoto “Vegetation Mediates Soil Temperature and Moisture in Arctic-Alpine Environments.” *Arctic, Antarctic, and Alpine Research*, vol. 45, no. 4, 2013, pp. 429–439., doi:10.1657/1938-4246-45.4.429. Aiken, S. G. *Flora of the Canadian Arctic Archipelago*. NRC Research Press, 2007.

Arama, Arlene, and Richard Bello. "Rainfall Interception by Lichen Canopies." (1989): 74-78. York University. Web. 5 Nov. 2015.

Arama, Arlene, and Rick Bello. Treeline Vegetation Interception, Soil Moisture and Thermal Regime. Ottawa: National Library of Canada = BibliothèqueNationale Du Canada, 1993. Print.

Arndal M. F., L. Illeris, A. Michelsen, K. Albert, M. Tamstorf and B. U. Hansen. “Seasonal Variation in Gross Ecosystem Production, Plant Biomass, and Carbon and Nitrogen Pools in Five High Arctic Vegetation Types.” *Arctic, Antarctic, and Alpine Research*, vol. 41, no. 2, 2009, pp. 164–173., doi:10.1657/1938-4246-41.2.164.

Anderson, Henry W.; Hoover, Marvin D.; Reinhart, Kenneth G. *Forests and Water: Effects of Forest Management on Floods, Sedimentation, and Water Supply*. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Dept. of Agriculture, 1976.

Antonopoulos, B ., Babajimopoulos,Ch, Grigoriadis, D.and LLIas, A., 1992. Sensitivity analysis of the Penman method, Proceeding of 5th conference of H.Y.U., P.132-140.

Asplund, Johan, and David A. Wardle. “How Lichens Impact on Terrestrial Community and Ecosystem Properties.” *Biological Reviews*, vol. 92, no. 3, Nov. 2016, pp. 1720–1738., doi:10.1111/brv.12305. 2

Barron, Eric J., Starley Thompson, and William W. Hay. “The Hydrologic Cycle: A Major Variable during Earth History.” *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 75, no. 3, 1989, pp. 157–174., doi:10.1016/0031-0182(89)90175-2.

Bello, R.L., and Smith, J.D. 1990. The effects of weather variability on the energy balance of the lake in the Hudson Bay Lowlands, Canada. Arctic and Alpine Research, 22, 1, 98-107.

Bello R.L. and Arama A. 1989. Rainfall Interception in Lichen Canopies. Climatological Bulletin 23(2), 74-78

Bengtsson, Lennart. “The Global Atmospheric Water Cycle.” *Environmental Research Letters*, vol. 5, no. 2, Sept. 2010, p. 025202., doi:10.1088/1748-9326/5/2/025002.

Beven, Keith. “A Sensitivity Analysis of the Penman-Monteith Actual Evapotranspiration Estimates.” *Journal of Hydrology*, vol. 44, no. 3-4, 1979, pp. 169–190., doi:10.1016/0022-1694(79)90130-6.

Bolton, William Robert. *Dynamic Modeling of the Hydrologic Processes in Areas of Discontinuous Permafrost*. 2006.

Boltman, Robert, Larry Hinzman, and Kenji Yoshikawa."Water Balance Dynamics of Three Small Catchments in a Sub-arctic Boreal Forest."*Northern Research Basins Water Balance* (2004): 213-240. Print.

Bonan, G. 2018. Ecological Climatology: Concepts and Applications 3rd ed. Cambridge University Press,New York, 692 pp.

Bonan, G. "Environmental Factors And Ecological Processes In Boreal Forests." *Annual Review of Ecology and Systematics* 20.1 (1989): 1-28. Web. 30th Nov. 2016.

Brown, S. M., R. M. Petrone, L. Chasmer, C. Mendoza, M. S. Lazerjan, S. M. Landhäusser, U. Silins, J. Leach, and K. J. Devito. "Atmospheric and Soil Moisture Controls on Evapotranspiration from above and within a Western Boreal Plain Aspen Forest." *Hydrol. Process. Hydrological Processes* 28.15 (2013): 4449-462.

Buck, A. L.,1981 New equations for computing vapor pressure and enhancement factor, *J. Appl. Meteorol.*, 20: 1527–1532.

Calder, I.r., J Harding, and P.T.W Rosier. “An Objective Assessment of Soil-Moisture Deficit Models.” *Journal of Hydrology*, vol. 60, no. 1-4, 1983, pp. 329–355., doi:10.1016/0022-1694(83)90030-6.

Carlyle-Moses., Darryl E., and John H. C. Gash. “Rainfall Interception Loss by Forest Canopies.” *Forest Hydrology and Biogeochemistry Ecological Studies*, 2011, pp. 407–423., doi:10.1007/978-94-007-1363-5_20.

Chahine, Moustafa T. “The Hydrological Cycle and Its Influence on Climate.” *Nature*, vol. 359, no. 6394, 1992, pp. 373–380., doi:10.1038/359373a0.

Chapin, Francis Stuart. *Arctic Ecosystems in a Changing Climate: an Ecophysiological Perspective*. Acad. Press, 1992.

Cowan, I. R. "The Interception and Absorption of Radiation in Plant Stands." *The Journal of Applied Ecology* 5.2 (1968): 367. Print.

Crockford, R. H., and D. P. Richardson. "Partitioning of Rainfall into Throughfall, Stemflow and Interception: Effect of Forest Type, Ground Cover and Climate." *Hydrol. Process. HydrologicalProcesses*(1999): 2903-920. Print.

Curry, Judith A., Elizabeth E. Ebert and Julie L. Schramm. “Sea Ice-Albedo Climate Feedback Mechanism.” *Journal of Climate*, vol. 8, no. 2, 1995, pp. 240–247., doi:10.1175/1520-0442(1995)0082.0.co;2.

Dickinson, Robert E., Ann Henderson-Sellers, Cynthia Rosenzweig and Piers J. Sellers. “Evapotranspiration Models with Canopy Resistance for Use in Climate Models, a Review.” *Agricultural and Forest Meteorology*, vol. 54, no. 2-4, 1991, pp. 373–388., doi:10.1016/0168-1923(91)90014-h.

Dodorico, Paolo., Francesco Laio, Amilcare Porporato, Luca Ridolfi, and Andrea Rinaldo, Ignacio Rodriguez-Iturbe,. “Ecohydrology of Terrestrial Ecosystems.” *BioScience*, vol. 60, no. 11, 2010, pp. 898–907., doi:10.1525/bio.2010.60.11.6.

Domingo, F., G. Sanchez, M.J Moro, A.J Brennerc and J. Puigdefa. “Measurement and Modelling of Rainfall Interception by Three Semi-Arid Canopies.” *Agricultural and Forest Meteorology*, vol. 91, no. 3-4, 1998, pp. 275–292., doi:10.1016/s0168-1923(98)00068-9.

Estévez, Javier., Joaquín Berengena and Pedro Gavilán. “Sensitivity Analysis of a Penman-Monteith Type Equation to Estimate Reference Evapotranspiration in Southern Spain.” *Hydrological Processes*, vol. 23, no. 23, 2009, pp. 3342–3353., doi:10.1002/hyp.7439.

Gaio-Oliveira, Gisela., Lena Dahlman, Cristina Maguas, and Kristin Palmqvist. “Responses of the Lichen XanthoriaParietina (L.) Th. Fr. to Varying Thallus Nitrogen Concentrations.” *The Lichenologist*, vol. 37, no. 2, 2005, pp. 171–179., doi:10.1017/s0024282904014598.

Gash, Jhc. “An Analytical Model of Rainfall Interception by Forests.” *Quarterly Journal of the Royal Meteorological Society*, vol. 105, no. 443, Jan. 1979, pp. 43–55., doi:10.1256/smsqj.44303.

Gavazzi, M J., Ge Sun, Steve McNulty, E.A Treasure and M.G Wightman. “Canopy Rainfall Interception Measured over Ten Years in a Coastal Plain Loblolly Pine (Pinus Taeda L.) Plantation.” *Transactions of the ASABE*, vol. 59, no. 2, 2016, pp. 601–610., doi:10.13031/trans.59.11101

Germer, Sonja., Helmut Elsenbeer and Lisa Werther. “Have We Underestimated Stemflow? Lessons from an Open Tropical Rainforest.” *Journal of Hydrology*, vol. 395, no. 3-4, 2010, pp. 169–179., doi:10.1016/j.jhydrol.2010.10.022.

IH (1998) *Broadleaf Woodlands: the Implications for Water Quantity and Quality*. Report to the Environment Agency. Environment Agency Research and Development Publication No.5, Stationary Office, London.

Irmak, Suat, and Denis Mutiibwa. “On the Dynamics of Canopy Resistance: Generalized Linear Estimation and Relationships with Primary Micrometeorological Variables.” *Water Resources Research*, vol. 46, no. 8, 2010, doi:10.1029/2009wr008484.

Irmak, Suat, and Denis Mutiibwa. “On the Dynamics of Canopy Resistance: Generalized Linear Estimation and Relationships with Primary Micrometeorological Variables.” *Water Resources Research*, vol. 46, no. 8, 2010, doi:10.1029/2009wr008484.

Jackson, Michael B. *Interacting Stresses on Plants in a Changing Climate*. Berlin: Springer- Verlag, 1993. Print

Kershaw, Kenneth A. *Physiological Ecology of Lichens*. Cambridge: Cambridge UP, 1985. Print.

Klaassen, Wim., Harry J.M. Lankreijer, and Arthur W.L. Veen. “Rainfall Interception near a Forest Edge.” *Journal of Hydrology*, vol. 185, no. 1-4, 1996, pp. 349–361., doi:10.1016/0022-1694(95)03011-5.

Kline, Meghan, "Peatland-Stream Hydrological and Biogeochemical Connectivity in the James Bay Lowland, Ontario" (2014). Electronic Thesis and Dissertation Repository. Paper 2467.

Kuzmina, Maria L., Paul DN Hebert, Karen L Johnson, and Hannah R. Barron. “Identification of the Vascular Plants of Churchill, Manitoba, Using a DNA Barcode Library.” *BMC Ecology*, vol. 12, no. 1, 2012, p. 25., doi:10.1186/1472-6785-12-25.

Lambert, Steve. “Northern Manitoba Rail Line Cut off after 'Catastrophic' Flood Damage.” *The Globe and Mail*, 10 June 2017, https://www.theglobeandmail.com/news/national/northern-manitoba-rail-line-cut-off-after-catastrophic-flood-damage/article35279392/.

Lange, Otto L. “Ecophysiology of Photosynthesis: Performance of Poikilohydric Lichens and Homoiohydric Mediterranean Sclerophylls: The Seventh Tansley Lecture.” *The Journal of Ecology*, vol. 76, no. 4, Dec. 1988, p. 915, 10.2307/2260624.

Levia, D.F., Frost, E.E., 2003. A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. Journal of Hydrology 274, 1–29.

Levia, D.F., Herwitz, S.R., 2005. Interspecific variation of bark water storage capacity of three deciduous tree species in relation to stemflow yield and solute flux to forest soils. Catena 64, 117–137.

Liang Shunlin., Xiaowen Li and Jindi Wang. "Vegetation Production in Terrestrial Ecosystems." *Advanced Remote Sensing*, 2012, pp. 501–531., doi:10.1016/b978-0-12-385954-9.00016-2.

L Levia, D.F., Van Stan II, J.T., Mage, S.M., Kelley-Hauske, P.W., 2010. Temporal variability of stemflow volume in a beech-yellow poplar forest in relation to tree species and size. Journal of Hydrology 380, 112–120.Meltofte, H. *Arctic Biodiversity Assessment: Status and Trends in Arctic Biodiversity*. CAFF International Secretariat, 2013.

Mcmillan, W. D., and R. H. Burgy. "Interception Loss from Grass." *Journal of Geophysical Research*, vol. 65, no. 8, 1960, pp. 2389–2394., doi:10.1029/jz065i008p02389.

Monteith J.L. and Unsworth M., 1990 Principles of Environmental Physics 2nd ed. Butterworth-Heinemann, Oxford, 291 pp.

Morison, Matthew Q., LeeAnn Fishback, Merrin L. Macrae, and Richard M. Petrone . "Capturing Temporal and Spatial Variability in the Chemistry of Shallow Permafrost Ponds." *Biogeosciences*, vol. 14, no. 23, Apr. 2017, pp. 5471–5485., doi:10.5194/bg-14-5471-2017.

Murphy, Charles E., and Kenneth R. Knoerr. “The Evaporation of Intercepted Rainfall from a Forest Stand: An Analysis by Simulation.” *Water Resources Research*, vol. 11, no. 2, 1975, pp. 273–280., doi:10.1029/wr011i002p00273.

Muzylo, A., P. Llorens, F. Valente, J.j. Keizer, F. Domingo, and J.h.c. Gash."A Review of Rainfall Interception Modelling."*Journal of Hydrology* 370.1-4 (2009): 191-206. Print.

Nascimbene, Juri, Lorenzo Marini, Renzo Motta and Pier Nimis. “Influence of Tree Age, Tree Size and Crown Structure on Lichen Communities in Mature Alpine Spruce Forests.” *Biodiversity and Conservation*, vol. 18, no. 6, May 2008, pp. 1509–1522., doi:10.1007/s10531-008-9537-7.

Nash, Thomas H. *Lichen Biology*. Cambridge: Cambridge UP, 2008. Print.

Nash, T.H, and T.J Moser. “Vegetational and Physiological Patterns of Lichens in North American Deserts.” *The Journal of the Hattori Botanical Laboratory*, 30 June 1982, pp. 331–336.

Nimis, Pier, and Wolesely Patricia. *Monitoring with Lichens: Monitoring Lichens*. Dordrecht Kluwer Academic Published in Association with the NATO Scientific Affairs Division, 2002. Print.

Pearce, A. J., and Rowe, L.K.. “Nighttime, Wet Canopy Evaporation Rates and the Water Balance of an Evergreen Mixed Forest.” *Water Resources Research*, vol. 16, no. 5, 1980, pp. 955–959., doi:10.1029/wr016i005p00955.

Porada, Philipp., Christian Beer, and Altug Ekici. “Effects of Bryophyte and Lichen Cover on Permafrost Soil Temperature at Large Scale.” *The Cryosphere*, vol. 10, no. 5, 2016, pp. 2291–2315., doi:10.5194/tc-10-2291-2016.

Ritchie, J. C. *The Vegetation of Northern Manitoba III: Studies in the Subarctic*. Johnson, 1972.

Rohina, Ayat., Ayob Bahranifard, Mohsen Dehghan and Mohammad Karami. “Comparison of Various Sensitivity Approaches to Estimate Evapotranspiration, to Climatic Variables in Fasa-Synoptic station_Iran.” *Advanced Biological and Biomedical Research*, vol. 1, no. 4, 2013, pp. 459–466.

Sales, Kris., Jessie Gardner and Laurie Kerr. “Factors Influencing Epiphytic Moss and Lichen Distribution within Killarney National Park.” *Bioscience Horizons*, vol. 9, 2016, doi:10.1093/biohorizons/hzw008.

Shuttleworth, W. J. “Evaporation Models in the Global Water Budget.” *Variations in the Global Water Budget*, 1983, pp. 147–171., doi:10.1007/978-94-009-6954-4_11.

Shuttleworth, W. J. “Putting the ‘Vap’ into Evaporation.” *Hydrology and Earth System Sciences*, vol. 11, no. 1, 2007, pp. 210–244., doi:10.5194/hess-11-210-2007.

Shuttleworth, W. James, and Robert J. Gurney. “The Theoretical Relationship between Foliage Temperature and Canopy Resistance in Sparse Crops.” *Quarterly Journal of the Royal Meteorological Society*, vol. 116, no. 492, 1990, pp. 497–519., doi:10.1002/qj.49711649213.

Tan, C. S., and T. A. Black. “Factors Affecting the Canopy Resistance of a Douglas-Fir Forest.” *Boundary-Layer Meteorology*, vol. 10, no. 4, 1976, pp. 475–488., doi:10.1007/bf00225866.

Thomas, David S. G. *The Dictionary of Physical Geography*. John Wiley & Sons, 2016.

Thornthwaite, C.W, and H.G Wilm. “Report of Committee on Evaporation and Transpiration, 1944–1945.” *Transactions, American Geophysical Union*, vol. 26, no. 3, 1945, p. 451., doi:10.1029/tr026i003p00451.

Trenberth KE (1998) Atmospheric moisture residence times and cycling: implications for rainfall rates and climate change. Clim Change 39:667–694.

Trenberth, Kevin E. “Conceptual Framework for Changes of Extremes of the Hydrological Cycle With Climate Change.” *Weather and Climate Extremes*, 1999, pp. 327–339., doi:10.1007/978-94-015-9265-9_18.

Trenberth, Kevin E. “The Impact of Climate Change and Variability on Heavy Precipitation, Floods, and Droughts.” *Encyclopedia of Hydrological Sciences*, 2008, doi:10.1002/0470848944.hsa211.

Turetsky, M. R., McGuire AD, Tuittila ES, Bond-Lamberty B, Euskirchen E, Talbot J, and Frolking S. “The Resilience and Functional Role of Moss in Boreal and Arctic Ecosystems.” *New Phytologist*, vol. 196, no. 1, 2012, pp. 49–67., doi:10.1111/j.1469-8137.2012.04254.x.

Verratti M. 2003. Parameterization of evaporative and meteorological variables from a lichen dominated system at Churchill Manitoba. Unpublished BSc Thesis Department of Geography, York University, 69pp.

Walsh, John E. “A Comparison of Arctic and Antarctic Climate Change, Present and Future.” *Antarctic Science*, vol. 21, no. 3, 2009, pp. 179–188., doi:10.1017/s0954102009001874.

Ward, R. C., and M. Robinson. *Principles of Hydrology*. McGraw-Hill, 2011.

Wessel, David A., and Wayne R. Rouse. “Modelling Evaporation from Wetland Tundra.” *Boundary-Layer Meteorology*, vol. 68, no. 1-2, 1994, pp. 109–130., doi:10.1007/bf00712666.

White, J., Hall, R., Wolfe, B., Light, E., Macrae, M. and Fishback, L. (2014). Hydrological Connectivity and Basin Morphometry Influence Seasonal Water-Chemistry Variations in Tundra

Ponds of the Northwestern Hudson Bay Lowlands. *Arctic, Antarctic, and Alpine Research*, 46(1), pp.218-235.

Wielgolaski, F. E., and Thomas Rosswall. *Tundra Biome: Proceedings International Meeting on the Biological Productivity of Tundra, Leningrad USSR, October 1971*. IBP, 1972.

Wolseley, Pat., Daniel Carpenter, Paul Eggleton, Holger Thüs, and Neil Sanderson. "Patterns and Drivers of Lichen Species Composition in a NW-European Lowland Deciduous Woodland Complex." *Biodiversity and Conservation*, vol. 26, no. 2, 2016, pp. 401–419., doi:10.1007/s10531-016-1250-3.

Zimmermann A, Wilcke W, Elsenbeer H. "Spatial and Temporal Patterns of Throughfall Quantity and Quality in a Tropical Montane Forest in Ecuador." *Journal of Hydrology*, vol. 343, no. 1-2, 2007, pp. 80–96., doi:10.1016/j.jhydrol.2007.06.012.

Zimmermann B, Zimmermann A, Lark MR, Elsenbeer H. "Sampling Procedures for Throughfall Monitoring: A Simulation Study." *Water Resources Research*, vol. 46, no. 1, 2010, doi:10.1029/2009wr007776.