Assessing the role of tree growth patterns on the spatial variability of evapotranspiration on a subalpine transition zone in Kananaskis, Alberta

by

Jessica Williamson

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Geography (Water)

Waterloo, Ontario, Canada, 2020

Author’s Declaration

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

I understand that my thesis may be made electronically available to the public.

Abstract

Canada's Rocky Mountains provide a large and essential supply of freshwater to downstream ecosystems and communities. Previous research has demonstrated that warmer temperatures, associated with climate change, are expected to increase the recruitment of trees towards alpine zones, by way of tree islands and krummholz. Tree islands and krummholz are coniferous trees that grow in isolated patches. Tree islands are stunted and deformed, yet their stems grow above the shrub layer, leaving them exposed to winter snowdrifts, unlike krummholz, which grow stunted or in matts, below the snowpack. These trees are unique, relative to conifers below the treeline limit, as they have growth mechanisms which allow them to persist in areas that are otherwise too harsh for full treeline expansion.

This thesis addresses the complex relationships between the spatial variability of evapotranspiration (ET) in tree islands and krummholz on a subalpine ridge slope in Kananaskis, Alberta. As well, relationships between these canopies and controls on ET, such as snowcover, meteorological fluxes and vegetation characteristics are assessed. By addressing these objectives, this study will reduce existing knowledge gaps on how forest transition zones in mountain ecosystems may contribute to ecosystem water loss, should these tree patches continue to prosper at higher elevations.

Atmometers, which measure the rate of ET from heterogenous landcover to the atmosphere, were used at FRS to determine the rate of potential crop evapotranspiration (ET_C) from krummholz and tree islands. ET_C was then converted to actual evapotranspiration (ET_A) using patch-specific correction coefficients (K_C) in order to address the influence of canopy dynamics and water availability on ET.

ET_A during the growing season was greater in the krummholz (190 mm) than the tree islands (131 mm). Krummholz were observed to be moisture rich tree patches that were shorter in height and more exposed than tree islands. Because of this, krummholz ET was controlled by the advection of sensible heat transported from drier areas downward over the krummholz resulting in oasis-effect ET ($Q_E > Q^*$). Horizontal advection of sensible heat from the taller tree islands to the shorter krummholz increases clothesline-effect ET at FRS. In addition, the exposure of the krummholz to the effects of solar radiation to the their subsurface increases the rate of early growing season ET_A by increasing soil water evaporation.

Tree islands, which extend above the annual snowpack were capable of sheltering windblown snow, increasing the amount of water available to the tree islands and krummholz for the growing season. Water balances for the tree islands and krummholz indicated that SWE was the primary source of water to the patches and did not suggest water deficits during the observed growing season. Tree island ET rates were controlled by the evaporation of intercepted precipitation (2 - 58%), and growth characteristic such as increased canopy density, which increased subsurface sheltering, reducing soil water evaporation, while maintaining inner-canopy VPD (increases transpiration).

The results of this study improve our knowledge of how tree islands and krummholz will influence ecosystem water storage, especially in terms of ET, and determined what dominant controls exist on ET in subalpine systems. As climate change is expected to decrease annual snowpack levels and increase seasonal air temperatures, ET from tree island and krummholz may contribute to water deficits in subalpine ecosystems.

Acknowledgements

I would like to acknowledge that this thesis was conducted on Treaty 7 territory, the traditional territories of the Blackfoot Nations, including Siksika, Piikani, and Kainai, the Tsuut'ina Nation and Stoney Nakoda First Nations. I acknowledge all of the many First Nations, Métis, and Inuit, whose footsteps have marked these lands for centuries (ASCA, 2020).

There have been many people who have contributed their time, work and support to this project over the last two years. I would like to start by thanking my supervisor, Dr. Richard Petrone for your assistance and commitment to the making of this thesis. Since starting as an undergrad co-op under your leadership in 2015, I have learned valuable skills, tackled challenging problems and pushed myself further than I thought possible. I can't thank you enough for granting me the opportunity to work my dream job in the Rockies, as well as the countless opportunities you gave me to share my research across the country.

I would like to thank Dylan Hrach, Sheryl Chau and Lindsey Langs for their help during field work. Field days were long, challenging and sometimes dangerous (special shout out to Bear 80 and her cub), and you all helped to keep things organized, light-hearted and got the work done. Thank you to the many people from the Hydrometeorology Research Group and the University of Saskatchewan's Centre for Hydrology for your assistance. I'd like to thank Dr. Myroslava Khomik, Brandon Van Huizen, Karisa Tyler, Eric Kessel and Adam Green, for your help and advice in the lab, answering my endless questions and assisting with quality data processing. Thank you to Jennifer Williamson, for assisting in the creation of tree island and krummholz graphics, you made scraggly trees look beautiful. As well, thank you to Tyler Prentice and Dylan Hrach for your patience and time in helping me to understand R, and the optimism that was greatly needed before big presentations and in the final months on this thesis.

“Mountain Mel”, Mel Folden, thank you for your enthusiasm every time we arrived on site, for keeping us informed on different risks, and for the many stories shared at the KPOW Lounge after a long day’s work. I would also like to thank the shareholders and managers of Fortress Mountain Ski Resort, for granting our team site access and helping with safety plans and logistics.

Lastly, thank you to my family for your love and care over the last two years. Mom, Dad, Jen and Mike, thank you for constantly supporting my passions, and being there to talk, even when I’m on the other side of the country, you all contributed to this thesis more than you may ever know.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction and review of literature

1.1 Introduction

Canada's Rocky Mountains are the headwaters to many reliant downstream communities and ecosystems (Hauer et al., 1997). Runoff from snow and glacial reserves feed into the Saskatchewan River Basin (SRB) and supplies water to the three Prairie Provinces of Canada; Alberta, Saskatchewan and Manitoba (Fang & Pomeroy, 2020). In total, Rocky Mountain headwaters contribute to approximately 87% of the SRB's water supply for domestic, industrial and agricultural usage (Fang & Pomeroy, 2020; Redmond, 1964). In Canada, these diverse environments are expected to be highly susceptible to impacts due to climate change, such as droughts, wildfires and flooding events (Jackson et al., 2016; Lenoir et al., 2008; Dirnböck et al., 2011). As well, climate change projections anticipate that water supply may become diminished in these areas as air temperatures are expected to rise, increasing early season snow and ice runoff (Stewart et al., 2004). In turn, this poses a threat to ecosystem functionality, both locally and downstream.

Temperature increases due to climate change may have adverse effects on natural ecosystem functions. One example is treeline migration to areas that were previously inhospitable to species establishment and growth. Treeline is the elevational boundary for forest growth in montane ecosystems (Schwörer et al., 2017). Warmer temperatures in response to climate change are projected to increase the reproduction and recruitment of trees, expanding the treeline to higher elevations that were previously considered too harsh for tree growth due to their cooler temperatures and higher wind speeds (Bertin, 2008). Growth for coniferous trees typically occurs below their temperature optimum, meaning that when air temperatures increase, so does the trees ability to function (Way & Oren, 2010; Ryan, 2010). When temperatures rise, plant respiration and photosynthesis occur, leading to a growth response (Ryan, 1991; Ryan, 2010). As well, increased temperatures can delay autumn senescence, prolonging the growing season length (Way, 2011). Ultimately, climate change is leading to higher air temperatures, increased precipitation rates and an extended growing season, due to earlier snowmelt (Fang & Pomeroy, 2020). These meteorological controls are the primary drivers to changes in evapotranspiration rates in alpine and subalpine ecosystems. Furthermore, climate change may lead to ecohydrological shifts in montane environments, which could lead to an imbalance in local hydrology, ultimately effecting downstream water users.

Due to differences in climatic (i.e. high winds, low temperatures) and topographical gradients (such as cliffs), treeline expansion is not possible on all mountain ridges (Malanson et al., 2007). Instead, new zones of krummholz trees, which are patches of trees that are deformed or stunted in growth and persist along horizontal stems, can take form above the forest treeline (Shiels & Sanford, 2001). There are two forms of krummholz patches: krummholz and tree islands. Krummholz are short, stunted trees that are typically no greater that 1 m, whereas tree islands are stunted and deformed trees that are able to grow greater than 1 m in height (Albertsen et al., 2014; Wardle, 1968; Marr, 1977; Hadley and Smith, 1986). Krummholz and tree islands occur when seedlings survive (<10% survive in first year of dispersal, Smith et al., 2003) damage from extreme growing conditions above the treeline. Snow burial, reduced sunlight exposure and low temperatures in the winter causes plant stress that impacts seedling survival into the summer (Malanson et al., 2007). Therefore, mountain ecosystems that were previously incapable of treeline expansion are likely to receive tree patch development due to the ability of krummholz to adapt to harsh conditions. Ultimately, new tree development at higher elevations will increase the uncertainty regarding the water balance of these areas, and the proportion of runoff partitioned to downstream ecosystems, resulting in the need for increased research on impacts to hydrological conditions affecting water supply.

1.2 Literature Review

1.2.1 Hydroclimatology of the Canadian Rocky Mountains and Climate Change

Canada's Rocky Mountains region is made up of an array of unique microclimates, which lead to distinct hydroclimatological characteristics in this area. The regional climate is defined by cold long winters, and short mild summers (Hauer et al., 1997). Precipitation rates can vary with elevation, slope, aspect or under different orographic conditions (Hauer et al., 1997). The Rocky Mountains receive most of their annual precipitation as snow in the winter (Hauer et al., 1997). Snow accumulated during the winter season later becomes the largest source of streamflow runoff during the snowmelt period (Fang & Pomeroy, 2020).

Snow characteristics, such as the depth and density of snow, are controlled by both ecological (i.e. tree density, forest fragmentation, canopy size) and atmospheric (i.e. air temperature and wind speed) properties. Blowing snow transport by wind in montane ecosystems in an important control on microscale water supply and climate (Pomeroy, 1991). Snow redistribution occurs by horizontal transport, where snow on the surface becomes eroded and moves from more exposed areas with low aerodynamic resistance, through the process of saltation (i.e. skipping) and suspension, to sheltered areas of higher aerodynamic roughness (Pomeroy & Brun, 2001; Pomeroy and Gray, 1990; Budd et al., 1966; Pomeroy and Male, 1992; MacDonald et al., 2010). Blowing snow is also subject to sublimation in unsaturated air conditions, controlled by wind turbulence, temperature, humidity, incoming radiation and particle size (Dyunin, 1959;

Schmidt, 1984, 1986; MacDonald et al., 2010). The transport of wind-blown snow downslope leads to the accumulation of snow within forested areas and surface depressions, leading to increased spatial variability of snow accumulation (Pomeroy, 1991; Pomeroy et al., 1991).

Snowmelt takes place between the months of April and June in the Rocky Mountains (Pederson et al., 2011). Snowmelt on the eastern slopes form the headwaters to the Athabasca and Saskatchewan Rivers, which flow towards the Prairie Provinces, supplying water for agricultural and oil sands production (Fang et al., 2013). Additionally, meltwater on the western slopes supplies water for processes such as hydroelectricity generation in British Columbia, by the Columbia and Fraser Rivers (Fang et al., 2013). Streamflow runoff from meltwater in this region is estimated to supply up to 87% of the total water supply to the SRB (Fang & Pomeroy, 2020; Redmond, 1964). The timing or duration of snowmelt and the quantity of snow is of critical importance to water users and ecosystems, in terms of available water supply, especially as populations steadily rise in these provinces (Pederson et al., 2011). Snowmelt runoff in mountain ecosystems is sensitive to rising air temperatures, which makes them highly vulnerable to climate change (Fang et al., 2013). Snow sublimation via canopy interception, which is estimated to control 10-45% of the winter water balance in this region, is also anticipated to greatly influence snowpack and melt processes (Pomeroy et al., 2012; Pomeroy and Gray, 1995). The average increase in air temperature in western Canada has been 0.5 to 1.5°C from 1900 to 1998 (Pomeroy et al., 2015). Winter mean temperatures at mid-elevations have increased by 2.6°C since the 1960's in Canada's Rocky Mountains (Pomeroy et al., 2015). Studies suggest that an increase in winter days with air temperatures exceeding 0°C (Lapp et al., 2005), combined with a reduced spring snowpack (more precipitation falling as rain than snow) (Brown & Robinson, 2011; Pederson et al., 2011; Knowles et al., 2006) will result in an earlier start to the snowmelt period and lower annual streamflows

(Stewart et al., 2004; St. Jacques et al. 2010, Fang et al., 2013). Understanding how water supply may change in Canada's Rocky Mountains is of critical importance to ensure water security downstream. However, most studies on water supply in this region focus on the impact of climate change on snowpack and glacial reserves in the winter and spring. Limited studies have addressed how changing vegetation, in response to climate change, may impact growing season water loss, especially by evapotranspiration (ET), and if this change will impact water security downstream.

1.2.2 Subalpine Forest Hydrology

Subalpine zones (1300 – 2300m in elevation, Alberta Parks, 2015) in Canada's Rock Mountains can vary in vegetation characteristics. Some ridges within this elevational boundary may be fully covered by forest growth, others may exhibit more fragmented, or sparse, tree and shrub vegetation that grow low to the ground in the form of mats or cushions in order to withstand high windspeeds. Subalpine zones are a major influence on water availability in montane ecosystems. Hydrological processes include inputs into to these areas such as precipitation, blowing snow transport, snowmelt, canopy interception and upslope runoff, and outputs by way of evapotranspiration (ET), sublimation, snow redistribution and downslope runoff (Winkler et al., 2010).

Differences in vegetation type, density and canopy size can determine hydrological patterns within subalpine zones. Canopy interception is the fraction of precipitation that is captured by the forest or tree canopy before it reaches the ground (Winkler et al., 2010). Rainfall interception rate during the non-snow-covered period is dependent on rainfall intensity, duration, weather characteristics (wind speed, direction, humidity) and the type of vegetation present (Winkler et al., 2010). Interception loss is the proportion of incident precipitation that is captured by the forest canopy and subsequently lost due to evaporation or sublimation during or after precipitation events (Price & Carlyle-Moses, 2003). Studies by Zinke (1967), Ford and Deans

(1978) and Calder (1990) have found that up to 25% of annual rainfall in coniferous forests may be intercepted and therefore never reach the forest floor (Spittlehouse, 1998). In the winter, coniferous foliage can intercept snowfall and reduce snow accumulation rates at the ground surface. In western Canada, studies have shown that 30 to 45% of annual snowfall may be lost to the atmosphere by sublimation from intercepted snow (Pomeroy & Gray, 1995; Pomeroy et al., 1998; Ellis et al., 2010).

Due to the harsh nature of montane ecosystems, vegetation adaptions are necessary to withstand low temperatures and high wind speeds. For this reason, shrub-like, matted vegetation structures are common and grow below the depth of the snowpack in order to be protected and insulated during the snow cover period (Daly, 1984). Snow accumulation and ablation are highly sensitive to vegetation structure (Musselman, 2008, Budd et al., 1965). Coniferous vegetation in alpine forests influence snow accumulation and melt by way of tree wells, microscale features with low accumulation rates underneath the canopy (Musselman, 2008). The increased spatial variability of snow depth promoted by small tree patches and scattered open canopy areas in alpine zones influences variability in snow accumulation and melt (Varhola et al., 2010). Additionally, an increase in exposure on mountain ridges has shown to lead to the formation and persistence of snow drifts (Musselman et al., 2015). In this region, snow drifts have been shown to accumulate on leeward slopes by snow transported from barren ridges at higher elevations (Musselman et al., 2015).

Low tree density patches, or small tree patches may lead to accelerated melting rates due to a lack of shading to the ground surface (Varhola et al., 2010). A study modelling snowmelt and turbulent heat fluxes over mountainous shrub tundra in the Yukon found that shrubs are warmed by the absorption of solar radiation, due to their low albedo, and warm to temperatures higher than the air or snow surrounding them. In turn, this increases sensible heat fluxing to the canopy, even at a time when the ground is snow covered (Bewley et al., 2010). Additionally, this study also found that shrubs that are more exposed can increase an areas surface roughness, leading to increased turbulent fluxing (Bewley et al., 2010). Increased shrub exposure has been shown to lead to lower albedo, less transmittance of shortwave radiation to the snowpack, increased positive net longwave radiation at and above the snow surface, lower net radiation below the shrub canopy, reduced snowpack sublimation, increased sensible heat loss, positive sensible heat fluxing from the shrubs to the snowpack and increased snowmelt rates (Pomeroy et al., 2006).

ET rates are largely controlled by water supply, vegetation, vapour pressure gradients and energy supply, as well as spatial differences such as aspect and elevation. South-facing aspects for example are defined by having higher temperatures, lower relative humidity levels and a greater vapour pressure deficit, which leads to increased ET rates (Kelsey et al., 2018). Different tree stands show variability in tree density, fragmentation, species composition and size, which all can control the rate of radiation transfer through the canopy to the forest floor. When more energy is available to a tree canopy, tree growth, stomatal conductance levels and ET will increase (Black & Kelliher, 1989).

More research must be conducted on how changes in vegetation in subalpine systems may impact the local hydrological cycle. Additionally, research is needed to address microscale differences in vegetation cover in alpine and subalpine ecozones, especially as it pertains to the interactions between treeline progressions in the wake of climate change projections. Therefore, this study will address a specific type of tree development in this ecozone, namely krummholz tree patches.

1.2.3 The Krummholz Zone

Krummholz are clusters or patches of trees that are stunted or deformed in response to wind abrasion and tend to grow between 0.5 to 3 m in height (Shiels & Sanford, 2001). Common coniferous tree species that become krummholz through impacts of wind abrasion in Canada's Rocky Mountains include *Picea engelmannii* (Engelmann spruce), *Abies lasiocarpa* (subalpine fir) and *Pinus flexilis* (limber pine) (Holtmeier, 1981). The krummholz zone is the term given to the transitional area between the subalpine treeline and alpine tundra zone (Figure 1-1), where the establishment of small, dwarfed trees is possible (Grace et al., 2002). Krummholz exist in two main forms: tree islands and krummholz patches (Figure 1-2). Tree islands consist of clusters of trees that are isolated above the treeline, while being stunted and deformed in growth, however, grow considerably tall, reaching above the shrub layer (Albertsen et al., 2014). Krummholz patches are shorter compared to tree islands, usually only growing to a maximum of 1 m in height, while also possessing traits of stunted and deformed growth (Albertsen et al., 2014; Wardle, 1968; Marr, 1977; Hadley and Smith, 1986). Krummholz and tree islands are predominately influenced by wind exposure while also being controlled by variables such as moisture, soil depth and nutrient compositions, snow drift and melt processes (Peet, 1981). Krummholz and tree islands form in shallow depressions on windswept ridges, as they develop, they form snowdrifts downwind during the winter, which alters the microclimate on the leeward side of the patch (Walker et al., 2001). The windward side undergoes greater physiological stresses, such as drought and frost damage (Walker et al., 2001). On the leeward side, the trees are capable of advancing, through the process of layering, as they are sheltered by the snowdrift, other vegetation, and microtopographical depressions (Marr, 1977; Walker et al., 2001). On steep slopes or within avalanche tracks, krummholz tend to grow with stems and branches pressed down to the soil due to pressure from snowpack accumulation in the winter season (Holtmeier, 1981).

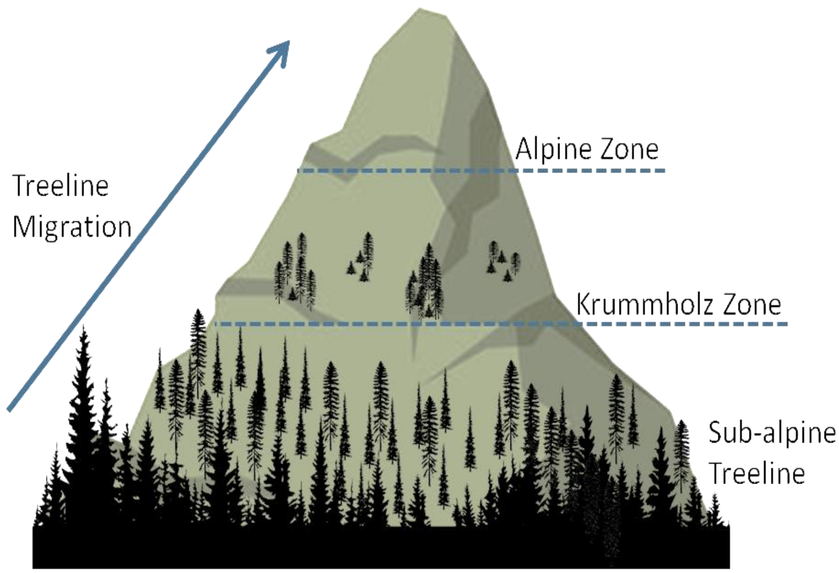

Figure 1-1. The upper elevational boundaries of mountains, including: the lower subalpine treeline, the krummholz zone and the barren alpine zone which are subject to treeline migration from climate change.

Atmospheric influences, by way of wind speed or force heavily impact the way krummholz can take form (Peet, 1981). In the Rocky Mountains, high winds prevail from the west and in turn, tree branches within the krummholz zone have been shown to bend or "flag" in the opposite, east, direction (Wardle, 1968). Temperature also has a substantial control on krummholz development. In mountain ecosystems, elevation is negatively correlated with air temperature and positively correlated with wind velocity, which becomes even more prominent in the winter season, when temperatures are cooler (Wardle, 1968). Early studies suggest that cooler temperatures reduce the formation of the leaf cuticle and therefore lead to disturbances to plant growth (i.e. deformed branches, dead or no new needles) in the spring and winter months (Grace et al., 2002). This could cause needles on the coniferous krummholz trees to die, presenting their unique, deformed stature (Wardle, 1968). However, other studies suggest that wind-blown snow, rather than low air temperatures, is the main factor influencing needle and branch desiccation to these trees. Windblown particles may take the form of ice crystals in the winter season, resulting in a further developmental threat in cooler conditions (Trant et al., 2011).

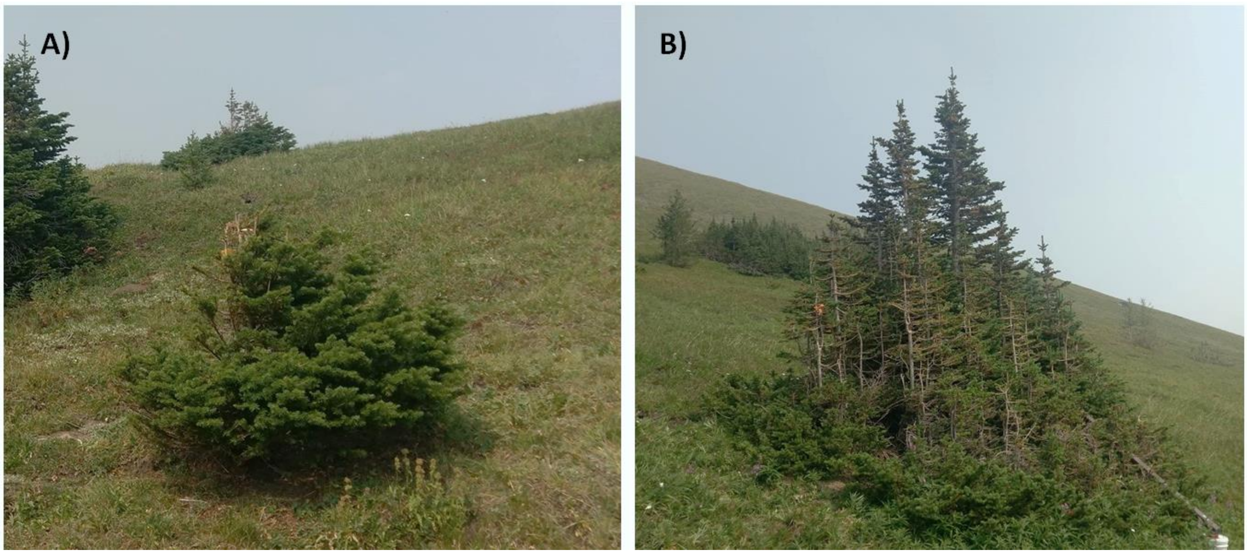

Figure 1-2. Krummholz zone tree patches, including: A) Krummholz and B) Tree Islands

Annual temperature increases for Canada's Rocky Mountains are anticipated to surpass global mean projections, making them especially vulnerable to climate change (Bentz et al., 2010). Plant phenology is expected to be impacted by climate warming by earlier species flowering or budding and increased annual growth due to an extended growing season (earlier spring snowmelt, warmer seasonal temperatures into the fall) (Dunne et al., 2003). In subalpine systems, this could reduce the control temperature has on limiting species development. In response, krummholz establishment could become more frequent, depending on environmental controls such as water availability and wind. Krummholz trees have abnormal growth patterns, which suggest that warming in any season would lead to tree growth (Kullman, 2007; Rickebusch et al., 2007; Harsch et al., 2009). Warmer temperatures could also lead to less damage by snow and ice (Harsch et al., 2009). As temperatures rise, there is uncertainty as to how this will impact krummholz and tree island development. For example, increasing temperatures during the summer months may not lead to krummholz expansion due to their self-shading nature. It is perceived that krummholz control their own root temperatures due to their dense canopy structure, which results in less solar radiation being able to penetrate the soil beneath them (LaMarche & Mooney, 1972). Increased shading over the root zone has thus been attributed to reduce growth potential for krummholz. In such case, as the climate warms, trees may find increased temperatures allow them to advance beyond their standard elevational boundary. However, once krummholz begin to take form, further advancement or growth could be limited by a reduction in solar radiation reaching the soils.

1.2.4 Hydrological Processes in the Krummholz Zone

Krummholz and their development can be controlled by several hydrological functions within subalpine ecosystems. First, krummholz often grow beneath the snowpack where they can be protected from harsh winds and receive insulation from winter temperatures (Trant et al., 2007). Tree island stems can extend above the annual snowpack. In winter months, most severe desiccation occurs on shoots or branches that protrude above the snow snowpack, in the saltation zone (near snow surface layer where snow redistribution by saltation occurs) (LaMarche & Mooney, 1972). Exposed needles above the snow are more at risk of damage due to enhanced exposure to the cool air and wind (LaMarche & Mooney, 1972). For exposed branches, snow drifts can act as a wind block that reduces abrasion (Malanson et al., 2007). Therefore, as cool temperatures may limit growth, the winter snowpack can in turn protect krummholz and tree islands that have already been established (Malanson et al., 2007).

Snow hydrology influences krummholz in several ways, both restricting and enhancing the development or persistence of patches. For example, on the windward side of these tree patches, the trees receive more physiological stresses, such as drought and wind-blown particle damage, whereas on the leeward side, which is better protected by snow drifts, patches are able to advance (Marr, 1977; Walker et al., 2001)

Some studies have shown that in subalpine environments, the main components of the hydrological cycle that krummholz directly influence are snowpack preservation and accumulation (Malanson et el., 2007; Walsh et al., 1994; Hiemstra et al., 2006; Seastedt & Adams, 2001; Holler et al., 2001). In such cases, strong relationships between snow accumulation and vegetation presence takes place, allowing for insulation processes, which contributes to further snow accumulation. In krummholz patches, unique moisture and temperature gradients within the canopy lead to deeper snow cover and longer duration of cover (Holler et al., 2001), which allow for higher moisture availability to krummholz over a longer period of time during the growing period compared to surrounding bare ground (Hiemstra et al., 2006). Krummholz and tree islands receive most of their growing season moisture supply from spring snowmelt (Malanson et al., 2007). Increased soil moisture has been correlated with high growth success in krummholz. Soil moisture availability is often related to a larger snowpack deposited during the winter season (Weisberg & Baker, 1995), so long as the upper limit of the water holding capacity of the soil has been reached.

In addition to controlling that spatial distribution of snow, krummholz have also been linked to reduced sublimation, by allowing snowpack development below the canopy (Hiemstra et al., 2002). Currently, there is much debate over whether krummholz at high elevations aid in controlling snowpack size or patterns. Past studies suggested that sublimation is more common from coniferous species because they can collect more snowfall on branches compared to deciduous trees (Pomeroy and Gray, 1995; Pomeroy et al., 1998; Parviainen & Pomeroy, 2000). When this occurs, less snow is expected to reach the ground below the canopy where it can become compacted. Instead the exposed intercepted snow becomes more susceptible to leaving the system through sublimation (Varhola et al., 2010). Rasouli et al. (2019) suggests that subalpine trees are important sinks for blowing snow accumulation and that the development of tree patches at higher elevations increases snow drifting and the sublimation of intercepted snow above the treeline and reduces moisture availability to subalpine forests. This limitation on water supply below the treeline may have detrimental impacts, such as drought and wildfires. Therefore, the migration of trees to higher elevations has been associated with changes in system hydrology, including the formation of snow drifts, increased interception and sublimation, and reduced water supply to subalpine forests downslope from krummholz and tree islands (Malanson et al, 2007).

The relationship between krummholz patches and local hydrology has been studied extensively for winter snow and spring melt, however less research has focused on growing season processes, such as ET (Dirnböck & Grabherr, 2000). In heterogeneous landscapes, studies have observed that local advection can control ET between patches of trees or shrubs and their surroundings, such as krummholz patches and adjacent subalpine meadows (Figuerola & Berliner, 2005; Park & Paw, 2004; Turner, 1991). Advection is the transport of vapour or heat by wind as a result of horizontal heterogeneity and can be observed when sensible heat flux (Q_H) transfers energy towards a surface ($-Q_H$), which increases energy for the advective enhancement of ET beyond what is supplied by available energy (net radiation less ground heat flux) (Chorley, 2019, Hillel, 1998; Kool et al., 2018; McNaughton and Jarvis, 1983; Oke, 1987; Prueger et al., 1996; Tolk et al., 2006). Advection occurs between surfaces where surface type and roughness are variable due to differences such as albedo, canopy height, water availability, temperature and vapour pressure deficit (VPD) (McAneney et al., 1994; Park & Paw, 2004). McNaughton and Jarvis (1983) determined that the advection of dry or moist air, and its influence on VPD, could either increase or decrease ET rates. Park and Paw (2004), assessed the differences in vertical and horizontal advection within inhomogeneous canopies and determined that horizontal advection is greatest at the edge of canopies and decreases with fetch as well as height from tall to shorter canopies due to diffusivity (Park & Paw, 2004). This is an example of advection leading to a "clothesline effect" on ET, where sensible heat transfer by wind moves through a heterogenous site (taller to shorter canopies) and increases ET in vegetation patches that are more exposed to wind (Chang, 1968; Chorley, 2019; Kirkham, 2014).

Previous studies on the advective enhancement of ET focus on water deficient areas and irrigated crop fields where patches of higher moisture supply are referred to as "oases" compared to their drier surroundings (Rosenberg, 1969a, 1969b; Rosenberg and Verma, 1978; Tanner, 1957). Local advection between these areas of higher and lower moisture supply has been termed as an "oasis effect" on ET (Turner, 1991; Wang et al., 2019). Oasis effect refers to the advection of warm air passing over drier surfaces that transfers sensible heat downward onto areas of higher moisture supply, which increases evaporative cooling (Chorley, 2019; Wang et al., 2019). Differences in soil moisture, air temperature and VPD between krummholz patches, and their surrounding subalpine meadows may influence changes in ecosystem ET rates in subalpine krummholz zones.

1.3 Research Gaps

Past studies have acknowledged that one of the main challenges for research in mountain systems is temporal and topographical variability (Bavay et al., 2013). Few studies exist that look at the potential influence of climate change on subalpine landscapes (Luckman & Kavanagh, 2000). This is especially true when assessing ecological and hydrological responses to climate change in terms of advancing treelines and tree establishment (Malanson et al., 2007). Subalpine landscapes transition into areas dominated by krummholz, the growth and development mechanisms of which are controlled by atmospheric, topographical and ecological factors. However, researchers have yet to agree on the rate of krummholz development and persistence under climate change conditions.

There is also limited knowledge on how krummholz influence multiple components of the hydrological cycle, including runoff, snow accumulation, soil moisture and ET (Dirnböck & Grabherr, 2000). Understanding how krummholz use, and release water would aid in understanding how water is being stored or released from these alpine systems. This would in turn increase knowledge on water supply for downstream-reliant ecosystems and communities.

Several studies to date have related krummholz to the formation of snow drifts in high alpine landscapes, however there are differing results as to whether krummholz aid in increasing the size of winter snowpack or reduce it. Holler et al. (2000) suggests that krummholz help preserve and increase the size and density of snowpack once established above the treeline by increasing an even distribution of snowpack. However, Varhola et al. (2010) highlight that increased tree cover has led to higher canopy interception rates, leading to less snow accumulation, due to more snow being readily available for evaporation/sublimation from the canopy. Little is known of how krummholz tree patches influence ET rates in subalpine regions. Studies must therefore focus on the combined loss of water by way of evaporation from the surface of krummholz trees, the soil beneath them and the transpiration loss from within these trees to the atmosphere.

1.4 Research objectives

The objectives of this thesis are to: (1) evaluate the spatial variability in evapotranspiration (ET) in a subalpine transition zone between two types of successional tree patches: Krummholz and Tree Islands; and (2) assess the interactions between ET and snow, vegetation and micrometeorology, in order to assess the changes in the hydrological cycle driven by differences in canopy cover in Canada's Rocky Mountains. This study was conducted on a south-facing mountain ridge in Kananaskis, Alberta that is dominated by tree islands and krummholz patches.

Chapter 2: Research site and methodology

2.1 Study Site

Research for this study took place in Kananaskis, Alberta, at the Fortress Mountain Snow Laboratory, part of the Canadian Rockies Hydrological Observatory (50°49’23.37” N 115°11’52.76” W). Fortress Mountain is bordered by Spray Valley Provincial Park and is located on privately operated crown land. Fortress Mountain is hydrologically connected to the Marmot Creek Watershed, headwaters to the Bow River. The site selected for this research is referred to as Fortress Ridge South (FRS). It is approximately 3000 m^2 in size and is located below the crest of Fortress Mountain Ridge, on a south-facing aspect. Forest Mountain has previously been developed for recreational activities including skiing. Discussions with property managers and fellow researchers suggest that FRS had received minimal ecological impact from such developments. FRS is approximately 2300 m a.s.l. at the centre of the site on an 18° slope and is defined as an upper subalpine forest transition zone that consists of multiple tree islands and krummholz tree patches (Harder et al., 2016; Wayand et al., 2018). For the purpose of this study, data was collected between July 2017 and August 2018, with one additional survey in July of 2019.

FRS is characterized by long, cold, wet winters and short, cool, wet, spring conditions and early summer temperature conditions, climatically normal of Canada’s Rocky Mountains (Pomeroy, Fang & Ellis, 2012). Average daily temperatures in this area range from 14.5℃ in July to -11.7℃ in January, according to the 1981-2010 climate normals (Environment Canada, 2015). Annual precipitation within this area ranges between 600-1100 mm, with increased precipitation falling at higher elevations (Pomeroy, Fang & Ellis, 2012). The majority of the annual precipitation within this region falls as snow between the months of October through to May, however, snow can occur within any season, especially at higher elevations in the subalpine and alpine zones (Pomeroy, Fang & Ellis, 2012).

Six subplots were set up along three transect lines, where vegetation samples, soil moisture and temperature data were collected (Figure 2-1). The three transect lines were constructed to represent the spatial variability of the site, and as such each ran through multiple tree islands, krummholz and open canopy meadows (Figure 2-1). Subplots consisted of three tree islands: Tree Island 1, Tree Island 2 and Tree Island 3, as well as three open canopy areas with multiple krummholz patches within them, referred to as: Krummholz 1, Krummholz 2 and Krummholz 3. Each subplot was selected in order to represent differences in tree stand size and development, in order to better understand differences in ET based on changes in ecological characteristics.

Dominant tree species at FRS included the Subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) and some Tamarack larch (*Larix laricina*). Trees at FRS grow in two types of colonial growth patches, referred to as tree islands and krummholz. Krummholz patches at this study site were exclusively *Abies lasiocarpa* with ground vegetation surrounding them, including *Chamerion angustifolium*, *Vaccinium scoparium*, and *Dryas hookeriana (Juz.).* Tree islands consisted primarily of *Abies lasiocarpa*, with some *Picea engelmannii* and *Larix laricina* trees present, primarily lower on the slope, within Tree Island 3, which was closer to the limit of the closed canopy forest treeline. Ground vegetation within the tree islands 2 and 3 were limited to <5% cover of Fireweed (*Chamerion angustifolium*), no vegetation was present at the ground level in Tree Island 1.

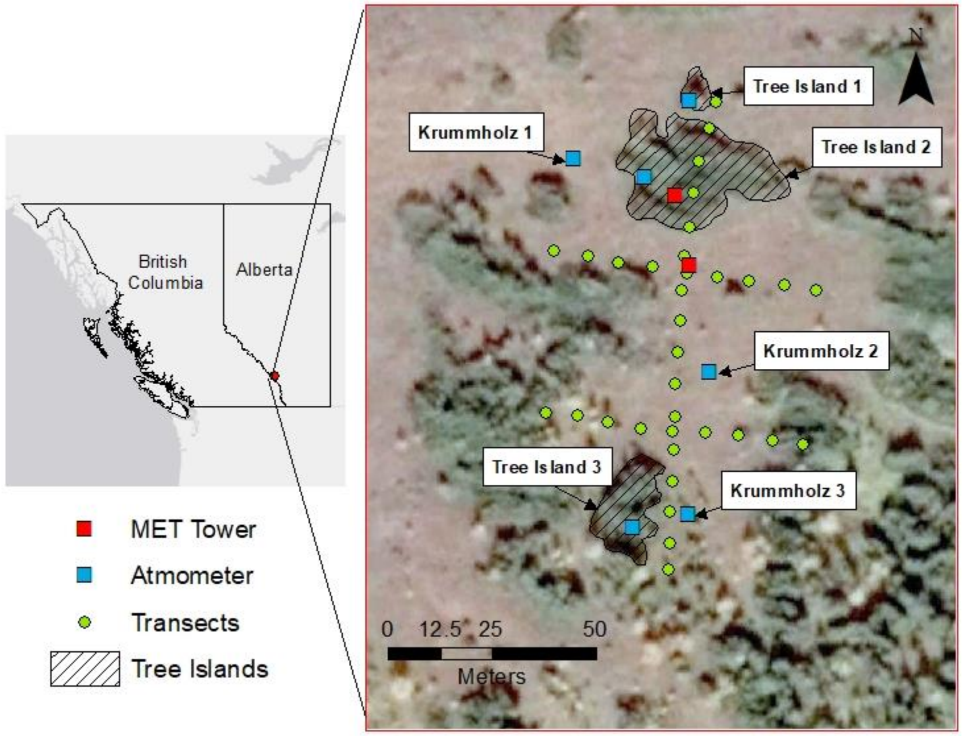

Figure 2-1. Site map of Fortress Ridge South (50°49'23.37" N 115°11'52.76" W), Kananaskis Country, Alberta, including labels on the locations of all subplots, transect points, atmometers and MET towers.

2.1 Field and Lab Methods

2.1.1 Snow Surveys

Snow surveys were conducted between the first snowfall in October of 2017 and until snow melt was complete in June of 2018. Sampling was conducted once a month from October to February, and once every two weeks from March until June, in order to capture snowmelt rates more consistently. Surveys were conducted across a transect line selected based on its perpendicular position with wind direction, to reduce the effect of wind-swept snow redistribution on snow depth. Between 10 and 12 points were sampled during each snow survey. At each point snow depth was recorded using a measuring pole, and once at every third point snow density and snow water equivalent (SWE) were assessed using a snow corer. An ESC 30 snow sampler (based on Farnes et al., 1980) was used to core when depths were shallow, and a Mount Rose sampler was used for greater snow depths.

2.1.2 Canopy, Vegetation and Soil Surveys

Surface vegetation and a tree community analyses were performed between July and August 2017. Ground vegetation was assessed using the Daubenmire Method along each transect point within the study site using a 20 cm by 50 cm sampling frame (U.S. Department of Agriculture, 1999). Species identification, as well as an estimate for species percent cover was recorded for each point along all transects. The strategic sampling design of this survey allowed for an understanding of how vegetation changes across, and up or down, slope, as well as within sheltered tree islands and krummholz subplots.

A community analysis was performed within each tree island and krummholz. For the purpose of this study, all trees within each subplot were assessed. Within each subplot each tree was first counted and identified for their species using the Alberta Parks for Kananaskis Country field guide (Alberta Parks, 1999). This allowed for a total count of the number of each type of dominant tree that persists in each subplot and would allow for an understanding of species diversity within the site, both spatially and overall. Additionally, trees height was measured using a telescoping tree measuring pole and Diameter at Breast Height (DBH) was measured using DBH measuring tape at the height of 1.3 m (only for trees or stems that were >1.3 m). Finally, tree cores were extracted from 3 trees within each tree island in order to determine an estimate for species age within each tree island subplot. In order to reduce bias, the three candidate trees chosen for coring within each subplot were determined by selecting trees of varying heights, typically one below average tree, one average tree and one tree above average; based on community analysis results. One tree was harvested in each of the krummholz subplots for dating; sample size was reduced in order to limit destruction to the krummholz which are smaller in size than the tree islands. In total 9 tree cores, and 3 tree cookies (cross-sections from harvested cores) were obtained for species dating. Cookies were processed by finely sanding samples and then running them through a flatbed scanner (Epson Perfection 4990 Photo) and CooRecorder software (Cybis Elektronik & Data AB) to count tree rings and cross date results. Cores were finely sanded and processed using the Velmex Tree Ring Measuring System (Velmex, 2016) and J2X tree ring measuring program (VoorTech Consulting, 2016).

Soil was collected for analyses in two forms: as one integrated vertical core and as separated loose soil samples. Soil was collected at each subplot at FRS, except for a vertical core at Tree Island 1, where soil was too shallow and contained too high of gravel content to extract an intact sample core. Intact core samples were taken to the maximum depth possible at each subplot using a 3-inch PVC pipe inserted vertically into the soil. Loose soil samples were collected using a hand-auger, also inserted to the maximum depth possible at each subplot. Augered soil samples were divided into 10 cm intervals and bagged from the top organic horizon, to the maximum depth collected. Column samples were analyzed for soil properties including bulk density, specific yield and porosity using standard methods (Freeze & Cheery, 1979). Separated samples were processed for soil texture using the Horiba LA-950 V2 Particle Size Analyzer. Soil particle size classes included sand (62.5 μm – 2 mm), silt (3.90625 – 62.5 μm), and clay (< 3.90625 μm) according to the Krumbein Phi-Scale.

2.1.3 Leaf Area Index

Leaf Area Index (LAI) was assessed in order to determine differences in canopy structure so that comparisons between canopy size and transpiration and interception could be made. Data was collected using a LAI-2200 plant canopy analyzer using the 90° viewing cap, in order to reduce operator interference on the lens (LI-COR, USA). LAI is one half of the total intercepting area of the canopy per unit ground surface area (Chen & Black, 1992). LAI was measured once a week in each of the six subplots from June until August. Randomized sampling was conducted within each the of the tree islands, where 10 to 15 measurements were taken during each sampling period to account for variation in canopy structure. In smaller krummholz patches, 3 to 5 measurements were taken to estimate LAI. At each sampling point, below canopy (ground level) and mid-canopy readings were taken. The LAI-2200 was adjusted for slope by leveling the instrument, as to not inflate or reduce LAI results. LAI was only taken on days where cloud overcast occurred, as the instrument is sensitive to light and variable cloud cover that could lead to the saturation of the sensor. Before each tree island and krummholz were assessed, above canopy measurements were taken in an open area on top of the ridge in order to reduce tree interferences. Field measurements were processed using LI-COR software FV2200 to obtain effective LAI values (L_e) (LI-COR, USA). Optical based measurements of LAI are subject to error due to canopy and woody material clumping. In order to address this error L_e values were corrected using a coniferous canopy correction factor (constants derived from Black Spruce, Chen et al., 1997) which was calculated using equation 1 (Chen et al., 1997; Liu, Jin & Zhou, 2015).

$$LAI = (1-\alpha)Le \left(\frac{\Upsilon E}{\Omega E}\right) \quad (1)$$

In equation 1, α represents the woody-to-total area ratio (1 – α = 0.84, Chen et al., 1997), L_e is the effective LAI value processed by the optical instrument; in such case the LAI-2200 plant canopy analyzer, Υ_E (1.4, Chen et al., 1997) is the needle to shoot area ratio, and Ω_E (0.7, Chen et al., 1997) is the clumping index which quantifies the effect of foliage clumping for scales that are larger than shoots (Liu, Jin & Zhou, 2015).

2.1.4 Meteorological Stations

A meteorological (MET) station operated by the Centre for Hydrology (Fortress Mountain Snow Laboratory of the Canadian Rockies Hydrological Observatory) was located at the intersection of the NS and top EW transect arm (Figure 2-1). This MET station was an open canopy tower that collected multiple year-round surface to atmosphere variables including radiation, precipitation, wind and soil data. A CR3000 Data Logger (Campbell Scientific, Edmonton, Alberta), which had a logging execution interval of 10 seconds, collected and stored data in 30 minute averages. Average air temperature and relative humidity (RH) were collected using a HC-S3 Temperature & Humidity Probe (Rotronic, Stoney Creek, Ontario). Rainfall was collected using a TB4 Tipping Bucket Rain Gauge (Hydrological Services America, Lake Worth, Florida) and a Pluvio precipitation gauge (OTT HydroMet, Loveland, Colorado) for both rainfall and snowfall. Incoming and outgoing net, longwave and shortwave radiation, as well as surface albedo were collected using a CNR4 Net Radiometer (Zipp & Zonen, Sterling, USA), positioned at approximately 3 meters above the ground surface. A 05103-10 Wind Monitor (R.M. Young, Traverse City, Michigan) was equipped at 5.2 m above the ground to measure changes in wind speed and direction. Snow depth was monitored using a SR50A Sonic Ranger (Campbell Scientific, Edmonton, Alberta) and snow temperature was measured above the ground at 20 cm and 150 cm using Type E Thermocouple (Omega Environmental, St-Eustache, Quebec). Ground properties including soil heat flux were measured just below the surface using a HFP01 Soil Heat Flux Plate (Hukseflux, Center Moriches, New York). Volumetric water content and soil temperature were measured using a CS650 from Campbell Scientific (Edmonton, Alberta).

In addition to the open canopy MET station, an additional MET station was positioned underneath the Tree Island 2 canopy in order to account for differences in exposure to wind and changes in temperature gradients within and outside of the krummholz. This MET station was in operation from June 5th to August 16th, 2018. A CR1000 Data Logger (Campbell Scientific, Edmonton, Alberta) took measurements every 30 seconds and displayed results using 30 minute averages. This MET station was simplified to account for differences primarily in soil and radiation between the open and closed canopy plots. Volumetric water content was measured using two CS 650 (Campbell Scientific, Edmonton, Alberta) soil moisture probes, one probe was inserted into the soil at a depth of 30 cm (parallel to the soil surface), and the second probe was inserted vertically into the ground to reach a maximum depth of 30 cm. Soil temperature was also measured at depths of 5, 10, 15 and 30cm using Type K Thermocouple inserted in a closed soil pit (Omega Environmental, St-Eustache, Quebec). Additionally, net radiation was captured using an NR Lite Net Radiometer (Zipp & Zonen, Sterling, USA) positioned about 1 m above the soil surface, underneath the shading of the canopy, in order to assess differences in shading dynamics on energy transfer within the sheltering of the tree islands.

MET data from closed and open canopy stations, as well as corrected ET values from atmometers (ET_A) were used to produce energy budgets for the krummholz and tree island subplots at FRS,

$$Q^* = Q_E + Q_H + Q_G \tag{2}$$

where Q* is the total net radiation, Q_E is the latent heat flux, calculated using in-field atmometer results,

$$Q_E = ET(LV) \tag{3}$$

where ET represents the daily sum of actual ET (ET_A) at the observed subplot (mm/day) and LV is the latent heat of vaporization of water (2.45 MJ/m^2), QG is the ground heat flux, and Q_H is the sensible heat flux which was calculated as a residual of the energy balance equation. The Bowen ratio is derived from the energy balance equation and describes the ratio between sensible and latent heat fluxes, the equation is expressed as,

$$B = \frac{Q_H}{Q_E} \tag{4}$$

In addition to assessing the energy balance, which measures vertical energy transfer, vapour pressure deficit (VPD) was calculated in order to address atmospheric demand for water in relation to ET between each of the tree island and krummholz subplots,

$$VPD = e^s - e^a \tag{5}$$

where e^s is the saturation vapour pressure and e^a is the actual vapour pressure, calculated by,

$$e^s = 0.6108\exp\left[\frac{17.27T}{T+27.3}\right] \tag{6}$$

and

$$e^a = \frac{e^s(T_{min})\frac{RH_{max}}{100} + e^s(T_{max})\frac{RH_{min}}{100}}{2} \tag{7}$$

where T is equal to mean air temperature (°C), T_{max} is maximum air temperature (°C) and T_{min} is minimum air temperature (°C). RH_{min} is minimum relative humidity (%) and RH_{max} is maximum relative humidity (%).

2.1.5 Evapotranspiration

For the purpose of this study ET was measured three ways: (1) as potential ET (PET) in-field using atmometers, (2) as PET calculated by the FAO-56 Method for Penman-Monteith and (3) as actual ET (AET) by using values from both methods of PET collection to calculated site-specific canopy coefficients for coniferous correction. In field measurements of PET were conducted during the summer of 2018 from July 12th to August 15th. Measured in-field PET, referred to as crop ET (ET_C), rates were assessed using six ETgage Model E Atmometers (ETgage Company, Loveland, Colorado). Atmometers can estimate PET from small, highly heterogeneous areas, making them beneficial to studies with fragmented canopies of various heights and species, such as in this study. Atmometer PET rates are driven by processes or variables such as VPD, wind speed and available energy, which are also meteorological controls that are reflective of oasis effect and advection on ET (Fontaine & Todd, 1993). Therefore, the use of multiple atmometers, placed in both tree island and krummholz patches would allow for microscale observations of differences in PET, that would otherwise not be possible from other micrometeorological approaches (i.e. eddy covariance).

One Atmometer was placed on a wooden stake at approximately 1 m above the soil surface in each of the six subplots. Positioning atmometers at 1 m was done in order to reduce ground vegetation interference and to assess interactions within the canopies of the krummholz and tree islands. Differences in canopy height between krummholz and tree islands were addressed upon installation. Krummholz were shorter in height compared to the tree islands, however exposure to edge effects were greater. The position of atmometers at 1 m was within the canopy, as krummholz were on average 2.2 m in height. This allowed for the observation of ET changes within the krummholz canopy, as was the same for atmometers placed at 1 m in height for the tree islands.

Atmometers consist of a water reservoir with a pressurized ceramic evaporator on top, connected through an internal tube. When sunlight and wind are applied to the top of the atmometer, the ceramic evaporator can mimic the effects of solar energy absorption and vapour diffusion resistance, estimating in-field reference potential evapotranspiration (ET_O). ET_O measurements were automatically recorded every fifteen minutes as pulse counts of 0.254 mm. Diffusion cover style #30 reference grass was used as a resistance standard for each atmometer. Grass is a global plant standard for reference ET and can be converted by using a crop coefficient (K_C) to estimate the evaporative demand of specific plant species. A coniferous correctional factor (K_c=1.0, Allen et al., 1998) was applied to atmometer values in order to convert atmometer field measurements from ET_O (reference PET) to ET_C (crop PET) (Allen et al., 1998).

The FAO-56 Method for Penman-Monteith, a derivative of the Penman-Monteith equation, which was adjusted to determine relationships using canopy resistance, was used to calculate ET_O at FRS,

$$ET_o = \frac{0.408\Delta(R_n - G) + \Upsilon\frac{C_n}{T-273}u_2(e_s - e_a)}{\Delta + \Upsilon(1 + C_d u_2)} \quad (8)$$

where ET_o is the reference crop evapotranspiration rate (mm/day), T is the mean air temperature (°C) and u_2 is the wind speed (m s^{-1}) (Zotarelli et al., 2010). In this study the short crop equation for grass reference was used for the tree island and krummholz subplots, to keep consistent with atmometer measurements which were taken with the #30 grass reference cover (Zotarelli et al., 2010). C_n is the numerator constant for the reference crop type (Grass= 900) and C_d is the denominator constant for reference crop type (Grass= 0.34) (Zotarelli et al., 2010).

Next, actual ET (ET_A) was calculated for each of the tree islands and krummholz using patch-specific crop coefficients. In previous studies often focusing on agricultural crops, the FAO K_C standards are commonly used to adjust ET_O to ET_C, where ET_C is then assumed to represent AET. However, many studies focusing on coniferous tree species have found that the suggested K_C value is not representative of all conifers, the soils beneath them or the climate they are growing in (Liu & Luo, 2010; Gurski et al., 2018; Zhang et al., 2016). As such a K_C of 1 has the potential to over or underestimate AET and would thus not be representative on coniferous AET (Gurski et al., 2018). For the purpose of this study, patch-specific K_C values were developed for each of the tree islands and krummholz using,

$$K_C = \frac{ET_C}{ET_O} \tag{9}$$

where ET_C is equal to average crop ET for the growing season and ET_O is the average reference ET for the growing season (Gurski et al., 2018). This equation was used to calculate a K_C value for each of the 6 patches. These new patch-specific K_C values were then used to correct ET_C to ET_A.

2.1.6 Canopy Interception

Tree island subplots were equipped to measure interception. This was done in order to estimate the amount of water entering the system that may be captured by the canopy and would therefore be readily available for evaporation. Within each tree island, two 1.5 m long eavestroughs were used to collect rainfall, one positioned at mid-canopy height; approximately half the height of the total canopy (collected during tree surveys), referred to as “High” and the second was positioned at the ground surface, referred to as “Low”. Each eavestroughs was secured at a slight slope in order for the collected water to filter down a connected eavestrough into a funnel that would drain into a closed 2 gallon bucket. After each rainfall event, water from the buckets was measured using a graduated cylinder and converted from volume to depth using,

$$Depth = \frac{Volume\ (cm^3)}{Eavestrough\ area\ (cm^2)} * 10 \tag{10}$$

Once depths were recorded for each eavestrough within a subplot, the Low eavestrough depth was subtracted from the High eavestrough depth, which would calculate a general estimate of the amount of water that was incapable of reaching the forest floor. Measurements of canopy interception could then be later compared to associated rainfall events in order to determine how much rain was intercepted within each canopy during specific rain events.

2.1.7 Water balance of dominant hydrological fluxes

Once all hydrological properties were measured, simplified water balances of vertical fluxes for tree islands and krummholz were developed in order to assess changes in water availability between the patches during the growing season. For tree islands and krummholz the water balance equation,

$$SWE + P = ET_A + I + \Delta S \tag{11}$$

was used to assess moisture differences between patches. Peak *SWE* (mm) is available water from the snowpack, *P* is total precipitation (mm), ET_A is the total actual ET (mm), *I* is total canopy interception (mm), which was limited to tree islands only, and ΔS is the change in storage (mm) from the beginning to the end of the observed growing season (DOY 193 to 227). The chosen water balance equation was developed to only consider vertical fluxes in order to assess changes in moisture supply.

For the purpose of this study, it was assumed that all interception was lost to evaporation and was not partitioned to stemflow and drip measurements. ΔS was calculated from MET station VWC measurements by the equivalent surface depth (ESD) method (Dingman, 2002) for tree islands at 30 cm and krummholz at 40 cm. Therefore, ΔS for tree islands and krummholz assumes that the chosen depths were representative of the entire rooting zone above. Due to the potential for limitations caused by assumptions to the water balances, residual (e) values were addressed for both patches.

2.1.8 Data processing and statistical testing

All data was tested for normality ($p>0.05$) using the Shapiro-Wilkinson distribution test. ET results were tested for statistical significance using a one-way ANOVA test and the post hoc Tukey test. Meteorological controls were correlated with ET data using simple linear regressions. Data was analyzed in Rstudio using the packages: gridExtra, dplyr, reshape2 and cowplot for processing data, and the packages ggplot2 and ggbiplot for visualizing data (Rstudio Team, 2016).

Chapter 3: Results

3.1 Fortress Ridge South meteorological conditions and site characteristics

3.1.1 Climate and meteorological conditions

Meteorological data (relative humidity, air temperature and precipitation) was assessed for the growing season period, DOY 182 to 243 (July 1 to August 31, 2018) (Figure 3-1). Average daily air temperature was 10.9 °C (climate normal= 14°C; Environment Canada, 2015) with a maximum of 21.5 °C (August 10) and a low of 1.4 °C (August 27) (Figure 3-1). Average daily RH was 54 % for the growing season. The lowest recorded RH was 22.4 %, which took place on a rain free day, with minimal rainfall for the days leading up to this event (3.6 mm of rainfall recorded in the previous five days). The highest RH (89.8 %) occurred during a rain event of 6.6 mm on July 3, which had 22.2 mm of rain during the preceding two days. Daily precipitation averaged 2.9 mm per day, with the largest event (19 mm) occurring on the final day of the growing season on August 31st (Figure 3-1). Other notable precipitation events were July 10 (18 mm), July 31 -August 5 (17.8mm) and August 24 - August 31 (73.2mm).

Wind direction was primarily from the southwest; however southeasterly winds were also frequent throughout the season (Figure 3-2). A frequency distribution of wind direction shows that southwesterly winds occur >10 % (10-30 %), whereas northeasterly and northwesterly winds were observed < 10 % during the 2018 season. The highest wind speeds were recorded during the winter (January, November, and December) with an average wind speed of 3.4 ms^{-1} (Figure 3-2). The highest wind speed was observed on December 15 with wind gusts reaching 15.9 ms^{-1}. Lower seasonal wind speeds were recorded during the summer (June-August), followed by the spring

(March-May) with average wind speeds of about 2.2 ms^{-1} for each time period. The average wind speed for the fall (September-November) was 2.4 ms^{-1}.

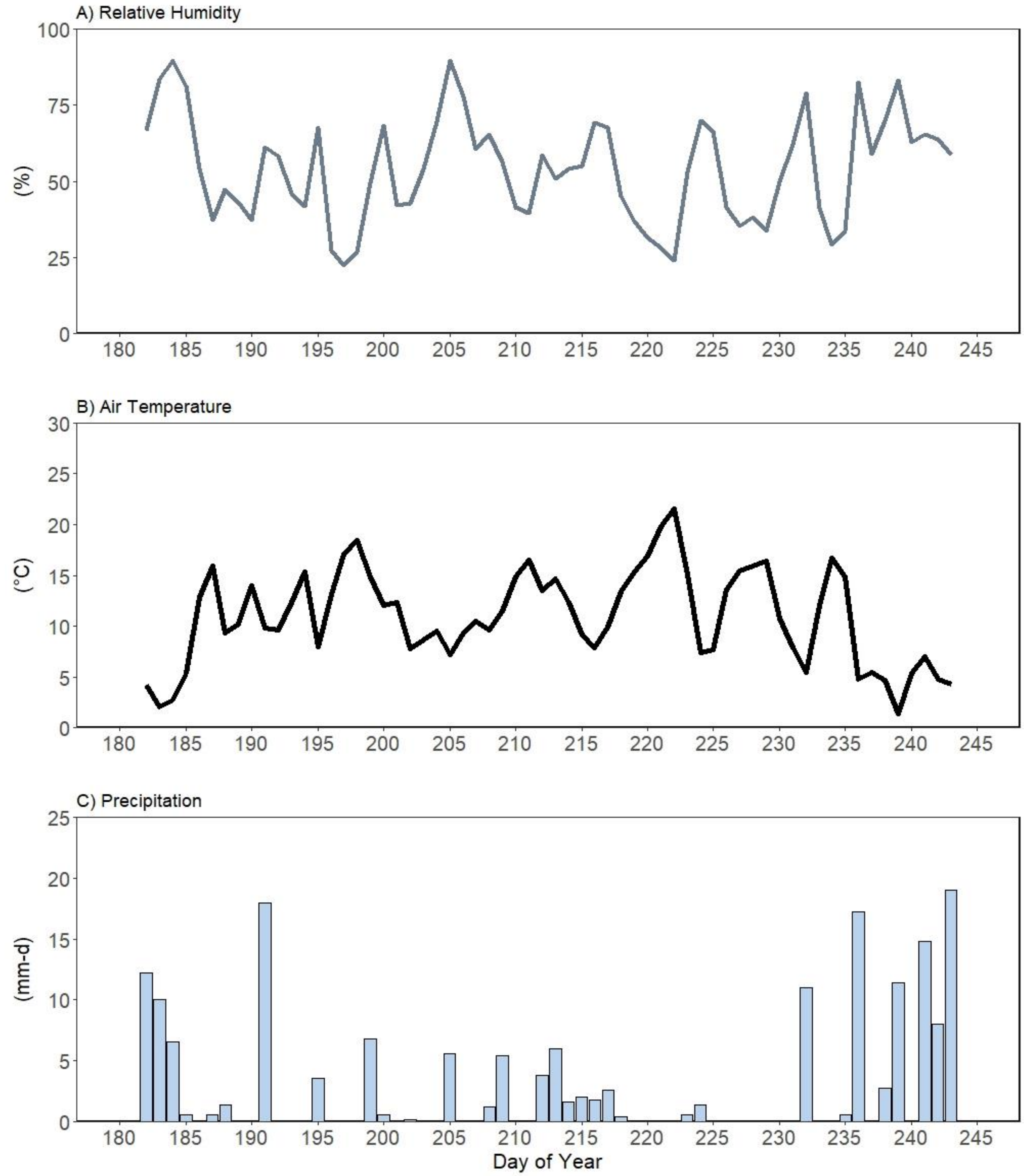

Figure 3-1. Meteorological conditions at Fortress Ridge South from July 1st (DOY 182) to August 31st (DOY 243), 2018. Graphs describe: A) daily average relative humidity (%), B) daily average air temperature (°C) and C) daily total rainfall (mm). Data was collected from the open canopy MET station.

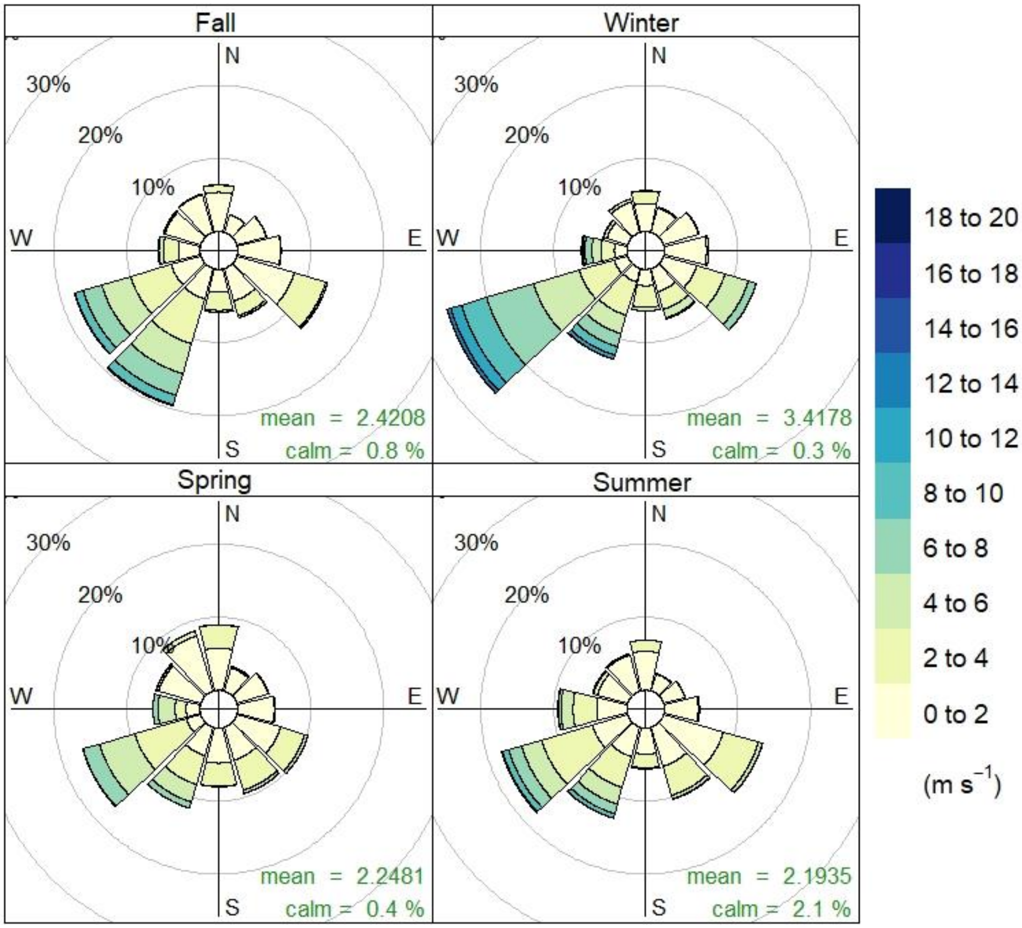

Figure 3-2. Hourly wind speeds (ms^{-1}) and directions (°) for Fall (SON), Winter (DJF), Spring (MAM) and Summer (JJA) seasons for the 2018 sampling year at FRS with associated frequency counts (%), Fortress Mountain, Alberta.

3.1.2 Snow accumulation and melt

The first snowfall ahead of the 2018 sampling season occurred on October 31, 2017 (DOY 304) and snow accumulated until April 17, 2018 (DOY 107), after which snowmelt began (Figure 3-3). Snow depth measurements at Fortress Ridge South were evaluated relative to Fortress Ridge Top (-115.22049, 50.83642), which receives less sheltering and increased exposure to wind. The average snow depth throughout the snow-covered period for Fortress Ridge Top was 13.6 cm (±10.3 cm), which was substantially lower than that of the Tree Islands (average of 163.4 cm ±79 cm) and Krummholz (142.9 cm ±73.7 cm) (Figure 3-3). The maximum snow depth at Fortress

Ridge South was recorded within the krummholz subplots at peak snow accumulation, with 257.2 cm on April 17, 2018. Snow depth was greater on average within the tree islands during the snow accumulation period compared to the krummholz. However, melt appeared to be faster within the tree islands (Figure 3-3). Air temperature began to rise early April (Figure 3-4), reducing depths, showing snowmelt had begun (Figure 3-3). Tree islands depths reduced at a faster rate compared to krummholz once temperatures increased by mid-April (Figure 3-3).

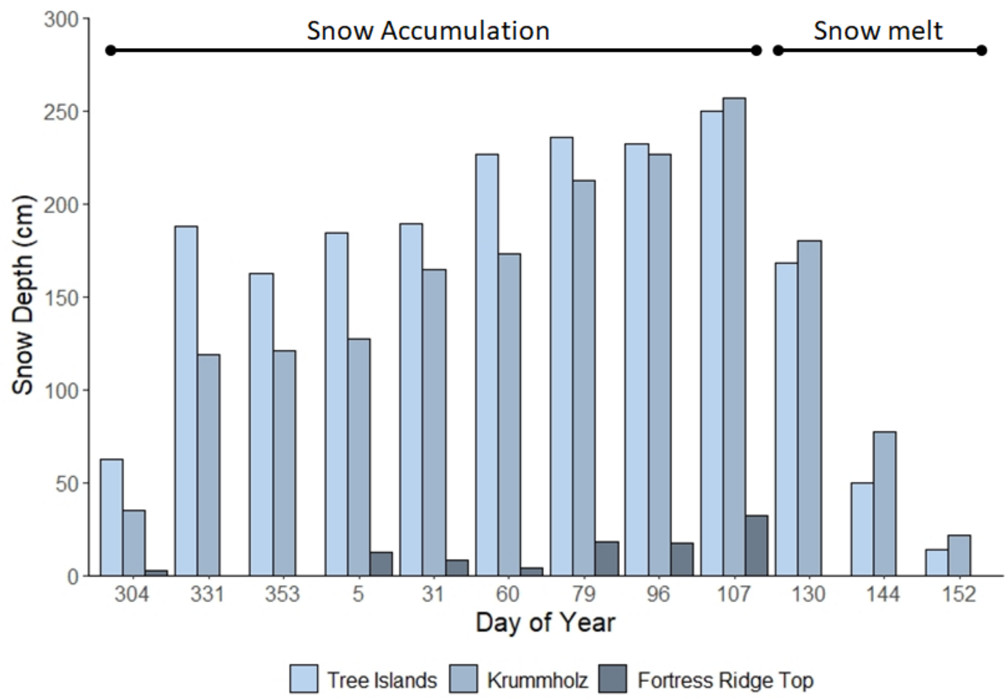

Figure 3-3. Snow depth (cm) at Fortress Ridge South for tree islands and krummholz compared to snow depth at Fortress Ridge Top from first snowfall in October 2017 until snowmelt in June 2018, Fortress Mountain, Alberta.

Snow water equivalent (SWE) results from the winter and spring snow surveys (October 31st, 2017 to June 1st, 2018) at FRS were compared to air temperature during the associated sampling dates (Figure 3-4). SWE was higher for tree island subplots than krummholz subplots during the snow accumulation period (October 2017 to April 2018), during which average air temperature was -5.7 °C with a minimum of -27.3 °C (approximately October 31st, 2017 to April 17th, 2018), while a maximum of 12 °C was observed during the snowmelt period (approximately

April 18th to June 1st , 2018) (Figure 3-4). The tree island subplots had a maximum (peak) SWE content of 825 mm for the sampling period on April 17, 2018. The krummholz tree patches showed greater SWE, with a maximum of 850 mm, which was also observed on April 17. SWE results for krummholz and tree islands were statistically different (p <0.05, mean= 518 mm ±255, n= 24). During the spring melt period SWE content was higher within the krummholz than the tree islands, suggesting that they were exhibiting slower melt rates than the tree island patches.

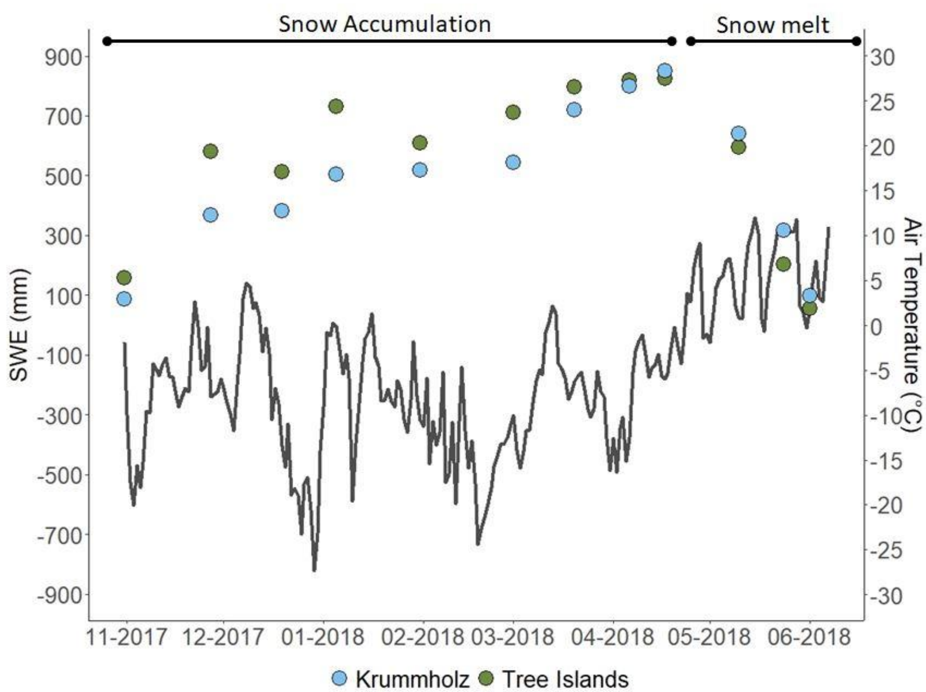

Figure 3-4. Average daily snow water equivalent (mm) and average daily air temperature (°C) (gray trendline) for Fortress Ridge South krummholz (blue dots) and tree island (green dots) subplots from October 31st, 2017 until June 1st, 2018, Fortress Mountain, Alberta.

3.1.3 Soil Characteristics

Soil texture across all six subplots showed limited variability (Table 3-1). Typically, all samples showed high sand content and were classified as sandy loam for all tree islands and krummholz. Some variation with depth was present, as silty loam (between 30-70 cm depths in Tree Island 2 and Krummholz 3) and loamy sand (in all subplots at varying depths) were also observed. Bulk density values were similar between each site but were greatest in Krummholz 1 and Krummholz 2 (1.4 g m^{-1}) (Table 3-1). Porosity values showed greater variation, where Tree Island 2 had the highest porosity (84.9%) and Krummholz 3 the lowest (57.2%). Tree Island 3 showed similar porosity to Krummholz 3 at 57.6%. Soil specific yield values were similar to porosity, where Tree Island 2 had the highest specific yield (12.7%) and Krummholz 3 the lowest (7.6%). When comparing the tree islands and krummholz separately, Tree Island 2 and Krummholz 2 both had the highest porosity and specific yield for their patch type. Additionally, Tree Island 3 and Krummholz 3 each had the lowest porosity and specific yield results. Tree Island 1 results were not recorded as an adequate depth (>2 cm) for characteristic tests was not possible.

Table 3-1. Soil characteristics for tree island and krummholz subplots at Fortress Ridge South, Kananaskis, Alberta.

Tree Patch	% Soil	% Gravel	Bulk Density (g ml^{-1})	Porosity (%)	Specific Yield (%)	Texture Class
Tree Island 1	40	60	--	--	--	Sandy Loam
Tree Island 2	52	48	1.3	84.9	12.7	Sandy Loam
Tree Island 3	39	61	1.3	57.6	7.9	Sandy Loam
Krummholz 1	51	49	1.4	73.6	9.3	Sandy Loam
Krummholz 2	76	24	1.2	67.4	10.3	Sandy Loam
Krummholz 3	40	60	1.4	57.2	7.6	Sandy Loam

The open canopy MET station measured average soil temperatures and volumetric water content (VWC) from several soil depths: 2, 20, 40, 80 and 136 cm. Average soil temperatures were 9.3 °C (±4.5 °C) at the surface, 8.2 °C (±4.1 °C) at 20 cm, 7.1 °C (±3.7 °C) at 40 cm, 5.1 °C (±2.9 °C) at 80 cm and 3.5 °C (±2.1 °C) at 136 cm. Soil temperature decreased with depth through the 2018 summer sampling period, as well as increased in deviation from the mean at shallower depths. Figure 3-5 shows that with increasing soil temperature there was decreased soil moisture. Soil moisture averages were 0.24, 0.19, 0.20, 0.22, and 0.25 for the 2, 20, 40, 80 and 136 cm depths, respectively. Overall, the VWC at 136 cm remained relatively constant once the snowpack was fully melted (approximately day 180, June 29th). Until the beginning of July, soil moisture at shallower depths (i.e. above 136 cm) all remained relatively constant until July 15th (DOY 196) when a drop in VWC began.

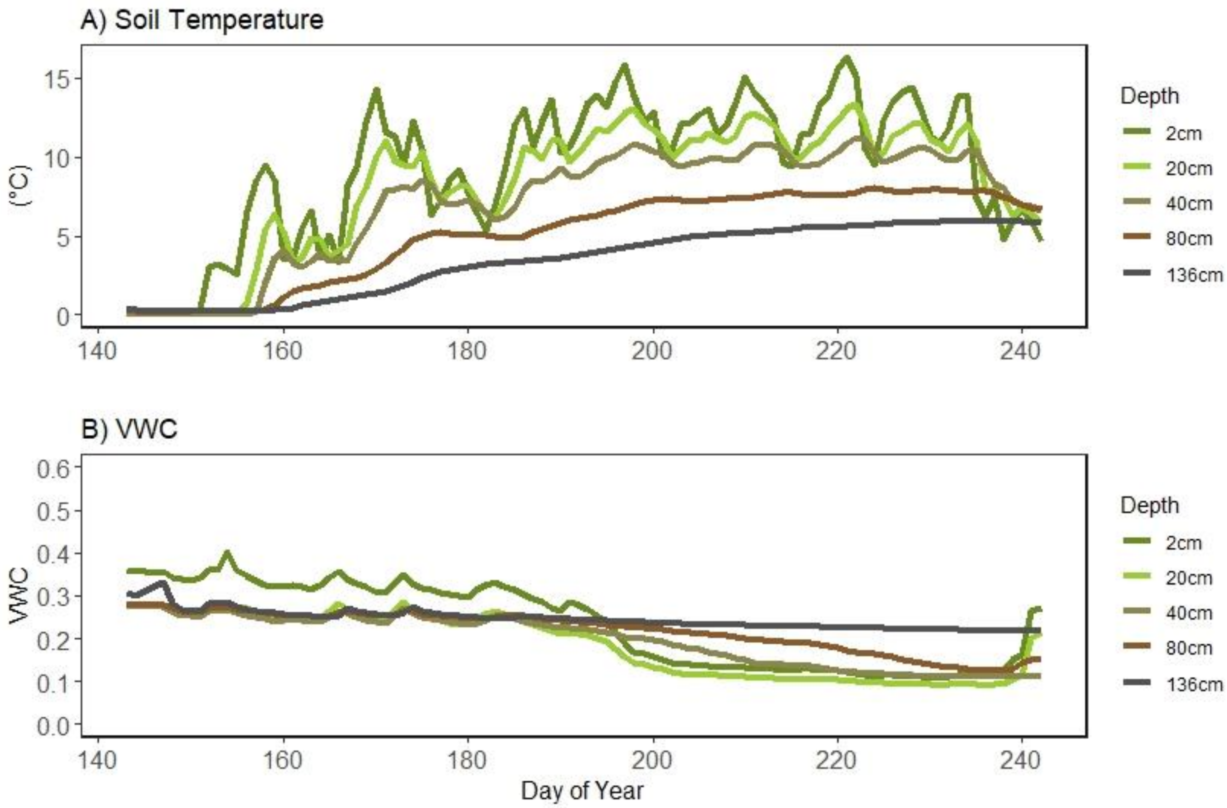

Figure 3-5. Soil temperature (ºC) and volumetric water content (VWC, dimensionless) measured at the open canopy MET station, at several depths: from surface (2 cm) to 136 cm, during the growing season 2018 (Day of Year 143 to Day of Year 242) at Fortress Mountain, Alberta.

The MET station beneath the canopy of Tree Island 2 measured seasonal average soil temperatures of 7.7 °C (±1.8 °C), 6.9 °C (±2.0 °C), 6.5 °C (±2.0 °C) and 5.8 °C (±1.9 °C) for soil depths of 5, 10, 15 and 30 cm, respectively. Soil temperature across all soil depths showed a steady increase throughout the growing season. VWC was on average 0.3 (±0.1) with a maximum value of 0.59 on June 5th and a minimum value of 0.18 on August 15th and 16th, showing that VWC was greatest at the beginning of the season and lowest towards the end of the sampling season (growing season) (Figure 3-6). Additionally, there are two notable soil moisture reduction events on June 6th to 7th and July 4th to 6th.

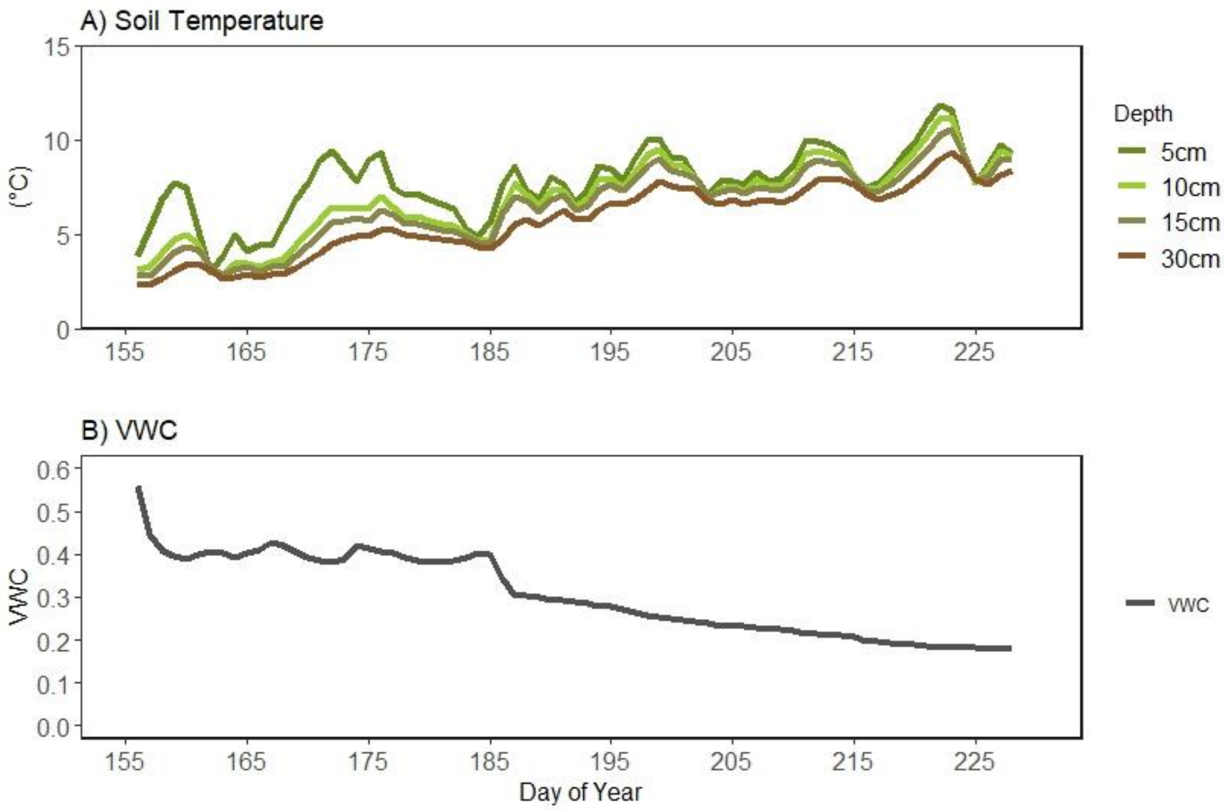

Figure 3-6. Soil temperature (°C) and volumetric water content (VWC, dimensionless) measured at the closed canopy MET station at Tree Island 2, at several depths: from surface (5 cm) to 30 cm for soil temperature and at 30 cm soil depth for VWC, during the growing season 2018 (Day of Year 156 to Day of Year 228) at Fortress Mountain, Alberta.

3.1.4 Canopy Dynamics

Tree patches were assessed for differences in species composition, % cover, height, diameter at breast height (DBH) (Table 3-2), species density, leaf area index (LAI), and age (years) (Table 3-3). Tree Island 1 was dominated by subalpine fir (*Abies lasiocarpa)* with an average height of 1.7 m (±0.7 m) and a mean DBH of 2.0 cm (±1.9 cm) (Table 3-2) and had the greatest tree density (5.5 Trees/m^2). Tree Island 2 was the largest in size of the tree island subplots (227 m^2) and consisted of the most recorded trees (n= 529), which were primarily *Abies lasiocarpa*. Tree height and DBH were similar between Tree Islands 1 and 2. Tree Island 2 also showed the greatest mean LAI (5.6). Tree Island 3 differed from Tree Islands 1 and 2 with higher values for both tree height and DBH for *Abies lasiocarpa* and *Picea engelmannii* species. Overall, Tree Island 3 had the lowest canopy density, but also possessed the oldest species, ranging from 49 to 75 years in age.

Table 3-2. Community analysis for tree patches at FRS 2017. Tree patches described by count (n), % cover, height (m) and diameter at breast height (DBH) (cm), Fortress Mountain, Alberta. * denotes DBH averages that were collected from smaller sample sizes, as the average tree heights were ≤1.3 m, signifying that a large proportion of trees were omitted for DBH readings for these patches.

Tree Patch	Species	n	% Cover	Height (m)	DBH (cm)
Tree Island 1	*Abies lasiocarpa*	72	100%	1.7 (±0.7)	2.0 (±1.9)
Tree Island 2	*Abies lasiocarpa*	517	97.7%	2.2 (±0.5)	2.6 (±1.2)
	Picea engelmannii	2	0.4%	1.8 (±0.0)	2.7 (±0.0)
	Larix laricina	10	1.9%	2.5 (±0.9)	3.1 (±2.4)
Tree Island 3	*Abies lasiocarpa*	122	99%	4.2 (±1.4)	6.8 (±2.8)
	Picea engelmannii	1	1%	6.2 (±0.0)	21.1 (±0.0)
Krummholz 1	*Abies lasiocarpa*	3	60%	0.9 (±0.1)	--
	Picea engelmannii	2	40%	1.3 (±0.1)	0.8 (±0.0)*
Krummholz 2	*Abies lasiocarpa*	8	53.3%	1.2 (±0.8)	2.6 (±1.0)*
	Picea engelmannii	1	6.7%	1.6 (±0.0)	1.7 (±0.0)
	Larix laricina	6	40%	1.9 (±0.6)	2.1 (±0.9)
Krummholz 3	*Abies lasiocarpa*	9	45%	3.2 (±1.0)	6.7 (±2.3)
	Picea engelmannii	2	10%	4.3 (±0.0)	15.7 (±0.2)
	Larix laricina	9	45%	3.4 (±1.3)	5.5 (±3.2)

Krummholz 1, 2 and 3 each showed low species density with less than 1 tree/m^2 (Table 3-3). This trend is associated to larger subplot sizes (approximately 500 to 662 m^2) and a reduced number of trees within the patches. Each krummholz patch was comprised primarily of Subalpine fir (*Abies lasiocarpa*) with some Engelmann spruce (*Picea engelmannii*) and Tamarack larch (*Larix laricina*) (Krummholz 2 and 3) (Table 3-2). LAI was estimated as 5.3 for all krummholz subplots after a technical error with the plant canopy analyzer resulted in lost data for several dates across krummholz 1, 2 and 3. An LAI value of 5.3 was calculated using the remaining data for the krummholz where errors were not present. Tree cores showed age ranges between 18-75 years old for the tree islands and 19-63 years old for the krummholz (Table 3-3).

Table 3-3. Tree patch descriptive characteristics including subplot area (m^2), canopy density (trees/m^2), LAI and age (years) with tree ring sample size (n) at FRS, Fortress Mountain, Alberta.

Tree Patch	Area (m^2)	Tree Density (trees/m^2)	LAI	Age (yrs)
Tree Island 1	13	5.5	6.0	18-37 (n= 3)
Tree Island 2	227	2.3	5.6	25-29 (n= 3)
Tree Island 3	156	0.8	4.9	49-75 (n= 3)
Krummholz 1	615	0.01	5.3	63 (n= 1)
Krummholz 2	662	0.02	5.3	19 (n= 1)
Krummholz 3	500	0.04	5.3	48 (n= 1)

Canopy interception was greater in Tree Islands 1 and 2, compared to Tree Island 3 (Figure 3-7). In Tree Island 1 interception of precipitation ranged from 19 to 24% in July (mean = ~16 mm), and 33 to 58% in August (mean = ~24 mm). In Tree Island 2 the percetage of rainfall intercepted by the canopy was between 22 and 45% in July (mean = ~15 mm), and 21 and 38 % in August (mean = ~16 mm). In Tree Island 3 canopy interception ranged from 6 to 29% of precipitation in July (mean = ~9 mm), and 2 to 10% in August (mean = ~7 mm). Tree Island 3 showed the lowest recorded interception capacities for both July and August (9.5 and 6.8 mm).

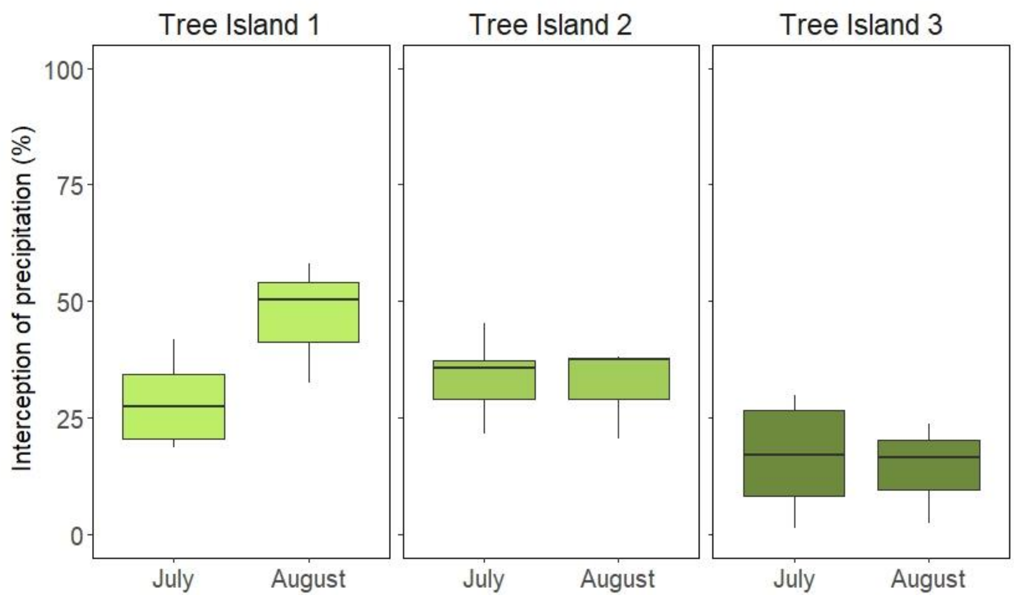

Figure 3-7. Interception of precipitation (%) for Tree Islands 1 (LAI= 6.0), 2 (LAI= 5.6) and 3 (LAI= 4.9) for the months of July and August, 2018 at FRS, Fortress Mountain, Alberta.

3.2 Evapotranspiration from tree patches

ET_C values were compared between different patch types and between the months of July and August. Atmometer values were greatest within the krummholz patches and lower within the tree islands (Figure 3-8). ET_C for the whole sampling period ranged from 0.2-3.6 mm/day for tree islands and 0.2-6.9 mm/day for krummholz. The average daily ET_C across the entire growing season, when considering all subplots, was approximately 2.3 mm/day (±1.3). The lowest daily ET_C of 0.2 mm/day was measured on July 24 within Tree Island 1 and in Krummholz 2 and 3 on July 12th and 22nd, whereas the highest daily ET_C was observed in Krummholz 1, on August 9th and 10th, where there was a total of 6.9 mm of water loss each day. A Shapiro-Wilkinson test was applied to the krummholz and tree island subplot ET_C rates to test for normality (i.e. a normal distribution) (α=0.05, p <0.05), followed by a test of variance (ANOVA). The mean daily ET_C was 2.2 mm at FRS. Within each individual subplot, mean ET_C was 1.5 mm/day for Tree Island 1, 1.3 mm/day for Tree Island 2, 1.4 mm/day for Tree Island 3, 2.9 mm/day for Krummholz 1, 3.0

mm/day for Krummholz 2 and 2.8 mm/day for Krummholz 3. There was a significant effect of subplot on ET_C ($F_{5,173}$ =13.9, p <0.05). Post hoc comparisons using the Tukey test (95% family-wise confidence level) found that there was a significant difference between Tree Island 1, 2 and 3 with Krummholz 1, 2 and 3 (p <0.05).

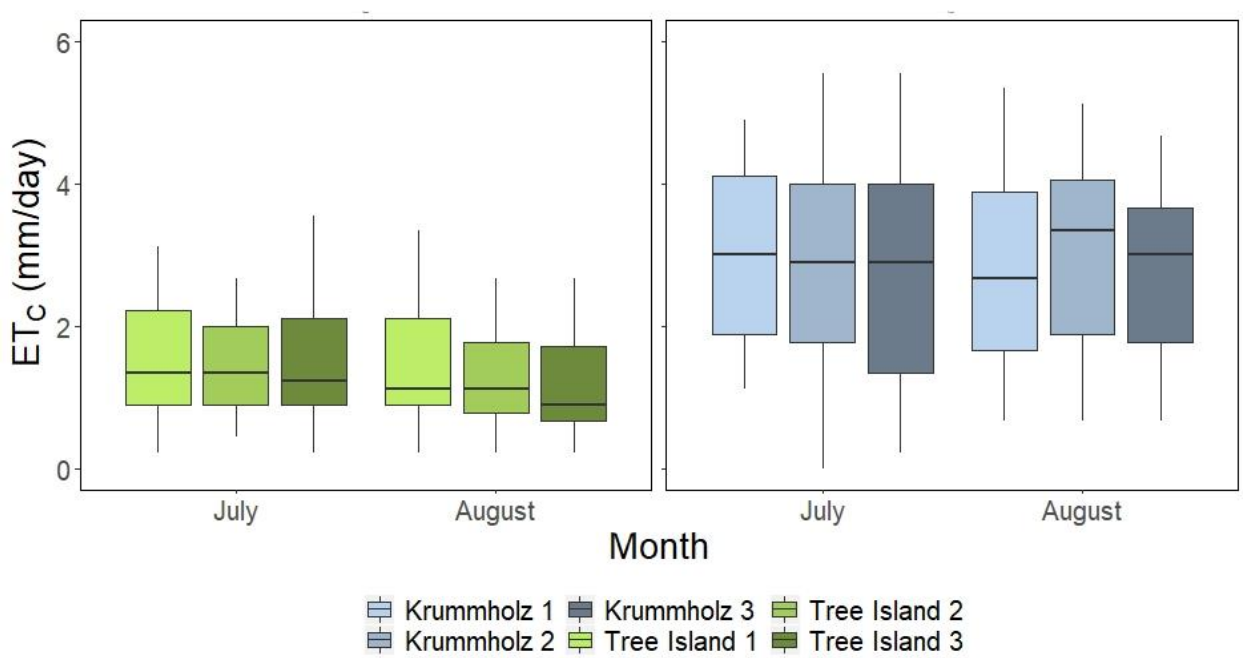

Figure 3-8. Comparing atmometer potential evapotranspiration (ET_C) rates (mm/day) for tree island and krummholz subplots in July and August 2018 at Fortress Ridge South.

ET_C and ET_O daily averages for each of the six patches were used to create site-specific K_C standards for each tree island and krummholz. Table 3-4 shows results for average daily ET_C and ET_O, as well as the calculated K_C values and resulting ET_A averages. K_C values for each of the six subplots were <1. This means that the FAO standard of K_C=1 would overestimate AET at FRS and thus, the new K_C values were used to adjust ET_C results in order to reduce any possible error when evaluating ET_A.

Table 3-4. Average daily ET_C, ET_O, ET_A (mm/day) and Kc values (dimensionless) for each of the six tree patches in July and August 2018 at Fortress Ridge South.

Tree Patch	ET_O (mm/day)	ET_C (mm/day)	K_C -	ET_A (mm/day)
Tree Island 1	1.6	1.5	0.98	1.5
Tree Island 2	1.5	1.3	0.88	1.2
Tree Island 3	1.5	1.4	0.93	1.3
Krummholz 1	3.4	2.9	0.87	2.6
Krummholz 2	3.6	3.0	0.84	2.6
Krummholz 3	3.7	2.8	0.76	2.1

ET_A was greatest within the krummholz subplots (Figure 3-9). Daily ET_A rates for krummholz and tree islands were relatively consistent throughout both observed months. Tree islands showed a range of 0.2 – 3.3 mm/day in ET_A, with a daily average of 1.3 mm/day (±0.8). Krummholz showed a range of 0.2 – 4.7 mm/day with the lowest daily ET_A occurring on July 24. The average daily rate of ET_A in the Krummholz subplots was 2.4 mm/day (±1.2). A normal distribution for ET_A values was shown using the Shapiro-Wilkinson test ($p < 0.05$) when testing differences in ET_A between krummholz and tree island subplots. A test of variance for the ET_A dataset was conducted by using a one-way ANOVA test. The mean ET_A at FRS was 1.9 mm/day when considering ET_A rates across each of the six subplots. Individually, mean ET_A for Tree Island 1 was 1.5 mm/day, 1.2 mm/day for Tree Island 2, 1.3 mm/day for Tree Island 3, 2.6 mm/day for Krummholz 1, 2.6 mm/day for Krummholz 2 and 2.1 mm/day for Krummholz 3. There was a significant effect between subplots on ET_A ($F_{5,173} = 11$, $p < 0.05$). Post hoc comparisons using the Tukey test found that there was a significant difference between Tree Island 1, 2 and 3 with Krummholz 1, 2 and 3 ($p < 0.05$), with an exception between Tree Island 1 and Krummholz 3 ($p = 0.2$).

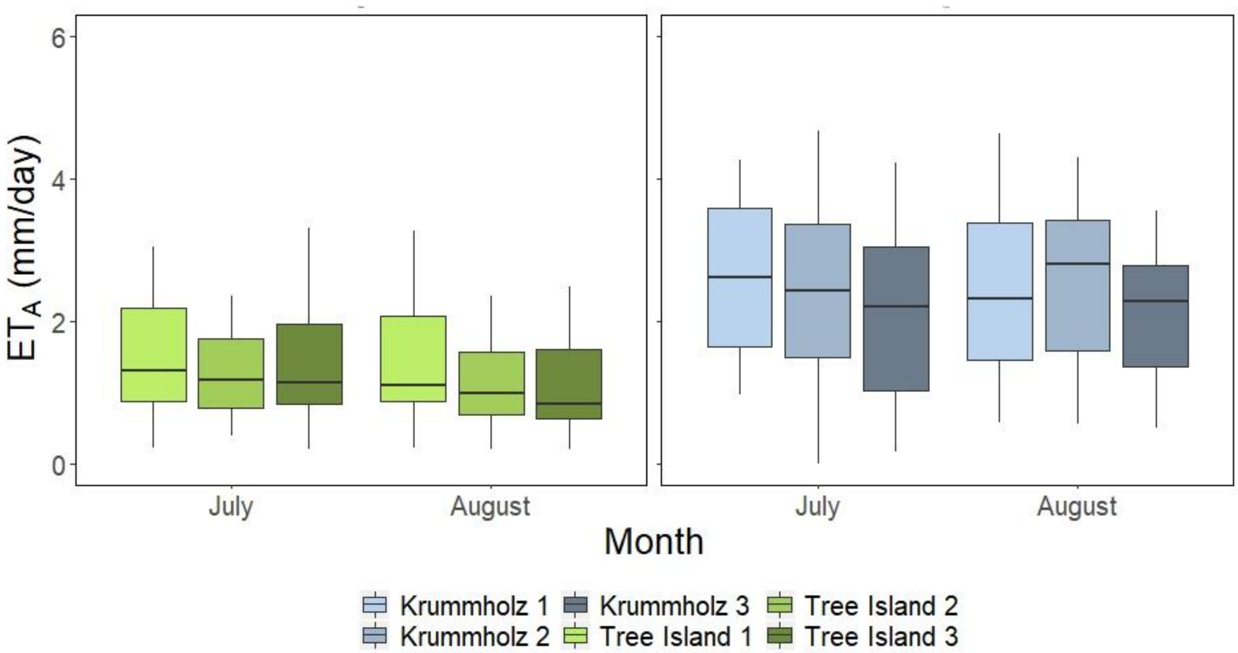

Figure 3-9. Comparing atmometer actual evapotranspiration (ET_A) rates (mm/day) for tree island and krummholz subplots in July and August 2018 at Fortress Ridge.

3.3 Effect of growing season hydrological fluxes on water balance

To summarize the changes in water availability at FRS, individual water balance estimates were conducted for tree islands and krummholz for the 2018 observed growing season (Figure 3-10). For both tree islands and krummholz, SWE was the greatest contributor of water supply to the patches, with values of 825 and 850 mm, respectively. In addition to SWE, precipitation (P) input was approximately 44 mm at FRS during the observed growing season. ET_A was the primary water loss for both tree islands (141 mm) and krummholz (229 mm). Canopy interception (I) measurements within the tree islands showed a high rate of canopy interception totaling 37.2 mm. Change in storage (ΔS) within the tree islands (30 cm ESD) was lower than the krummholz (40 cm ESD), with losses of approximately 32.2 and 42.4 mm during the observed growing season, respectively. Both tree islands and krummholz water balances showed substantial residual yields of water from equation 11. The tree island water balance resulted in a residual of 658 mm and the krummholz residual was approximately 622 mm, suggesting moisture surpluses within each patch and the potential for substantial outputs by horizontal fluxes that were not measured (i.e. runoff).

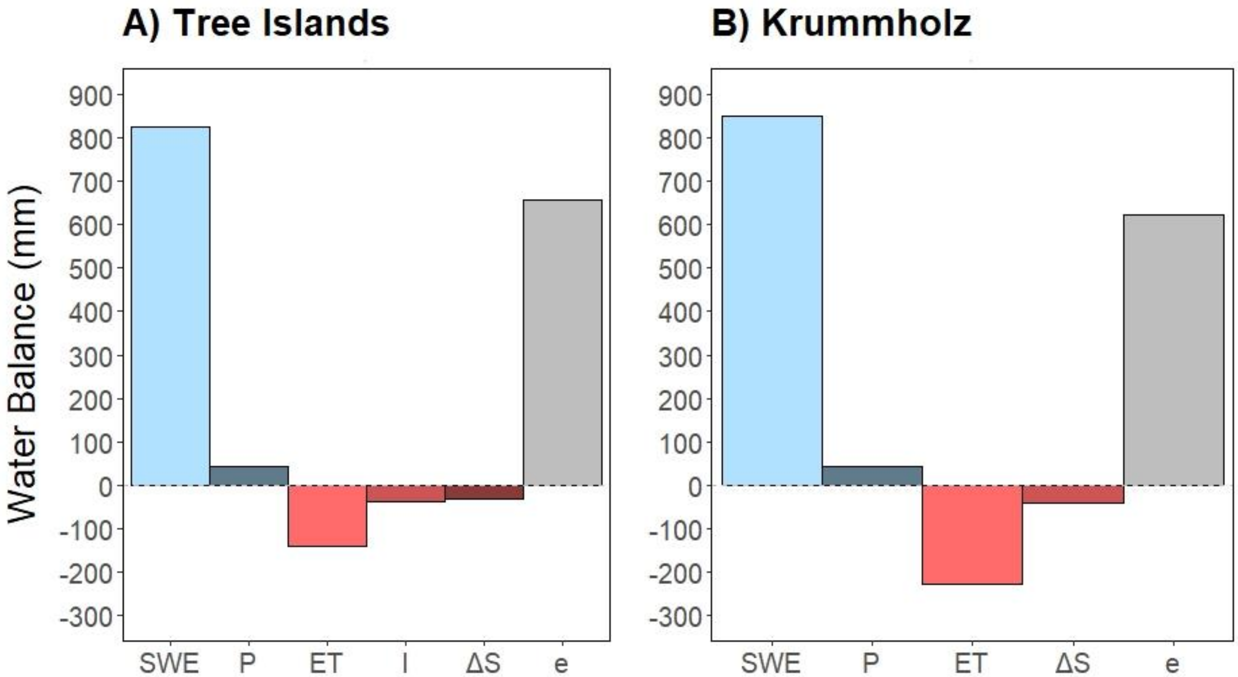

Figure 3-10. Water balances at FRS during the observed growing season (DOY 193 to 227) for A) Tree Islands and B) Krummholz. Hydrological inputs (blue) include peak snow water equivalent (SWE) and precipitation (P). Outputs (red) are actual ET (ET), interception (I) and change in storage (ΔS). Residuals (e) of the water balance (grey) are shown for each patch.

3.4 Evaluating meteorological controls on evapotranspiration

3.4.1 Fortress Ridge South Energy Partitioning

In order to assess energy fluxes within, and between tree islands and krummholz subplots, energy budgets were calculated for each tree patch and compared to variables such as the Bowen ratio (B) (Figure 3-11) from each subplot. Average daily Q* at FRS was 128.7 W/m^2 (±44.4 W/m^2) with daily peaks as high as 208.7 W/m^2. Average daily latent heat flux (Q_E) was 36.7 W/m^2 (±21.1 W/m^2) for the tree islands. Ground heat flux (Q_G) had minimal influence on the tree island energy balance, with an average daily value of 0.2 W/m^2. For the purpose of this study, sensible heat flux (Q_H) was computed as the residual of the energy balance equation (equation 2) and therefore follows an inverse trend with Q_E. Q_H showed greater average daily values than Q_E in the tree islands, where the daily mean was 91.9 W/m^2 (±33.1 W/m^2). Towards the end of the sampling season Krummholz Q_E was observed to peak slightly above Q* on day 222, where Q_E was 116.2 W/m^2 (Figure 3-11B). The average daily Q_E within the krummholz was 67.1 W/m^2 (±31.0 W/m^2). Krummholz Q_G rates were much greater than those of the tree island subplots with an average daily value of 8.1 W/m^2 (±7.9 W/m^2) (Figure 3-11B). Finally, Q_H within the krummholz was typically lower than Q_E, unlike the tree islands, with an average daily value of 53.4 W/m^2 (±32.1 W/m^2). The Bowen ratio was used to describe the relationship between sensible and latent heat fluxes and showed an average daily value of 3.5 (±2.6) for the tree islands and 1.1 (±1.0) for krummholz (Figure 3-11C).

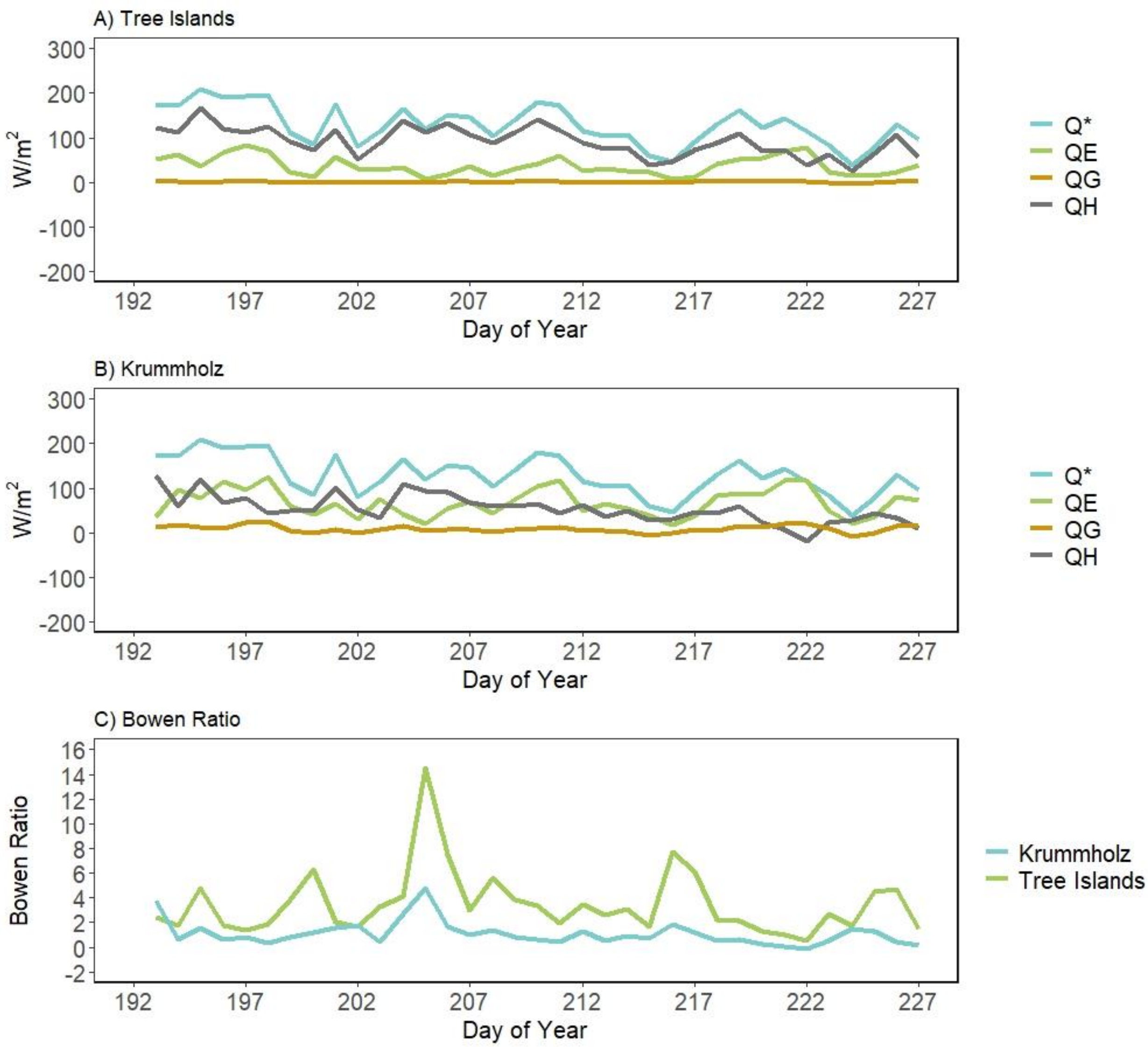

Figure 3-11. Energy budgets for A) Tree Islands and B) Krummholz subplots from July 12th (DOY 193) to August 15th (DOY 227), 2018 at FRS. Energy portioned by: net radiation (Q*) (blue), latent heat (QE) (green), ground heat flux (QG) (yellow) and sensible heat (QH). Bowen ratios (C) for Tree Islands (green) and Krummholz (blue) subplots from July 12th (DOY 193) to August 15th (DOY 227), 2018 at FRS.

3.4.2 Meteorological controls on tree islands and krummholz

Vapour pressure deficits (VPD) (Figure 3-12) were calculated for each tree islands and krummholz. Generally, all tree islands followed the same trends, with two notable VPD peaks observed towards the beginning and end of the growing season. Average daily VPD for Tree Island 1 was 0.7 kPa, 0.6 kPa for Tree Island 2 and 0.7 kPa for Tree Island 3. VPD for the krummholz showed very similar results to that of the tree island subplots. Average VPD for each krummholz was approximately 0.7 kPa.

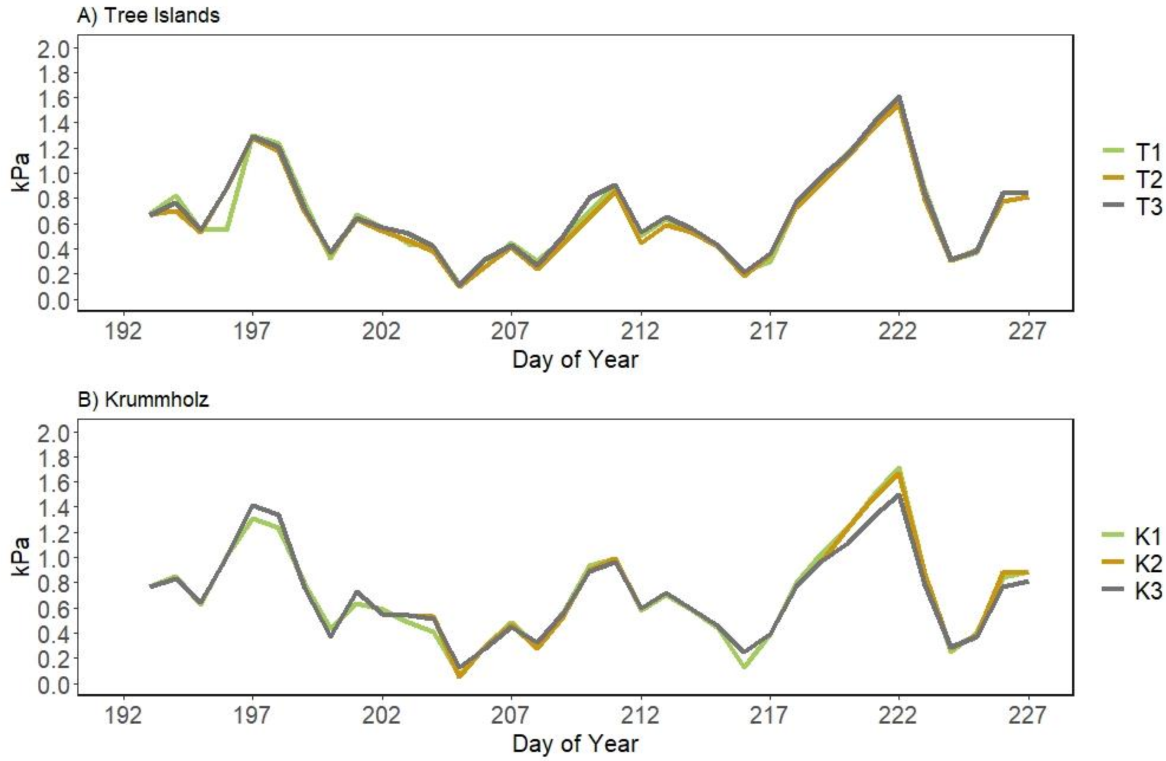

Figure 3-12. Vapour pressure deficits (kPa) for A) Tree Islands and B) Krummholz subplots from July 12th (DOY 193) to August 15th (DOY 227), 2018 at FRS.

Average daily wind speed results showed weak correlations with ET_A results across all subplots ($R^2 \leq 0.1$) (Figure 3-13). Tree Islands 2 correlations between wind speed and ET_A were statistically significant ($p < 0.05$). Tree Island 1, 3, as well as all the krummholz subplots were not statistically significant ($p > 0.05$) when correlating wind speed and ET_A.

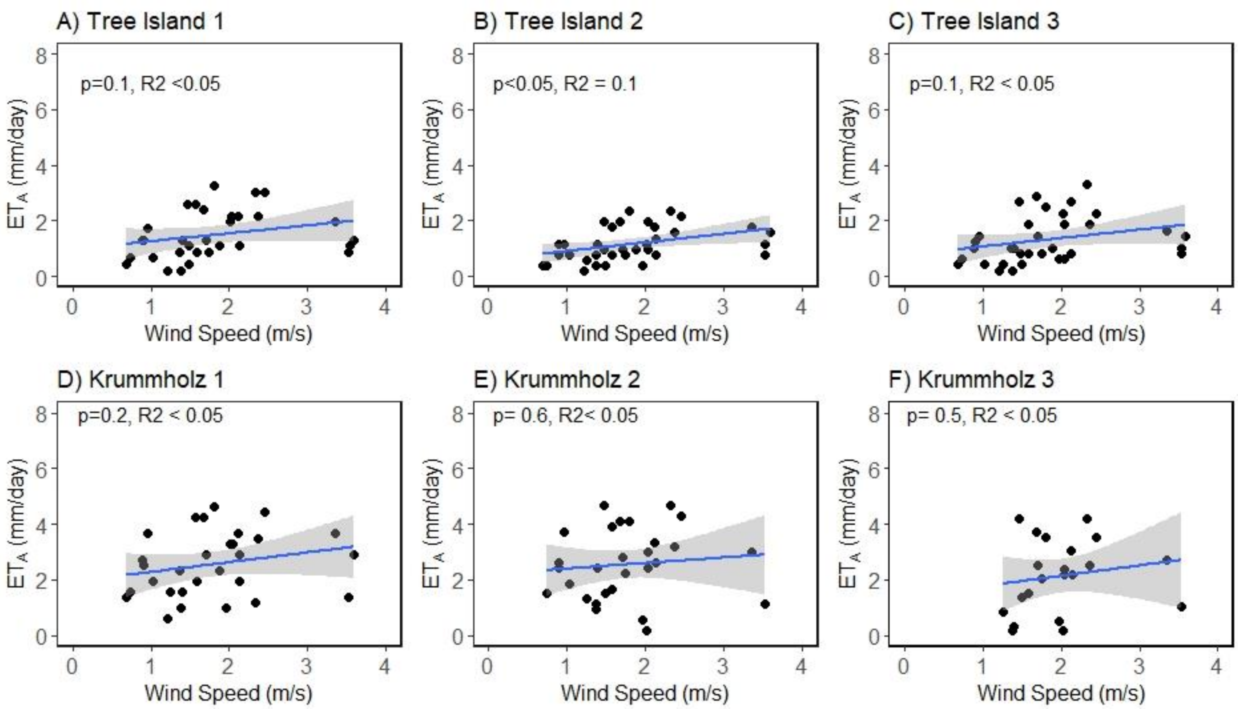

Figure 3-13. Regressions showing correlations between daily ET_A (mm/day) and average daily wind speed (m/s) in each subplot at FRS, Fortress Mountain, Alberta.

To further analyze the relationship between VPD and ET_A relationship, correlations from a linear regression model for each subplot were conducted (Figure 3-14). Results show that there is a strong, positive, and statistically significant relationship between VPD and ET_A for all subplots. Notably, Tree Island 1 and Krummholz 3 show the strongest positive correlation (R^2=0.7). Similar relationships were shown in Tree Island 2, Krummholz 1 and 2, which had a correlation with a R^2= 0.6. Tree Island 3 had the weakest correlation between VPD and ET_A (R^2= 0.5).

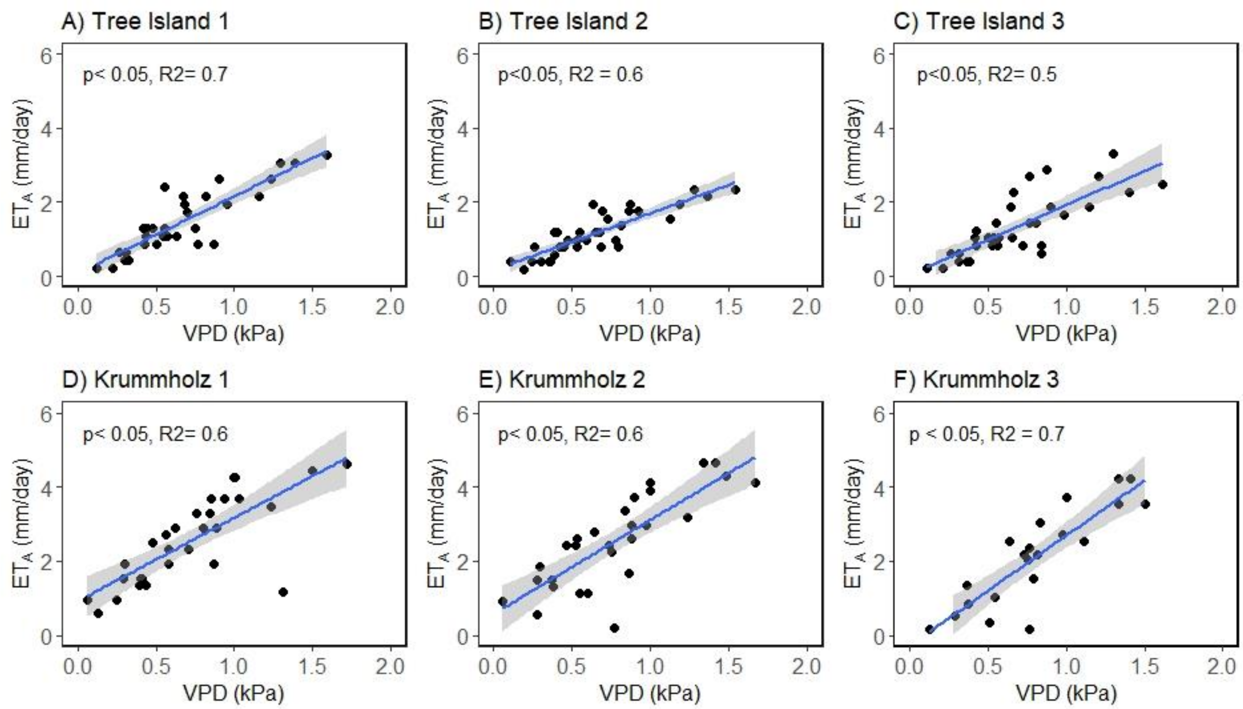

Figure 3-14. Regressions comparing daily Atmometer ET (ET_A) and daily VPD rates within each tree island and krummholz subplot of FRS, Fortress Mountain, Alberta.

Chapter 4: Discussion

4.1 Quantifying evapotranspiration of tree islands and krummholz

4.1.1 Evapotranspiration from atmometer ET gauges

As climate change influences the progression of trees to higher elevations, the development of new tree patches, krummholz and tree islands, threatens the storage of water in subalpine systems and to their downstream users. It is anticipated that the migration and establishment of coniferous vegetation into subalpine meadows will increase local ET rates during the growing season, leading to less available water to streamflow runoff, ultimately reducing surface-water supplies downstream (Goulden & Bales, 2014). In order to quantify the effects of treeline expansion on ET, atmometers were positioned within three tree islands and three krummholz on FRS. Atmometers were set a 1 m in height, which was considered to be approximately the mid-canopy of both krummholz and tree islands, where average canopy heights were 2.2 and 3.1 m, respectively. At the chosen height ET_C (and adjusted ET_A) readings would represent inner canopy micrometeorological effects on ET, such as wind or VPD, that would otherwise not be possible if atmometers were positioned within the subcanopy (matted vegetation lower to the ground not representative of the whole canopy) or upper-canopy (increased exposure reduces potential to observe vegetative controls on ET, i.e. sheltering).

Throughout the growing season ET_C and ET_A was observed to be greater in the krummholz patches than the tree islands (Figures 3-8 & 3-9). Total ET_C for the observed growing season was approximately 229 mm for krummholz and 141 mm for tree islands. ET_A showed similar results of 190 mm for krummholz and 131 mm for tree islands. These results are contrary to the initial theories, as it was perceived that with larger tree patches, increased density and greater height and

DBH classes, tree islands would exhibit a higher rate of ET than the krummholz, which were smaller in size, less dense, and more fragmented (Tables 3-2 and 3-3).

Marenholtz et al. (2010) measured the difference in evaporative demand between varying degrees of tree harvest application using atmometers and found that ET increased as harvest treatments resulted in more open canopy exposure. This suggests a “clothesline effect” on ET, where sensible heat travels horizontally (advection) by wind through a canopy of varying heights (heterogenous vegetation cover), leading to irregular ET that is higher in more exposed patches (Chang, 1968; Chorley, 2019; Kirkham, 2014; Allen et al., 1998). Similarly, at FRS vegetation cover is heterogenous as krummholz are shorter than surrounding tree islands. Krummholz also have smaller basal areas and canopy densities than tree islands which would increase edge and subcanopy exposure. The increase in exposure of krummholz to meteorological influences such as sensible heat transfer by wind would decrease the RH levels within their canopies, increasing patch vapour pressure deficits and atmospheric demand for water, ultimately leading to increased stomatal conductance to vapour pressure diffusion, or transpiration (Carter et al., 1988; McVicar et al., 2012a, 2012b; McMahon et al., 2013; Ben Neriah et al., 2014).

Wind typically reduces air temperatures by turbulent mixing (Holtmeier & Broll, 2010). However, krummholz grow low to the ground allowing them to take advantage of near-surface temperature gradients. Along with their reduced surface roughness (compared to the larger islands), turbulent mixing would be reduced, as would krummholz heat loss to the atmosphere, increasing their canopy temperature (Holtmeier & Broll, 2010; Wilson et al., 1987). Tree islands, which produce more vertical stems than krummholz would likely be subjected to increased turbulent mixing at mid and upper canopy heights, reducing patch temperature and stomatal conductance (i.e. closure of stomatal pores), leading to less transpiration from the islands (Lovett

& Reiners, 1986). This would increase the evaporative demand of krummholz and therefore, allow them to exhibit higher rates of ET than the tree islands. Ultimately, the spatial distribution of ET between krummholz and tree islands at FRS was greatest within krummholz, suggesting that increased patch size and density has less of a control on local ET at FRS. Instead, micrometeorological controls, such as wind, temperature gradients and VPD could control increases in transpiration in shorter, more exposed patches.

4.1.2 The effect of canopy interception on evaporation in tree islands

Increased interception of precipitation is more likely to occur in the tree islands than the krummholz due to their greater canopy densities, heights and LAI values (Tables 3-2 and 3-3) (Zwieback et al., 2019). For the purpose of this study it was assumed that all intercepted precipitation during the growing season was readily available for evaporation and did not consider input partitioning to the canopy water balance by stemflow or drip. Previous studies in alpine environments with fragmented vegetation including shrub species have shown rates of interception loss between 0-50% (Uehara & Kume, 2012; Zwieback et al., 2019). At FRS, tree islands were estimated to control between 2-58% of interception loss between the months of July and August. This suggests that canopy interception is an important control on the water balance at FRS. The water balance within the tree islands supported these findings, where approximately 85% of the rainfall during the observed growing season (DOY 193 - 227) was intercepted by the tree islands (Figure 3-10). Increased interception loss would result in a decrease of water available to ground surface infiltration, limiting the water available by precipitation to be taken up by the plants during the growing season.

Canopy interception at FRS increases within tree islands of greater tree density and LAI values, however, shows no correlation to increased canopy height. Interception was greatest in

Tree Islands 1 and 2, and notably lower in Tree Island 3 (Figure 3-7). Tree Islands 1 and 2 intercepted between 19 – 58% of precipitation during the growing season, whereas Tree Island 3, which had the greatest observed tree heights at FRS, showed interception rates between 2 – 29% (Figure 3-7). Tree Islands 1 and 2 showed densities of 5.5 and 2.3 trees/m^2, respectively, whereas Tree Island 3 showed a much lower density of 0.8 trees/m^2 (Table 3-3). In addition, LAI values of 6.0 for Tree Island 1 and 5.6 for Tree Island 2 were notably higher than Tree Island 3 (4.9) (Table 3-3). Therefore, at FRS vegetation characteristic that control interception include tree density and LAI and not tree height.

Canopy interception within tree islands would likely be subject to variability by tree height, wind direction, rainfall intensity, and vertical density within patches. Rain shadows within tree islands are likely to occur when vertical stems shelter leeward vegetation of reduced height (Zwieback et al., 2019). Because of this, it is unlikely that the high rates of interception loss at FRS are uniform within and between patches. Tree Islands 1 and 2 showed defined understories at about 30 cm above the ground surface, of intertwined offshoots/branches. This growth form was not present in Tree Island 3, likely due to its location further down the slope, where there was less exposure because of sheltering from surrounding tree islands, reducing the need for denser understory growth to protect against high windspeeds. Therefore, it is observed that when increased understory density was associated to higher elevation and exposure, interception loss effectively increased.

Other work in a subalpine krummholz zone showed interception loss was highly variable (19 – 65 % of gross rainfall) due to stemflow dynamics (difficult to measure due to angled growth), interception of occult precipitation (fog and clouds) and wind driven rainfall resulting in heterogenous rainfall cover (Köck et al., 2003; Herwitz & Slye, 1995). For this reason, the high proportion of interception observed by the tree island water balance could be a combined influence of measured rainfall and unmeasured influences of fog or wind driven rainfall. Results at FRS showed that canopy interception within a subalpine krummholz zone was not only influenced by tree growth structure, but also by meteorological influences. Therefore, interception within tree islands is likely to have a substantial effect on patch evaporation loss, limiting the water available for infiltration beneath the tree islands at FRS.

4.2 Assessing interactions between evapotranspiration and environmental controls

4.2.1 Snow and soil moisture influences on changes in evapotranspiration

Snow surveys conducted from the first snowfall in October 2017, through to snowmelt in the spring of 2018, showed high snow depth (Figure 3-3) and SWE (Figure 3-4) for both the tree island and krummholz subplots. Tree islands showed a greater snow depth and SWE compared to krummholz for most of the winter snow accumulation period. However, peak SWE was greater for the krummholz (850 mm) than the tree islands (825 mm). As temperatures began to rise and snowmelt followed, krummholz retained their snowpack for longer than the tree islands (Figure 3-4). These trends are likely associated with snow redistribution patterns and the sheltering effects of tree patches (Pomeroy & Brun, 2001; Pomeroy and Gray, 1990; Budd et al., 1966; Pomeroy and Male, 1992; MacDonald et al., 2010).

A study by Wayand et al. (2018) addressed snow cover indices for mountain regions that are dominated by snow redistribution patterns, and found that snow redistribution from exposed zones (i.e. ridge tops) by south-westerly winter winds caused snow drifts to accumulate within topographical features and vegetation patches (i.e. krummholz or tree islands). Additionally, it was determined that once snow is distributed within these vegetation features, snow erosion and distribution is reduced, meaning that snow becomes sheltered during the winter season once it is relocated to these patches (Ménard et al., 2014; Wayand et al., 2018). This suggests that snow redistributed by wind from upslope on Fortress Ridge (low surface roughness) would accumulate downwind (Figure 3-2) into the tree islands and krummholz patches (greater surface roughness) at FRS.

During the winter snow accumulation period south-westerly winds dominated FRS, which likely caused the redistribution of snow from Fortress Ridge Top to the krummholz and tree island downslope at FRS. Due to the nature of the krummholz, which typically grow between 1-3 m tall, snow depth exceeded their height and krummholz no longer became an influence on sheltering after burial. However, the tree islands, which largely persist at least partially above the snowpack, continued to exhibit sheltering properties, allowing them to continue to accumulate windblown snow from exposed sites, including the buried krummholz.

Melt occurred at an increased rate in the tree islands compared to krummholz. Coniferous trees often produce a spatial signature, called a “tree well”, which is a melt formation around the base on the tree trunk, during the snowmelt period (Faria et al., 2000; Musselman et al., 2008). Tree wells occur due to snow interception and sloughing, causing lower accumulation or density, as well as from variability in sublimation and snowmelt by enhanced incident thermal radiation from the tree trunk to the snowpack (Sicart et al., 2004, Musselman et al., 2008). Tree wells were present at FRS, most notably around the tree islands. Due to the effect of shortwave radiation from the uncovered trees to the snowpack, tree islands showed greater melt rates during the spring, compared to the krummholz which would not undergo the same micrometeorological flux until part-way through the melt season, once exposed to the atmosphere.

4.2.2 The effect of snowmelt on soil moisture and tree uptake at FRS

Krummholz and tree islands rely on a substantial winter snowpack to contribute to their spring and summer soil moisture supply (Germino & Smith, 1999; Malanson et al., 2007; Seastedt, & Adams, 2001). A well-defined snowpack was prominent ahead of the 2018 snowmelt period, which was associated with a high SWE content for both the krummholz and tree islands. Water balances constructed for the tree islands and krummholz strongly suggest that SWE was the main contributor of water to the patches at FRS (Figure 3-10). However, substantial residual yields were noted within both patches, suggesting hydrological controls, such as runoff likely controlled the flux of water out the site. Previous studies at Fortress Mountain showed that soils typically remain frozen and saturated for the duration of the winter (Smith et al., 2017). When these soil conditions are paired with the effect of sloping terrain, rapid meltwater runoff takes place by way of drainage channels, which is estimated to reduce the change in soil moisture storage during the melt period (Smith et al., 2017). However, during the snowmelt period at FRS in 2018, VWC was not observed to be frozen and/or saturated during the spring melt period (Figures 3-5, 3-6, Table 3-1 Porosity). Therefore, residual yield values from the water balances were likely partitioned to both runoff (effect of slope still present) and infiltration into the soil, where it could be taken up by the roots of the trees and partitioned to transpiration losses during the growing season.

Moisture supplies within both tree islands and krummholz were typically the greatest at the beginning of the growing season, up until the beginning of July when small remnant snow patches were still observed within the krummholz but not within tree islands. An increase in soil moisture supply at the beginning of the sampling period from the associated snowpack, in addition to increased air temperature, could be related to the observed increase in ET_A within both the tree islands and krummholz from July 13th to 17th, 2018 (DOY 194 to 198) onwards. Molotch et al.

(2009) assessed the influences of ecohydrological controls on snowmelt partitioning and found the in a mixed-conifer subalpine zone, latent heat flux increased evaporative loss of soil moisture (by 28%) to the atmosphere when an earlier onset of snowmelt infiltration was evident. Krummholz ET_A was notably greater than tree island ET_A during the start of the growing season, which once again can be attributed to prolonged snowmelt infiltration in the krummholz. However, differences in ET_A may also be associated to canopy height. A study that focused on the soil microclimate of tree islands found that increased canopy and tree height reduced the rate of surface soil drying, compared to their surrounding meadows (Van Miegroet et al., 2000). The tree islands increased shading effects to the soils beneath them and to their meadow edges, which received shadow protection from drying (Van Miegroet et al., 2000). These outcomes could support findings at FRS where tree islands showed reduced ET_A compared to krummholz. Tree islands at FRS are greater in height compared to krummholz, which would increase the effect of shading on reduced soil exposure and dry-out. The krummholz, which are shorter and more exposed to incoming solar radiation would therefore be more susceptible to soil evaporation losses.

Once the snowpack had fully diminished (approximately mid-June), and the soil temperatures began to rise, VWC showed a steady decrease in both krummholz and tree islands. Around day 185 soil moisture had shown a steady reduction in both patches within the rooting zone, approximately the top 40 cm of the soil (Figures 3-5 and 3-6). These findings were supported by the water balances constructed for the tree islands and krummholz. ΔS was reduced by approximately 32 mm in the tree islands and 42 mm in the krummholz between July and August (Figure 3-10). As VWC was reduced towards the wilting point, soil moisture was expected to limit the availability of water to ET_A. Coniferous species possess adaptive traits which allow them to have immense control of their stomata (Brodribb et al., 2014). When soil moisture supply is limited or reduced, conifers adapt by closing their stomata, which reduces transpiration loss from the canopy (Brodribb et al., 2014). Therefore, when ET_A declined between July and August, most notably in the tree islands, this was likely evidence of the limitation of soil moisture on transpiration from the patches.

4.2.3 Energy partitioning effects on evapotranspiration

The partitioning of energy by way of net radiation, latent heat, sensible heat and ground heat, is important to understanding the vertical transfer of energy and how it affects different microclimates and ultimately rates of ET in tree islands and krummholz Subalpine ecosystems are especially difficult to evaluate, due to their spatial and temporal variability in tree stand structure, air temperature, as well as the large wind gusts or eddies that move through these environments (Black & Kelliher, 1989).

Daily sensible heat measurements were consistently greater than latent heat fluxes within the tree islands (Figure 3-11 A). A daily average Bowen ratio of 3.5 supports the findings that within the tree islands, sensible heat partitioning exceeded latent heat (Figure 3-11 C). Energy partitioning within the krummholz however, showed greater variability in fluxing (Figure 3-11 B). The average Q_E for krummholz (67.1 W/m^2) was much greater than that of the tree islands (36.7 W/m^2) at FRS. Increases in latent heat fluxing within the krummholz were observed when sensible heat was reduced, or directed towards the surface. On day 222 an event where $Q_H < 0$ was noted. When sensible heat is partitioned towards the surface, and latent heat to the atmosphere, evidence of advection is present (Spronken-Smith, 2000). This is especially true on day 222 where $Q_E/Q^* > 1.0$, which quantifies the consumption of sensible heat at the soil surface (Verma & Rosenberg, 1997; Gerosa, 2011). The quantification of sensible heat advection within the krummholz subplots is supported by the spatial heterogeneity between increased moisture availability compared to their surrounding meadow or tree island subplots (Figure 3-10). The transport of drier air downslope, from open meadows or tree islands, by south-westerly winds (Figure 3-2), increases the amount of sensible heat partitioned downward over the moisture rich krummholz, increasing local ET_A, and supporting evidence of an oasis-effect control on ET at FRS (McIlroy & Angus, 1964). However, oasis effect advection has been found to decrease with fetch distance (Oke, 1987; Park & Paw, 2004; Spronken-Smith, 2000). As sensible heat moves downwind, differences in surface roughness and temperature gradients reduce the effect of horizontal advection (Oke, 1987). At FRS, within the krummholz, ET_A ranges decreased at lower elevations from Krummholz 1 to Krummholz 3 (Figure 3-9). The reduction in ET_A downslope toward the natural treeline supports the role of oasis-effect and its control on ET in highly heterogenous landscapes.

4.2.4 Vapour Pressure Deficit control on evapotranspiration

As VPD increases so too does the atmospheric demand for water (Massmann et al., 2018; Monteith, 1965; Penman, 1948). However, a negative relationship between ET and VPD is possible if vegetation is capable of closing their stomata to reduce water loss during periods of stress (Massmann et al., 2018). Such physiological trends have already been suggested as a control on ET within tree islands. Turbulent mixing could increase plant stress by decreasing temperature gradients in the mid and upper canopies of the islands, leading to a decrease in stomatal conductance and transpiration. However, at FRS VPD showed trends that were similar in agreement to increases and decreases in ET_A (Figure 3-14). Despite notable differences in canopy growth and tree structure between the tree islands and the krummholz, VPD showed similar trends and strong relationships with ET_A, showing that VPD within canopies is likely a dominant control on AET during the growing season (Figures 3-12 and 3-14).

A previous study on the effects of boreal harvesting on microscale ET also used atmometers to collect ET data. This study suggested that the increase of wind exposure and VPD (i.e. atmometers placed above the canopy) to atmometers within canopies would result in greater ET loss (Marenholtz et al., 2010). When assessing the effect of windspeed on ET_A at FRS, krummholz and tree islands showed weak relationships (Figure 3-13). Notably, the krummholz, despite having a weak relationship between windspeed and ET_A were still statistically significant (p <0.05). This was also true for Tree Islands 1 and 3, and not Tree Island 2. The growth adaptations that cause krummholz to be sparse and low growing could contribute to more exposure of the soil surface to high winds (Bowers & Bailey, 1989; Black & Kelliher, 1989). Despite an increase in exposure, atmospheric conditions, such as VPD will be maintained under windier (less sheltered) conditions present for the krummholz (average of 0.8 kPa). In tree islands, variable aerodynamic resistance and increased sheltering due to denser and taller canopies could be leading to inconsistent ET, where it is likely to rise and fall depending on the effect of windspeed to the canopy. Higher windspeeds can increase the deficit by reducing aerodynamic resistance and bringing drier air to a site at a higher rate, ultimately increasing VPD and ET, which is what likely is occurring at FRS, based on the overall strong relationship between VPD and ET.

The relationship between VPD and ET is important to continue monitoring as climate change is expected in increase air temperatures and reduce RH (i.e. increased VPD), making areas such as Canada's Rocky Mountains highly susceptible to increased water loss, and associated drought or wildfire disturbances (Byrne & O'Gorman, 2013).

4.3 Summary of relationships between evapotranspiration and dominant controls

Dominant controls at FRS within tree islands and krummholz were assessed in order to determine relationships between ET and snow, micrometeorology and vegetation. The prominent controls included snowpack (i.e. depth and SWE), soil moisture, tree physiology and growth structure, canopy interception, energy partitioning, as well as wind and VPD (Figure 4-1).

Tree islands are able to extend above the annual snowpack. Because of this, tree islands can increase the collection of windblown snow within and around of edges of their canopies. The taller stems which protrude from the snowpack are capable of collecting intercepted snow and thus, increasing sublimation rates during the winter, increasing annual ET. Krummholz, which quickly become buried by the snowpack are incapable of fostering redistributed snow and do not contribute to winter sublimation.

Snow depth and SWE from snowpacks remaining at FRS during the snowmelt period provided the tree islands and krummholz with a high moisture supply during the early growing season, which was associated with higher rates of ET_A in the krummholz and tree islands. Increased moisture by melt water earlier in the growing season was more likely to be evaporated from the exposed soil of the krummholz, increasing ground surface evaporation and ET_A compared to the more sheltered tree islands.

Tree physiology and canopy structure were also contributing factors to increases or decreases in ET at FRS. Within the tree islands, temperature gradients were suggested to decrease air temperature within the mid and upper canopies, as needles were further away from the higher temperature gradient closer to the ground surface. When the needles of the tree islands undergo more stress due to reduced air temperatures, stomatal conductance is decreased, reducing canopy transpiration. Krummholz, which grow considerably short and smaller than tree islands are subject to increased canopy exposure to wind and solar radiation, which is likely to increase ET within the entire canopy.

Figure 4-1. Summary of controls on evapotranspiration (ET) for tree islands and krummholz at FRS. Controls influence ET, plant surface evaporation (E_S), ground surface evaporation (E_G) and transpiration (T).

Canopy interception was monitored within the tree islands at FRS. Increased LAI and canopy density was associated to increased canopy interception within the tree islands, which would control the increase of evaporation from the surface of the trees. For tree islands, canopy height was not associated to increase ET. Instead an increase in subcanopy branch density was suggested to contribute to higher interception and evaporation. Krummholz had lower LAI values and were less dense, because of this it is likely that they would not contribute to high rates of canopy interception and thus would have less of a control on surface evaporation.

Within the tree islands daily sensible heat values were consistently greater than latent heat, reducing the effect of energy partitioning on ET_A. However, within the krummholz, latent heat fluxing above sensible heat was common, and at times peaked above available net radiation. These results suggested that ET_A within the krummholz was being controlled by advection by an oasis-effect. In addition, trends supporting the effect of advection by clothesline-effect ET were also noted. The spatial heterogeneity at FRS is likely to increase the partitioning of sensible heat from drier and taller tree islands to shorter and wetter krummholz.

VPD within the canopies of the tree islands and krummholz was a strong control on ET_A. In the tree islands, an increase in tree density led to greater sheltering potential for the trees, which reduced effect of windspeed on inner-canopy VPD. However, in the krummholz, where trees are more exposed to the effect of wind, VPD consistently showed a strong relationship with ET_A. The increase in exposure to wind for the krummholz likely led to the flux of dry air into the canopy, reducing canopy RH levels and increasing the evaporative demand within the canopy.

Chapter 5: Conclusions, limitations and suggestions for future research

5.1 Conclusions

The migration of the treeline to higher elevations by the development of fragmented tree patches called tree islands and krummholz has the potential to impact local hydrology by influencing changes to ET. In order to assess the role of tree islands and krummholz on ET, a study was conducted at FRS to determine the evaporative demand of these patches, as well as the dominant controls that exist to ET on a subalpine ridge slope.

The first objective of this study was to determine the spatial variability in ET by assessing the evaporative demand of krummholz and tree islands at FRS in the summer of 2018. Ultimately it was determined that krummholz at Fortress Ridge South (FRS) displayed higher rates of ET than tree islands. Krummholz, which are shorter and more exposed than tree islands, were observed to have an increase in canopy ET as a response to increased soil evaporation, the effect of wind and VPD on transpiration, and by the advection of sensible heat resulting in oasis-effect and clothesline-effect to ET. Krummholz were not observed to influence ET in the winter, as they are subject to burial by the annual snowpack. Interception and the role of evaporation from the surface of the krummholz was also less likely to control ET in these patches.

Tree islands, which are partially exposed in the winter, are more likely to increase annual ET by sublimation in the winter and aid in the collection of windblown snow, which contributes to a substantial water supply to both the tree islands and the krummholz during the spring melt period. The shading properties of tree islands shelter the soil beneath them and reduces soil water evaporation. As well, tree islands are likely to have a greater control over transpiration losses, as cooler temperature and higher wind gradients in the mid and upper canopies would result in the reduction of stomatal conductance in the islands. Tree islands are likely to undergo a great amount of water loss by the evaporation of intercepted precipitation, due to their increased canopy size. Tree island energy partitioning showed a consistent increase of sensible heat fluxing above latent heat fluxing. Though this may not have significant influence over the increase of ET within their own canopies, it is likely that the increase of sensible heat within the taller and warmer tree islands is advected toward the shorter and moisture rich krummholz.

Water balances for the tree islands and krummholz showed that growing season water supply is controlled by the substantial amount of water contributed by the winter snowpack. Tree islands aid in the capture of redistributed snow which would reduce the accumulation of snow to the forests below the treeline. Water budgets for krummholz and tree islands received minimal precipitation inputs for the remainder of the growing season, accompanied by gradual reductions in soil moisture and high ET. Significant residual water yields suggest that a substantial amount of water is lost to runoff earlier in the year, and that the remainder is supplied to the patches by infiltration. Currently, there is limited evidence to suggest that tree islands and krummholz ET rates are limited by moisture availability. However, there may already be a reduction in soil water partitioned downslope by the reduction of redistributed snow. As climate change is expected to increase air temperatures and reduce the amount of precipitation falling as snow, tree islands and krummholz may be impacted by a reduction in water supply (Fang & Pomeroy, 2020). Water supply to downstream ecosystems and communities is of critical importance, especially as populations are expected to rise. Regional general circulation models predict that temperature warming caused by climate change could result in an increase in evaporation by up to 55% within this area, exceeding precipitation inputs (Thornthwaite, 1948). With the additional concern that tree islands and krummholz may increase water loss by ET at higher rates than prior to their development, it is encouraged that tree island and krummholz ET rates are continued to be monitored in order to address the effect of climate change on subalpine hydrology.

5.2 Project limitations and suggestions for future research

Limitations for this study were primarily associated to time constraints and equipment malfunction. Due to a requirement that atmometers preform under conditions where air temperatures remain above freezing, equipment could not be deployed for the entire length of the growing season. At subalpine elevations where overnight lows below 0°C are common, the use of atmometers was difficult. Based on this study, it is recommended that when monitoring ET at higher elevations or in cold regions using atmometers, that the atmometers are paired with additional methods such as the use of evaporation pans or eddy covariance towers.

In this study, surface and subsurface processes including soil water infiltration or incoming and outgoing water runoff, were not included due to logistical constraints. Due to these limitations, estimating soil water storage and calculating water budgets were restricted by the potential for error. It is recommended that in future research or in similar studies, researchers develop methodologies to address these aspects of the hydrological cycle in order to further classify the influence successional tree patches may have on water supply and storage in mountain regions.

Results from this study include data from a relatively small section of one forest transition zone on a subalpine ridge, which may not be representative of the entire subalpine region of Canada's Rocky Mountains. Future research is necessary to address the spatial variability in ET between tree islands, krummholz, and perhaps other microclimates within other locations at the subalpine and alpine elevational range. The importance of long-term monitoring, when addressing interactions between trees and water loss, is of value in order to draw relationships between site data and climate change patterns. This is especially important as climate change projections are expected to greatly influence hydroecological functions within Canada's Rocky Mountains.

5.3 Significance of research

As climate change becomes more prevalent in Canada's Rocky Mountains, air temperatures will continue to rise, snow reserves and glaciers will diminish, and the establishment of trees at higher elevations is an anticipated ecological shift in the subalpine and alpine zones. Krummholz and tree islands can be viewed as a natural response to climate change. However, despite the unique nature of these successional tree patches, little research has been conducted on what relationships are present between them and the hydrological cycle, especially during periods of warmer temperatures (growing season). Tree islands and krummholz have the ability to increase local snow accumulation, which increases soil water availability within the patches, which may help offset the effect of water loss that tree islands and krummholz have by increasing ET. This study aimed to reduce knowledge gaps on subalpine hydrology, by addressing how krummholz and tree islands impact the local hydrology by water loss through ET during the growing season. Ultimately it was determined that krummholz exhibit higher rates of ET, which is supported by their proximity to tree islands (i.e. clothesline and oasis-effect). With the influx of water supply from the substantial winter snowpack, tree islands and krummholz currently do not seem to negatively effect the local water balance at FRS. However, continued research is necessary to address the effects of climate change on these patches and their ability to encourage water deficits in subalpine ecosystems.

References

Alberta Parks. (1999). Tracking the Trees and Shrubs of Kananaskis Country: Identification Key. Alberta Environment.

Alberta Parks. (2015). Natural Regions and Subregions of Alberta. A Framework for Alberta's Parks. Alberta Tourism, Parks and Recreation. Edmonton, Alberta. 72pp.

ASCA. (2020). Treaty Land Acknowledgement. Alberta School Councils' Association. Alberta Education. Edmonton, Alberta.

Albertsen, E., Harper, K. A., De Fields, D., & Giguère, N. (2014). Structure and Composition of Tree Islands and Krummholz within the Forest-Tundra Ecotone in Central and Eastern Canada. *Arctic*, 396-406.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Chapter 6-ETc-Single crop coefficient (KC). IN: Crop evapotranspiration—guidelines for computing crop water requirements—FAO irrigation and drainage paper 56. *FAO-Food and Agriculture Organization of the United Nations*. Rome, Italy. X0490E/X0490E00. htm.

Bavay, M., Grünewald, T., & Lehning, M. (2013). Response of snow cover and runoff to climate change in high Alpine catchments of Eastern Switzerland. *Advances in water resources*, 55, 4-16.

Ben Neriah A., Assouline S., Shavit U. & Weisbrod N. (2014). Impact of ambient conditions on evaporation from porous media. *Water Resources Re-search*, 50,6696–6712.

Bentz, B. J., Régnière, J., Fettig, C. J., Hansen, E. M., Hayes, J. L., Hicke, J. A., ... & Seybold, S. J. (2010). Climate change and bark beetles of the western United States and Canada: direct and indirect effects. *BioScience*, 60(8), 602-613.

Bertin, R. I. (2008). Plant phenology and distribution in relation to recent climate change. The *Journal of the Torrey Botanical Society*, 135(1), 126-146.

Bewley, D., Essery, R., Pomeroy, J., & Ménard, C. (2010). Measurements and modelling of snowmelt and turbulent heat fluxes over shrub tundra. *Hydrology & Earth System Sciences Discussions*, 7(1).

Black, T. A., & Kelliher, F. (1989). Processes controlling understorey evapotranspiration. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, 324(1223), 207-231.

Bowers, J. D., & Bailey, W. G. (1989). Summer energy balance regimes for alpine tundra, Plateau Mountain, Alberta, Canada. Arctic and Alpine Research, 21(2), 135-143.

Brodribb, T. J., McAdam, S. A., Jordan, G. J., & Martins, S. C. (2014). Conifer species adapt to low-rainfall climates by following one of two divergent pathways. *Proceedings of the National Academy of Sciences*, 111(40), 14489-14493.

Brown, R. D., & Robinson, D. A. (2011). Northern Hemisphere spring snow cover variability and change over 1922-2010 including an assessment of uncertainty. *The Cryosphere*, 5(1), 219.

Budd, W.F., Dingle, R. and Radok, U. 1965: The Byrd snowdrift project - outline of basic results. *American Geophysical Union, Antarctic Research Series 7*.

Budd, W. F., Dingle, W. R. J., & Radok, U. (1966). The Byrd snow drift project: outline and basic results. *Studies in Antarctic Meteorology*, 9, 71-134.

Byrne, M. P., & O'Gorman, P. A. (2013). Land-ocean warming contrast over a wide range of climates: Convective quasi-equilibrium theory and idealized simulations. *Journal of Climate*, 26(12), 4000–4016.

Calder, I. R. (1990). Evaporation in the Uplands. Wiley.

Carter, G. A., Smith, W. K., & Hadley, J. L. (1988). Stomatal conductance in three conifer species at different elevations during summer in Wyoming. *Canadian Journal of Forest Research*, 18(2), 242-246.

Chang, J, (1968). Climate and Agriculture, an Ecological Survey. *Aldine Publishing C*o., Chicago, Ill., 304 pp.

Chen J.M. and T.A. Black. (1992). Defining leaf area index for non-flat leaves. *Plant, Cell and Environment.* 15: 421-429.

Chen JM, Rich PM, Gower ST, Norman JM, Plummer S (1997). Leaf area index of boreal forests: theory, techniques, and measurements. *Journal of Geophysical Research*. 102: 29429-29443.

Chorley, R. J. (Ed.). (2019). Introduction to physical hydrology. *Routledge*.

Daly, C. (1984). Snow distribution patterns in the alpine krummholz zone. *Progress in Physical Geography*, 8(2), 157-175.

Dingman, S. L. (2002). Physical hydrology (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.

Dirnböck, T., Essl, F., and Rabitsch, W. (2011). Disproportional risk for habitat loss of high-altitude endemic species under climate change. Glob. Change Biol. 17: 990–996. doi:10.1111/j.1365-2486.2010.02266.x.

Dirnböck, T., & Grabherr, G. (2000). GIS assessment of vegetation and hydrological change in a high mountain catchment of the northern limestone alps. *Mountain Research and Development*, 20(2), 172-179.

Dunne, J. A., Harte, J., & Taylor, K. J. (2003). Subalpine meadow flowering phenology responses to climate change: integrating experimental and gradient methods. *Ecological Monographs*, 73(1), 69-86.

Dyunin, A. K. (1959). Fundamentals of the theory of snowdrifting, Isvestia Sibirski Otdeleniya Akademii Nauk SSSR, 12, 11–24 (trans. Belkov, G.: National Research Council of Canada Technical Translation 952, 26 pp., 1961).

Ellis, C. R., Pomeroy, J. W., Brown, T., & MacDonald, J. (2010). Simulation of snow accumulation and melt in needleleaf forest environments. *Hydrol. Earth Syst. Sci. Discuss*, 7(1), 1033-1072.

Environment Canada. (2015). Canadian Climate Normals Kananaskis Field Station 1981-2010 Station Data. Government of Canada.

Fang, X., & Pomeroy, J. W. (2020). Diagnosis of future changes in hydrology for a Canadian Rocky Mountain headwater basin. *Hydrology and Earth System Sciences Discussions*, 1-40.

Fang, X., Pomeroy, J. W., Ellis, C. R., MacDonald, M. K., DeBeer, C. M., & Brown, T. (2013). Multi-variable evaluation of hydrological model predictions for a headwater basin in the Canadian Rocky Mountains. *Hydrology and Earth System Sciences*, 17(4), 1635-1659.

Farnes, P., B. Goodison, N. Peterson, and R. Richards (1980), Proposed metric snow samplers, paper presented at 48th Western Snow Conference, pp. 107–119.

Fontaine, T. A., & Todd Jr, D. E. (1993). Measuring evaporation with ceramic Bellani plate atmometers. *Journal of the American Water Resources Association*, 29(5), 785-795.

Ford, E. D., & Deans, J. D. (1978). The effects of canopy structure on stemflow, throughfall and interception loss in a young Sitka spruce plantation. *Journal of Applied Ecology*, 905-917.

Figuerola, P. I., & Berliner, P. R. (2005). Evapotranspiration under advective conditions. *International journal of biometeorology*, 49(6), 403-416.

Germino, M. J., & Smith, W. K. (1999). Sky exposure, crown architecture, and low-temperature photoinhibition in conifer seedlings at alpine treeline. *Plant, Cell & Environment*, 22(4), 407-415.

Gerosa, G. (Ed.). (2011). Evapotranspiration: From Measurements to Agricultural and Environmental Applications. *BoD–Books on Demand*.

Goulden, M. L., & Bales, R. C. (2014). Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion. *Proceedings of the National Academy of Sciences*, 111(39), 14071-14075.

Grace, J., Berninger, F., & Nagy, L. (2002). Impacts of climate change on the tree line. *Annals of Botany*, 90(4), 537-544.

Gurski, B. C., de Souza, J. L. M., & Jerszurki, D. (2018). Crop coefficient in different densities of Pinus taeda. Advances in Forestry Science, 5(1), 249-252.

Hadley, J. L., & Smith, W. K. (1986). Wind effects on needles of timberline conifers: seasonal influence on mortality. *Ecology*, 67(1), 12-19.

Harder, P., Schirmer, M., Pomeroy, J., & Helgason, W. (2016). Accuracy of snow depth estimation in mountain and prairie environments by an unmanned aerial vehicle. *Cryosphere*, 10(6), 2559-2571.

Harsch, M. A., Hulme, P. E., McGlone, M. S., & Duncan, R. P. (2009). Are treelines advancing? A global meta-analysis of treeline response to climate warming. *Ecology letters*, 12(10), 1040-1049.

Hauer, F. R., Baron, J. S., Campbell, D. H., Fausch, K. D., Hostetler, S. W., Leavesley, G. H., & Stanford, J. A. (1997). Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada. *Hydrological Processes*, 11(8), 903-924.

Herwitz S R & Slye R E (1995): Three-dimensional modelling of canopy tree interception of winddriven rainfall. Journal of Hydrology, 168, 205-226.

Hiemstra, C. A., Liston, G. E., & Reiners, W. A. (2002). Snow redistribution by wind and interactions with vegetation at upper treeline in the Medicine Bow Mountains, Wyoming, USA. *Arctic, Antarctic, and Alpine Research*, 262-273.

Hiemstra, C. A., Liston, G. E., & Reiners, W. A. (2006). Observing, modelling, and validating snow redistribution by wind in a Wyoming upper treeline landscape. *Ecological Modelling*, 197(1), 35-51.

Hillel, D. (1998). Environmental Soil Physics. Academic Press, San Diego, CA.

Holler, P., Marsh, P., Walker, D., & Williams, M. (2001). Snow vegetation interactions: issues for a new initiative. In Soil-vegetation-atmosphere Transfer Schemes and Large-scale Hydrological Models: Proceedings of an International Symposium (Symposium S5). (No. 270, p. 299). *International Assn of Hydrological Sciences*.

Holtmeier, F. K. (1981). What does the term" Krummholz" really mean? Observations with special reference to the Alps and the Colorado Front Range. *Mountain Research and Development*, 253-260.

Holtmeier, F. K., & Broll, G. (2010). Wind as an ecological agent at treelines in North America, the Alps, and the European Subarctic. *Physical Geography*, 31(3), 203-233.

Jackson, M. M., Topp, E., Gergel, S. E., Martin, K., Pirotti, F., & Sitzia, T. (2016). Expansion of subalpine woody vegetation over 40 years on Vancouver Island, British Columbia, Canada. *Canadian Journal of Forest Research*, 46(3), 437-443.

Kelsey, K.C., Redmond, M.D., Barger, N.N. et al. Ecosystems (2018) 21: 125.

Kirkham, M. B. (2014). Principles of soil and plant water relations. *Academic Press*.

Knowles, N., M. D. Dettinger, and D. R. Cayan, (2006): Trends in snowfall versus rainfall in the western United States. J. Climate, 19, 4545–4559.

Köck, R., Härtel, E., Holtermann, C., Hochbichler, E., & Hager, H. (2003). Monitoring hydrological processes in montane and subalpine karst regions: comparison between different types of vegetation. *Experimental design, techniques and first results. of climate and land use change on alpine vegetation*., 147.

Kool, D., Ben-Gal, A., & Agam, N. (2018). Within-field advection enhances evaporation and transpiration in a vineyard in an arid environment. *Agricultural and Forest Meteorology*, 255, 104-113.

Kullman, L. (2007). Tree line population monitoring of Pinus sylvestris in the Swedish Scandes, 1973-2005: implications for tree line theory and climate change ecology. J. *Ecology*, 95, 41– 52

LaMarche Jr, V. C., & Mooney, H. A. (1972). Recent climatic change and development of the bristlecone pine (P. longaeva Bailey) krummholz zone, Mt. Washington, Nevada. Arctic and *Alpine Research*, 61-72.

Lapp, S., Byrne, J., Townshend, I., & Kienzle, S. (2005). Climate warming impacts on snowpack accumulation in an alpine watershed. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 25(4), 521-536.

Lenoir, J., Gégout, J.C., Marquet, P.A., de Ruffray, P., and Brisse, H. (2008). A significant upward shift in plant species optimum elevation during the 20th century. *Science*, 320(5884): 1768–1771. doi:10.1126/science.1156831. PMID: 18583610.

Liu, Z., Jin, G., & Zhou, M. (2015). Evaluation and correction of optically derived leaf area index in different temperate forests. *iForest-Biogeosciences and Forestry*, 9(1), 55.

Liu Y, Luo Y (2010) A consolidated evaluation of the FAO56 dual crop coefficient approach using the lysimeter data in the North China Plain. Agricultural Water Management 97: 31–40.

Lovett, G. M., & Reiners, W. A. (1986). Canopy structure and cloud water deposition in subalpine coniferous forests. Tellus B: *Chemical and Physical Meteorology*, 38(5), 319-327.

Luckman, B., & Kavanagh, T. (2000). Impact of climate fluctuations on mountain environments in the Canadian Rockies. *Ambio: A journal of the human environment*, 29(7), 371-380.

MacDonald, M. K., Pomeroy, J. W., & Pietroniro, A. (2010). On the importance of sublimation to an alpine snow mass balance in the Canadian Rocky Mountains. *Hydrology and Earth System Sciences*, 14(7), 1401-1415.

Malanson, G. P., Butler, D. R., Fagre, D. B., Walsh, S. J., Tomback, D. F., Daniels, L. D., & Bunn, A. G. (2007). Alpine treeline of western North America: linking organism-to-landscape dynamics. *Physical Geography*, 28(5), 378-396.

Marenholtz, E. H., Lieffers, V. J., & Silins, U. (2010). Evaporative demand across a range of microsites in partial-cut boreal forests. Scandinavian journal of forest research, 25(2), 118-126.

Marr, J. W. (1977). The development and movement of tree islands near the upper limit of Yree growth in the southern rocky mountains. *Ecology*, 58(5), 1159-1164.

Massmann, A., Gentine, P., & Lin, C. (2018). When does vapor pressure deficit drive or reduce evapotranspiration?. arXiv preprint arXiv:1805.05444.

McAneney, K. J., Brunet, Y., & Itier, B. (1994). Downwind evolution of transpiration by two irrigated crops under conditions of local advection. *Journal of Hydrology*, 161(1-4), 375-388.

McIlroy, I. C., & Angus, D. E. (1964). Grass, water and soil evaporation at Aspendale. *Agricultural Meteorology*, 1(3), 201-224.

McMahon T.A., Peel M.C., Lowe L., Srikanthan R. & McVicar T.R. (2013) Esti-mating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis. *Hydrology and Earth SystemSciences*, 17,1331–1363.

McNaughton, K. G., & Jarvis, P. G. (1983). Predicting effects of vegetation changes on transpiration and evaporation. *Water deficits and plant growth*, 7, 1-47.

McVicar T.R., Roderick M.L., Donohue R.J., Li L.T., Van Niel T.G., Thomas A., (2012a) Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *Journal of Hydrology*, 416–417,182–205.

McVicar T.R., Roderick M.L., Donohue R.J. & Van Niel T.G. (2012b). Less blus-ter ahead? Ecohydrological implications of global trends of terrestrial near-surface wind speeds. *Ecohydrology*, 5,381–388.

Ménard, C. B., Essery, R., Pomeroy, J., Marsh, P., & Clark, D. B. (2014). A shrub bending model to calculate the albedo of shrub-tundra. *Hydrological Processes*, 28(2), 341-351.

Molotch, N. P., Brooks, P. D., Burns, S. P., Litvak, M., Monson, R. K., McConnell, J. R., & Musselman, K. (2009). Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests. Ecohydrology: Ecosystems, Land and Water Process Interactions, *Ecohydrogeomorphology*, 2(2), 129-142.

Monteith, J. L. (1965). Symposia of the Society for Experimental Biology, 19, 4.

Musselman, K. N., Molotch, N. P., & Brooks, P. D. (2008). Effects of vegetation on snow accumulation and ablation in a mid-latitude sub-alpine forest. *Hydrological Processes: An International Journal*, 22(15), 2767-2776.

Musselman, K. N., Pomeroy, J. W., Essery, R. L., & Leroux, N. (2015). Impact of windflow calculations on simulations of alpine snow accumulation, redistribution and ablation. *Hydrological Processes*, 29(18), 3983-3999.

Oke, T.R. (1987). Boundary Layer Climates, 2nd edition. Taylor & Francis, Abingdon, UK.

Parviainen, J., & Pomeroy, J. W. (2000). Multiple-scale modelling of forest snow sublimation: initial findings. Hydrological Processes, 14(15), 2669-2681.

Park, Y., & Paw U, K. (2004). Numerical estimations of horizontal advection inside canopies.(Brief Article). *Journal of Applied Meteorology*, 43(10), 1530–1538.

Pederson, G. T., Gray, S. T., Ault, T., Marsh, W., Fagre, D. B., Bunn, A. G., ... & Graumlich, L. J. (2011). Climatic controls on the snowmelt hydrology of the northern Rocky Mountains. *Journal of Climate*, 24(6), 1666-1687.

Peet, R. K. (1981). Forest vegetation of the Colorado front range. *Vegetation*, 45(1), 3-75.

Penman, H. L. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London*. *Series A*, 193, 120–145.

Pomeroy, J. W. (1991). Transport and sublimation of snow in wind-scoured alpine terrain. Snow, Hydrology and Forests in Alpine Areas, edited by: Bergman, H., Lang, H., Frey, W., Issler, D., and Salm, B., *IAHS Press*, 205, 131-140.

Pomeroy, J. W., Bewley, D. S., Essery, R. L. H., Hedstrom, N. R., Link, T., Granger, R. J., ... & Janowicz, J. R. (2006). Shrub tundra snowmelt. *Hydrological Processes: An International Journal*, 20(4), 923-941.

Pomeroy, J. W., & Brun, E. (2001). Physical properties of snow. *Snow ecology: An interdisciplinary examination of snow-covered ecosystems*, 45-126.

Pomeroy, J. W., Davies, T. D., & Tranter, M. (1991). The impact of blowing snow on snow chemistry. *Seasonal Snowpacks* (pp. 71-113). Springer, Berlin, Heidelberg.

Pomeroy, J., Fang, X., & Ellis, C. (2012). Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. *Hydrological Processes*, 26(12), 1891-1904.

Pomeroy, J. W., Fang, X. I. N. G., & Rasouli, K. (2015). Sensitivity of snow processes to warming in the Canadian Rockies. *72nd Eastern Snow Conference* (pp. 9-11).

Pomeroy, J. W., & Gray, D. M. (1990). Saltation of snow. *Water resources research*, 26(7), 1583-1594.

Pomeroy, J.W & Gray, D.M. (1995). Snowcover Accumulation, Relocation and Management. *National Hydrology Research Institute Science Report No. 7*. Environment Canada: Saskatoon. 144.

Pomeroy, J. W., & Male, D. H. (1992). Steady-state suspension of snow. *Journal of hydrology*, 136(1-4), 275-301.

Pomeroy JW, Parviainen J, Hedstrom N, Gray DM. (1998). Coupled modelling of forest snow interception and sublimation. *Hydrological Processes*, 12: 2317±2337.

Rasouli, K., Pomeroy, J. W., & Whitfield, P. H. (2019). Are the effects of vegetation and soil changes as important as climate change impacts on hydrological processes?. *Hydrology and Earth System Science*s, 23(12), 4933-4954.

Price, A.G., & Carlyle-Moses, D. E. (2003). Measurement and modelling of growing-season canopy water fluxes in a mature mixed deciduous forest stand, southern Ontario, Canada. *Agricultural and Forest Meteorology*, 119(1-2), 69-85.

Prueger, J.H., Hipps, L.E., Cooper, D.I., (1996). Evaporation and the development of the local boundary layer over an irrigated surface in an arid region. *Agric. For. Meteorol*. 78 (3–4), 223–237.

Redmond, D. R. (1964). *Organization of inter-agency watershed research programs for Canada.*

Rickebusch, S., Lischke, H., Bugmann, H., Guisan, A. & Zimmermann, N.E. (2007). Understanding the low-temperature limitations to forest growth through calibration of a forest dynamics model with tree-ring data. *For. Ecol. Manage*., 246, 251–263.

Rosenberg, N.J. (1969a). Advective contribution of energy utilized in evapotranspiration by alfalfa in the east central Great Plains (U.S.A). *Agric. For. Meteorol*. 6:179–184.

Rosenberg, N.J. (1969b). Seasonal patterns in evapotranspiration by irrigated alfalfa in the central Great Plains. *Agron. J*. 61:879–886.

Rosenberg, N.J., and S.B. Verma. 1978. Extreme evapotranspiration by irrigated alfalfa: A consequence of the 1976 Midwestern drought. J. *Appl. Meteorol*. 17:934–941.

Ryan, M.G. (1991). The effect of climate change on plant respiration. *Ecol. Appl*. 1:157–167.

Ryan, M. G. (2010). Temperature and tree growth. *Tree Physiology*, 30(6), 667-668.

Schmidt, R. A., Meister, R., & Gubler, H. (1984). Comparison of snow drifting measurements at an Alpine ridge crest. *Cold Regions Science and Technology*, 9(2), 131-141.

Schmidt, R. A. (1986). Transport rate of drifting snow and the mean wind speed profile. *Boundary-Layer Meteorology*, 34(3), 213-241.

Schwörer, C., Gavin, D. G., Walker, I. R., & Hu, F. S. (2017). Holocene tree line changes in the Canadian cordillera are controlled by climate and topography. *Journal of Biogeography*, 44(5), 1148-1159.

Seastedt, T. R., & Adams, G. A. (2001). Effects of mobile tree islands on alpine tundra soils. *Ecology*, 82(1), 8-17.

Shiels, A. B., & Sanford, R. L. (2001). Soil nutrient differences between two krummholz-form tree species and adjacent alpine tundra. *Geoderma*, 102(3), 205-217.

Smith, W. K., Germino, M. J., Hancock, T. E., and Johnson, D. M. (2003) Another perspective on altitudinal limits of alpine timberlines. Tree Physiology, Vol. 23, 1101-1112.

Smith, C. D., Kontu, A., Laffin, R., & Pomeroy, J. W. (2017). An assessment of two automated snow water equivalent instruments during the WMO Solid Precipitation Intercomparison Experiment. *Cryosphere*, 11(1).

Spittlehouse, D. L. (1998). P1. 1 Rainfall interception in young and mature confier forests in British Columbia.

Spronken-Smith, R. A., Oke, T. R., & Lowry, W. P. (2000). Advection and the surface energy balance across an irrigated urban park. International Journal of Climatology: *A Journal of the Royal Meteorological Society*, 20(9), 1033-1047.

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2004). Changes in snowmelt runoff timing in western North America under a business as usual climate change scenario. *Climatic Change*, 62(1-3), 217-232.

St. Jacques, J. M., Sauchyn, D. J., & Zhao, Y. (2010). Northern Rocky Mountain streamflow records: Global warming trends, human impacts or natural variability?. *Geophysical Research Letters*, 37(6).

Thornthwaite, C.W. (1948). An approach toward a rational classification of climate, *Geographical Review*, Vol. 38, No. 1, 55-94.

Tolk, J. A., Evett, S. R., & Howell, T. A. (2006). Advection influences on evapotranspiration of alfalfa in a semiarid climate. *Agronomy journal*, 98(6), 1646-1654.

Trant, A. J., Jameson, R. G., & Hermanutz, L. (2011). Persistence at the tree line: old trees as opportunists. *Arctic*, 367-370.

Turner, K. M. (1991). Annual evapotranspiration of Natwe Vegetation in Mediterranean-type climate. *Journal of the American Water Resources Association*, 27(1), 1-6.

Uehara, Y., & Kume, A. (2012). Canopy rainfall interception and fog capture by Pinus pumila Regal at Mt. Tateyama in the Northern Japan Alps, Japan. *Arctic, Antarctic, and Alpine Research*, 44(1), 143-150.

U.S. Department of Agriculture. (1999). Sampling Vegetation Attributes: Interagency Technical Reference. *U.S. Department of the Interior*. P.55-63.

Van Miegroet, H., Hysell, M. T., & Johnson, A. D. (2000). Soil microclimate and chemistry of spruce–fir tree islands in northern Utah. *Soil Science Society of America Journal*, 64(4), 1515-1525.

Varhola, A., Coops, N. C., Weiler, M., & Moore, R. D. (2010). Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*, 392(3), 219-233.

Verma, S. B., & Rosenberg, N. J. (1977). The Brown-Rosenberg Resistance Model of Crop Evapotranspiration Modified Tests in an Irrigated Sorghum Field 1. *Agronomy Journal*, 69(2), 332-335.

Walker, D. A., Billings, W. D., & De Molenaar, J. G. (2001). Snow-vegetation interactions in tundra environments. *Snow ecology*, 266-324.

Walsh, S. J., Butler, D. R., Allen, T. R., and Malanson, G. P. (1 994) Influence of snow patterns and snow avalanches on the alpine treeline ecotone. *Journal of Vegetation Science*, Vol. 5, 657-672.

Wang, S., Zhu, G., Xia, D., Ma, J., Han, T., Ma, T., ... & Shang, S. (2019). The characteristics of evapotranspiration and crop coefficients of an irrigated vineyard in arid Northwest China. *Agricultural Water Management*, 212, 388-398.

Wardle, P. (1968). Engelmann spruce (Picea engelmannii Engel.) at its upper limits on the Front Range, Colorado. *Ecology*, 49(3), 483-495.

Way, D. A. (2011). Tree phenology responses to warming: spring forward, fall back?. *Tree physiology*, 31(5), 469-471.

Way, D.A. and R. Oren. (2010). Differential responses to changes in growth temperature between trees from different functional groups and biomes: a review and synthesis of data. Tree Physiol. 30:669–688.

Wayand, N. E., Marsh, C. B., Shea, J. M., & Pomeroy, J. W. (2018). Globally scalable alpine snow metrics. *Remote Sensing of Environment*, 213, 61-72.

Weisberg, P. J., & Baker, W. L. (1995). Spatial variation in tree seedling and krummholz growth in the forest-tundra ecotone of Rocky Mountain National Park, Colorado, USA. *Arctic and Alpine Research*, 116-129.

Winkler, R. D., Moore, R. D., Redding, T. E., Spittlehouse, D. L., Smerdon, B. D., & Carlyle-Moses, D. E. (2010). Hydrologic Processes and Watershed Response. *Compendium of forest hydrology and geomorphology in British Columbia. BC Min. For. Range*, *66*, 179.

Zhang, S. Y., Li, X. Y., Zhao, G. Q., & Huang, Y. M. (2016). Surface energy fluxes and controls of evapotranspiration in three alpine ecosystems of Qinghai Lake watershed, NE Qinghai-Tibet Plateau. *Ecohydrology*, 9(2), 267-279.

Zinke, P. J. (1967). Forest interception studies in the United States. *Forest hydrology*, 137-161.

Zwieback, S., Chang, Q., Marsh, P., & Berg, A. (2019). Shrub tundra ecohydrology: rainfall interception is a major component of the water balance. Environmental Research Letters, 14(5), 055005.