Quantifying coniferous subalpine tree transpiration and source water under seasonal and hydrological stress in the Canadian Rocky Mountains, Kananaskis, Alberta

by

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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, 2019

Author's Declaration

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

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

Abstract

Fresh water supplies in mountainous regions are at risk as snow and ice stores continue to decline under rising global temperatures, earlier winter snowmelt and changing climate regimes. Alpine forests are of particular importance due to their hydrological connectivity within watersheds controlling groundwater base flow, influencing evapotranspiration (ET) and snow storage dynamics. A change in the water availability to subalpine vegetation via changes in winter snowpack accumulation and quantities or differing summer precipitation (P) regimes could have a drastic effect on the long-term health of these forests. This makes it imperative to understand and quantify their hydrological connectivity within these watersheds. Study sites located at Fortress Mountain in Kananaskis, Alberta are composed of co-occurring coniferous tree stands of *Abies lasiocarpa* and *Picea engelmannii*. Little is known about water use dynamics of these species at high elevations, specifically the quantity and timing of transpiration (T) in addition to the water sources most important for T during the entire length of the growing season.

This study used a combination of hydrological and meteorological tools to address coniferous subalpine tree water use behaviours before, during and after the growing season (June-September). Methodologies focussed on determining seasonal T patterns using the non-invasive stem-heat balance method to determine sap flow and eddy covariance to capture stand ET. The source water of the studied trees was determined using δ^{18}O and δ^2H stable water isotopes and further partitioned using the MixSIAR Bayesian Mixing Model (BMM). Groundwater monitoring wells, soil tensiometers, P gauges, and meteorological stations were used to determine baseline environmental conditions. Stable water isotopes δ^{18}O and δ^2H were collected from all source waters (P, snow cover, soil water, groundwater) in addition to xylem water samples from the coniferous trees within the study area.

Understanding tree response to P and drying events was the main objective addressed, yielding stark differences between the growing seasons of 2016 and 2017. Stand T was higher in 2017 (165 mm) than 2016 (118 mm) despite a much drier and warmer season (155 mm of rain in 2017 compared to 283 mm in 2016). A deeper, sustained snowpack in 2017 coupled with higher net radiation allowed for higher T rates. Paired with δ^{18}O and δ^2H stable isotope source partitioning, this study was able to identify soil water as the most important source to season-long tree productivity, with groundwater the most important for early growing season. Well-drained soils and shallow depth to bedrock inhibited groundwater access for the studied trees after the snowmelt period concluded. Thus soil moisture supplied a majority of water to the tree population during mid growing season,

determined both hydrometrically and isotopically. Dry conditions in 2017 showed a clear trend between soil moisture levels and tree water use, with 2016 having almost double the soil moisture and tree productivity in the tail end of the growing season. By closely examining the patterns of subalpine tree water use, we can begin to clarify how these important ecosystems services will be impacted under a changing climate in addition to helping us better manage our forest and freshwater resources.

Acknowledgements

Firstly, I would like to thank Dr. Rich Petrone. Without your belief and support, I never would have been able to do a Masters thesis based program. By giving me the opportunity to work for the Hydrometeorology Research group as an undergraduate in charge of establishing our Kananaskis research site you inspired me to believe I was capable of pursuing more. You gave me the tools to turn my passion and wonder for science into a career, while supporting my scientific journey throughout an undergraduate thesis (never thought I'd do that), and also my Masters thesis (also never thought I'd do that!). Thank you for all of your support and mentorship, I am especially grateful.

I cannot express enough thanks to my colleagues at this point extending across Canada and many institutions. I have been especially lucky to have a solid base of support in the form of the Hydrometeorology Research Group, weekly lab meetings, and beverage breaks - an important component. I'd especially like to thank the technicians responsible for the startup of the Kananaskis project, George Sutherland and Corey Wells, you were pivotal in showing me what great leadership looks like which included solid problem solving skills for any occasion. You were also the first people to inspire me to do an undergraduate thesis, so I could continue asking more science questions… I definitely didn't need any more courses to graduate. In addition, I'd like to thank my 'Kan Fam'. Spending hard-working summers in the mountains was even better with the companionship and friendships I was lucky to make; Carlie Elliot, Jess Williamson, Dylan Hrach, and many more.

A special thanks to members of the University of Saskatchewan Coldwater lab. In particular: Angus Duncan, Eric Courtin, Robin Heavens, Nicolas Le Roux, Caroline Aubrey-Wake and Greg Galloway. I am grateful to have had your support and friendship throughout the years and am even more thankful to have you as my community now that I live in Canmore.

To my Winchester family: Amy Dietrich, Matt Coulas, Peter Wray and Alex Glaros. Thank you for being the best friends I ever could have asked for during this journey. You are all wonderful humans and I'm thankful for the lifelong friendships gained.

To Mountain Mel, Mel Folden, thank you for being the light of Fortress Mountain. Your passion and love for the mountains is inspiring and unforgettable. The gratitude and respect you cultivate for every part of Fortress from Honey bear to those ravens will continue to inspire me throughout my lifetime. Thank you for everything you have given me.

To my family: Mum, Dad, Kristie and Murph. Thank you for your unending and relentless support. You have always believed in me with anything I put my mind to. I couldn't be more thankful for your unconditional love. A special shout out to my lifelong friend, Anna Poulton. You have been by my side through every up and down, you are my family too.

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Chapter 1:   General Introduction

1.1   Background and Rationale for Research

Mountain headwaters supply freshwater for over half the world's population (IPCC, 2007). In Canada this equates to a large majority of western Canada through major river tributaries including the Columbia, Peace, Fraser and North and South Saskatchewan Rivers. These freshwater stores, in the form of snow, ice and groundwater, provide downstream communities such as Calgary, with water for industrial, agricultural and private use. Recent studies have highlighted the rate of warming in Canada is approximately double the global average, with higher altitudes and latitudes experiencing even faster warming (Bush and Lemmen, 2019). Due to the altitudinal gradients adding hydrological complexity in mountain regions, climate induced changes are expected to be variable in their outcomes. What is known, is snowmelt is expected to occur earlier in addition to longer duration growing seasons (Cayan, *et al.,* 2001; Stewart et al., 2005; Clow, 2010). Although some studies have highlighted increases of precipitation (P) across much of Canada (Bush and Lemmen, 2019), quantities and patterns of P in the Rocky Mountains have been harder to observe with climate models (Groismas *et al*, 1994; Whitfield & Cannon, 2000; Stewart *et al*, 2005). Overall, changes occurring in growing season dynamics will impact the forests within mountain catchments. Forests provide an ecosystem service by controlling and maintaining runoff and baseflow levels through collection of winter snow and evapotranspiration (ET). Thus, impacts to subalpine forests via climate change could alter seasonal water budgets in alpine headwater catchments and water quantities arriving downstream (Pomeroy *et al*, 2012).

In the interest of understanding mountain water availability to downstream regions, studies were completed in the 1980's in order to understand the role of forests in mountain watersheds. The particular aim of a study by Swanson and Bernier (1986) was to experiment with forest harvesting to achieve the greatest flow of water in the Saskatchewan River, in order to increase water supplies downstream. The authors concluded that harvesting did increase flow, but recent studies by Pomeroy *et al* (2012) and Harder *et al* (2015) concluded flow had returned to levels similar to pre-harvesting, and forests were more resilient that once thought. These results called upon more research on subalpine forests, to understand their connectivity within these watersheds and the processes governing their behaviours.

1.2   Research Objectives

The research objectives of this thesis are designed in order to understand the behaviour and water use characteristics of two subalpine tree species. These objectives were divided between two papers, which comprise the manuscript thesis presented. Paper 1 is designed to understand and quantify forest ET under environmental stressors of high altitude such as wind speeds, temperatures, severe weather and snow regimes, and limited water availability. The objectives of this paper are to: I) quantify stand T by partitioning sub-alpine forest stand ET, during wet and dry growing seasons; II) examine soil (soil moisture, soil tension) and climatic (P, snow melt, available energy and atmospheric demand) controls on transpiration (T); and III) understand how sub-alpine forests obtain and use water during the growing season with limited groundwater access. These objectives aim to address how mountain forests could respond to environmental impact such as harvesting, and to shed light on how these forests may respond to increased environmental and climate change in the future. Paper 2, focuses on understanding water use through δ^{18}O and δ^2H stable water isotopes, addresses three main objectives on trees at the Fortress Mountain study sites: I) determine subalpine forest source water during pre-, mid- and end- of the growing season; II) partition relative source water contributions of xylem water within *Abies lasioscarpa* and *Picea engelmannii* using a simple two component mixing model; and III) evaluate which source waters are most important for subalpine tree T, and how long term climate pattern changes could affect forest health.

1.3   Thesis Structure

This thesis consists of 4 main chapters. The first chapter provides a general overview and provides context for the topics covered in this thesis and additionally outlines the research objectives.

The second chapter is paper 1, which investigates subalpine forest water use behaviours during two hydrologically varying growing seasons, during 2016 and 2017. This chapter contains an introduction, study site description, methodologies for the research conducted, results, discussion and conclusions.

The third chapter is paper 2, which investigates subalpine forest water use using δ^{18}O and δ^2H stable water isotopes and employs the Bayesian Mixing Model, MixSIAR. This chapter contains an introduction, a study site description, methodologies for the research conducted, results, discussion and conclusions.

The fourth chapter summarizes the main conclusions drawn from the two presented research papers. It also aims to highlight how this knowledge could inform additional research in the future,

and will discuss longer-term subalpine forest health based on the findings of this research. It will also discuss challenges or difficulties with the methodologies presented in this paper and will provide recommendations for future research on the understanding of subalpine forests.

Chapter 2: Quantifying subalpine forest water-use during two hydrologically varying growing seasons in the Canadian Rocky Mountains, Kananaskis, Alberta

2.1 Introduction

Forests within the Canadian Rocky Mountains experience very short growing seasons, typically spanning only 3 months, from June-August. Heavily influenced by altitudinal gradients and orographic constraints, climate patterns in these systems are complex with the majority of annual runoff being generated by deep winter snow packs. These snow packs comprise about 70-75% of the year's precipitation (P) and are vital to early growing season vegetation (Storr, 1967). Under a changing climate, this region is expected to experience earlier snowmelt (Cayan, *et al.,* 2001; Stewart et al., 2005; Clow, 2010) and changes in regional P patterns and quantities (Groismas *et al*, 1994; Whitfield & Cannon, 2000; Stewart *et al*, 2005), which may impact the health of forests (Harder *et al*, 2015). Additional forest disturbances such as the mountain pine beetle (Aukema *et al.*, 2008; Winkler *et al.*, 2008), wildfire (Fauria and Johnson, 2006, 2008), forestry (Swason and Bernier, 1986) and other land use management practices highlight a need for a further understanding of the response of high-elevation forests to disturbance. The productivity and resilience of forests in response to these disturbances are of particular importance, due to the coupled relationship between forests and runoff generation (Swanson and Bernier, 1986; Pomeroy *et al*, 2012; Harder *et al*, 2015), the quantity of runoff directly affects downstream communities and is currently declining (St. Jaques *et al*, 2010).

To date, current research highlights a gap in mountainous or sub-alpine forest transpiration (T) quantification, with most studies conducted at lower elevations (Tenhunen *et al*, 1998; Kräuchi *et al*, 2000; Matyssek *et al*, 2009). This knowledge gap limits the current understanding of mountain forests on high altitude water balances, and hinders accuracy in modeled water budgets of these regions (Matyssek *et al*, 2009; Fang *et al*, 2013). Various studies have developed an understanding of runoff generation due to clear cutting or forest harvesting treatments (Swanson & Bernier, 1986; Whitaker *et al*, 2002; Pomeroy *et al*, 2012), but few have highlighted forest resiliency and productivity in response to these impacts specific to the Canadian Rocky Mountain region (Harder *et al*, 2015). Coupled with physical human change, high altitude areas are considered sensitive indicators of climate change and are expected to respond to an increasing global temperature more rapidly than lower elevations (Kirschbaum, 1995; Breshears *et al*, 2009; Tague *et al*, 2009).

In recent years, quantification of tree T has improved with minimally invasive methodologies such as the stem-heat balance technique (Cermak *et al*, 1973; Granier, 1985). This method quantifies sap flow using a flexible thermopile heater with continuous heat applied to the stem or trunk, passing to plant xylem and performing a balance of water lost in the form of heat (Granier, 1985, 1987; Grime, 1995; Smith, 1996). This method has been successfully used to quantify T of forests at varying altitudes (Matyssek *et al*, 2009) in addition to providing insights on tree health and physiology (Steppe *et al*, 2015). For these reasons, in addition to ease of use in a remote mountain environment, the stem-heat balance (SHB) technique was used in this study to quantify tree T at two study sites of similar coniferous tree compositions (*Abies lascioscarpa* and *Picea engelmannii*) but differing in main physical characteristics (tree height, DBH and density). The SHB technique was supplemented with eddy covariance methods of stand evapotranspiration (ET), and other hydraulic measurements including wells, soil moisture probes, and general meteorological variables to address study objectives.

This study is designed to understand and quantify forest ET under environmental stressors at high altitude such as, variable temperature, growing seasons, variable and severe climate conditions and limited water availability. The objectives of this study are to: I) partition sub-alpine forest stand ET into tree transpiration (T) in wet and dry growing seasons; II) examine soil (soil moisture, soil tension) and climatic (P, snow melt, available energy and atmospheric demand) controls on T; and III) understand how sub-alpine forests obtain and use water during the growing season with limited groundwater access. These objectives aim to address how mountain forests are responding to environmental impact and to shed light on how these forests may respond to increased environmental and climate change in the future.

2.2   Materials and Methods

2.2.1   Study Site

The data for this study was collected at Fortress Mountain in the Kananaskis River Valley of the Canadian Rocky Mountains in Alberta. Research campaigns and data collection occurred from May-September in 2016 and 2017. Fortress Mountain is located on crown land, within the greater Kananaskis valley with a climate that is highly seasonal with variability due to winter Chinooks and summer snowfalls, but typically has long cold winters and cool wet summers falling in the humid

continental category (Beckstead & Veldman, 1985; Alberta Environment and Sustainable Resource Development, 2014).

Data from the Kananaskis Field Station from 1981-2010 (Environment Canada, 2015) shows the warmest month, July, to have daily average temperatures of 14.1 °C, and the coldest month, December, a daily average of -6.2 °C. The highly variable climate allows for extreme maximums ranging from -45.6 °C to 34.5 °C. Chinook winds are also common in this area of the Rocky mountains, characterized as strong westerly winds flowing over the leeward sides of the mountains bringing high temperatures and low humidities (Longley, 1967; Whitfield, 2014). The frequency of these winds, approximately 30 times per winter, has implications on climate and hydrology patterns experienced in the valley (Longley, 1967; MacDonald *et al*, 2015). P during the study growing seasons totaled 283 mm and 155 mm in 2016 and 2017, respectively. Due to a 45% difference in P across both study years and higher levels of season-long moisture availability (considering snow water equivalent and precipitation) in 2016, the 2016 study year will be referred to as a "wet" summer and 2017, a "dry" summer. Average monthly temperatures were within the range of monthly normals by 2 °C (Environment Canada, 2015).

Vegetation in the Kananaskis valley varies greatly along an elevational gradient, with zones defined by the tree species that grow within them. A *lower zone* (1000 - 1400 m) consists primarily of lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*). An *upper zone* (1400 - 2100 m) is comprised mainly of *Abies lasiocarpa* and *Picea engelmannii* (Johnson, 1986). The sites used in this study were located within the upper zone, with *Abies lasioscarpa* and *Picea engelmannii* being the dominant trees.

The valley is approximately 55 km long, and runs NNW - SSE. Ridges in the valley that dip WSW are thrust sheets and fault blocks composed of resistant Paleozoic carbonate rocks, with the valley characteristic of weak Mesozoic clastic rocks (Johnson, 1986). The last glaciation in this area occurred during the current geologic time period, the Quaternary, with some glaciers still existing in the Kananaskis including a debris covered glacier within the Fortress Mountain study area. The surface geology is predominantly well drained glacial till consequent of the most recent glaciation (Beckstead & Veldman, 1985) overlaying fractured bedrock with varying thickness. In the area used for this study, depth to bedrock was as shallow as 1.5 m, but showed great variation.
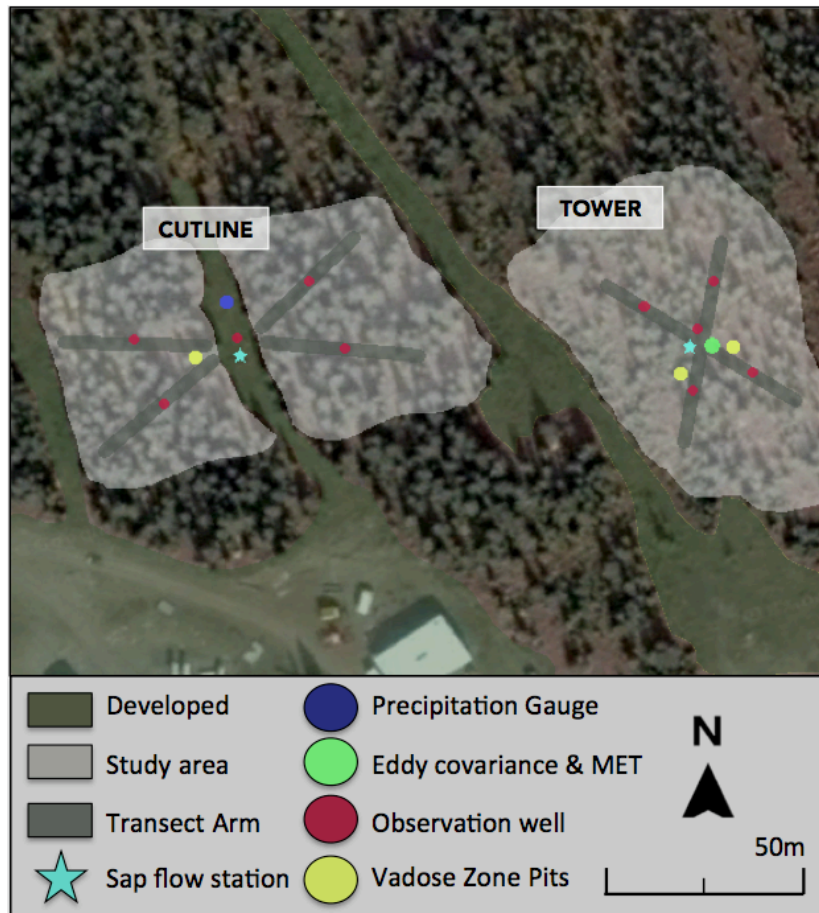
Figure 2-1. Instrumentation distribution and transect locations at the Tower and Cutline at Fortress Mountain, Kananaskis, AB.

Two adjacent sub-alpine sites were used in this study at Fortress Mountain to ensure proper representation of the diverse forest structure at the elevation examined for this study. The first site, hereafter referred to as Tower, is described as a well-populated shorter growth (relative to Cutline) forest patch at 2079 m of elevation (50.825746 N, 115.196725 W). The second site, hereafter referred to as Cutline, is a less populated taller growth (relative to Tower) forest patch at 2083 m of elevation (50.825782 N, 115.198290 W). A transect system with arms spanning approximately 50 m in each cardinal direction, with 10 sampling locations along each segment was established at each site (Figure 2-1). The two sites are approximately 115 m apart, as defined by the centres of each transect.

2.2.1.1 Vegetation and Forest Surveys

The forest inventory followed guidelines of the *Reforestation Standard of Alberta* (Alberta Environment and Sustainable Resource Development, 2012). Circular plots of 100 m^2 (5.64 m radius) were established at the ends and centre of the cross-transect arrangements, totaling 5 sampling areas at each study site. Within the greater 100 m^2 plot, was a smaller 10 m^2 (1.78 m radius) circle. Diameter at breast height (DBH), height, basal area, and tree species identification were collected from each 100 m^2 plot. Trees with a DBH greater than the smallest tree being collected for sap flow measurements (2.5 cm at Cutline, 2 cm at Tower) were catalogued for the 100 m^2 plot. Species type for saplings and trees heights > 30 cm in were the only variable collected for the inner 10 m^2 plots.

Tree height was measured using a telescoping tree measuring pole, or a clinometer (Suunto, Vantaa, Finland) where necessary. DBH was measured using a 60 cm tree caliper. Tree species were identified using the field guide by Alberta Parks for Kananaskis Country (Alberta Parks, 1999). In addition to basic physical characteristics, tree cores were obtained from trees with sap flow sensors using a Haglof increment borer and placed in wooden block inserts and sanded to visually count tree rings.

Ground vegetation surveys were completed to determine percent ground cover and ground species types that populated the two study sites. The Daubenmire method (20 cm by 50 cm frame) was used along the earlier defined transects at a frequency of every other sampling point, which totaled 20 overall sampling locations per study site (Daubenmire, 1959; U.S. Department of Agriculture, 1999). This method was chosen for its simplicity and flexibility for use among vegetation and land types. Species were identified using the field guide by Hallworth and Chinnappa (1997), and the herbarium established at the Biogeoscience Institute of the University of Calgary in Kananaskis, Alberta. Vegetation surveys for both study sites were completed once in late July – early August 2015.

Leaf area index (LAI) values for both study sites were obtained with a LAI-2200 plant canopy hand analyzer (LI-COR, USA) using a 90-degree view cap. Values obtained include understory vegetation (LAI$_U$), canopy (LAI$_C$), and total (LAI$_T$) along transect arms oriented in each cardinal direction at two main study sites at Fortress Mountain. Values were processed in the FV-2200 software (version 2.1) provided by LI-COR and were corrected for sunlight scattering using the model by Kobayashi et al (2013). Due to the coniferous tree populations of the study areas, a conifer correction was applied to the LAI measurements using Canadian Rockies correction models in order to address clumping (Davidson et al, 2000; Hall et al, 2003). Specific conifer-correction factors were

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combined based on tree species by weighting the relative abundance of species among surveyed trees (Davidson *et al*, 2000; Lie *et al*, 2015). LAI measurement frequency was once per week for the growing season duration from June-August in 2016 and 2017. Values were obtained at 40 points along a transect arms (Figure 2-1).

2.2.1.2   Tower Site Vegetation and Climate

The Tower site is the most easterly of the two sites (Figure 2-1), and is closest to a nearby slope of declining elevation. At the Tower site, there is a high overall tree population comprised mainly of *Abies lasiocarpa* and *Picea engelmannii* relative to Cutline (Table 2-1). The average diameter at DBH for *Abies lasiocarpa* was 6.7 cm (±5.5), while the average height was 4.4 m (±2.3) (Table 2-1). *Picea engelmannii* had an average DBH of 6.2 cm (±4.2) and an average height of 4.0 m (±1.7). Although there were two additional tree species at this location, their cumulative populations of 1.4% of the total population deemed them insignificant to report (Table 2-1). Of the species examined at this site, *Abies lasiocarpa* was the most common at 73.2% and *Picea engelmannii* second most common at 25.5% (Table 2-1).

Table 2-1. Forest inventory data for Tower and Cutline sites from completed forest characteristic survey. Data collected in August 2015 at Fortress Mountain, Kananaskis, AB.

Site	Species	n	% of total	Mean DBH (cm)	Mean Height (m)
Tower	*Abies lasiocarpa*	112	73.2%	6.7 (±5.5)	4.44 (± 2.31)
	Picea engelmannii	39	25.5%	6.2 (±4.2)	4.2 (±1.67)
	Pinus contorta	1	0.7%	7 (±0)	4.8 (±0)
	Larix lyalli	1	0.7%	2.3 (±0)	2.93 (±0)
Cutline	*Abies lasiocarpa*	48	70.6%	14.4 (±6.4)	8.75 (±2.54)
	Picea engelmannii	20	29.4%	20.3 (±9.2)	9.49 (±3.3)

Compared to Cutline, trees at Tower appear to be younger, and shorter with a higher population density consistent with successional progression common of the dominant species at this site. In 2016, Leaf area index (LAI) of the canopy at Tower was 2.64, with a mean stand total LAI of 4.36 (including understory), which is smaller than that of Cutline for the same year (Table 2-2). The most common ground species are *Vaccinium scoparium*, followed by *Erigeron peregrinus* and

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Parnassia fimbriata. The percentage of ground species was commonly around 50%, ranging between 10 - 80% cover.

2.2.1.3   Cutline Site Vegetation and Climate

Cutline is located west of the Tower site (Figure 2-1). This site is characterized as less densely populated, but with higher canopy density than Tower, which can be seen in the tree survey statistics (Table 2-1) and reported LAI values (Table 2-2). Cutline was dominated by *Abies lasiocarpa* and *Picea engelmannii*, with the former having an observed average DBH of 14.4 cm (±6.4) and height of 8.75 m (±2.54), both variables being almost double of the tower location with half the population size (Table 2-1). *Picea engelmannii* had an average DBH of 20.3 cm (±9.2) and an average height of 9.49 m (±3.3), which was also more than double the reported values at the Tower site for the same species (Table 2-1). The most prevalent tree species here were the same at Tower site, *Abies lasiocarpa and Picea engelmannii*. Population compositions differ slightly between the sites, having a lower *Abies lasiocarpa* population totaling 68.4% (compared to 73.2%) and a higher *Picea engelmannii* population of 31.6% (compared to 25.5% at Cutline) (Table 2-2). In 2016, canopy LAI for Cutline was 3.25, with a mean total site LAI of 4.56, both higher (denser vegetation) than Tower (Table 2-2). Understory vegetation was characterized primarily by: *Vaccinium Scoparium, Erigeron peregrinus, Parnassia fimbriata* and various moss and sedge species. Ground cover percentage of the understory was similar to Tower site, ranging from 10 - 80% cover.

Table 2-2. Mean LAI values for Cutline and Tower sites collected weekly over the summer growing season from May-August in 2016 at Fortress Mountain, Kananaskis, AB.

Year	Site	Mean Canopy LAI	Mean Understory LAI	Mean Stand LAI
2016	Tower	2.64	1.72	4.36
	Cutline	3.25	1.32	4.56
	Combined	2.95	1.52	4.46

2.2.2   *Hydrometeorological Sampling and Field Instrumentation*

Groundwater wells were established at both sites to quantify spatiotemporal water table patterns and flow pathways. A total of five wells were placed at each site (10 total); one at the middle of each transect arm with an additional placed at the centre, where the arms crossed (Figure 2-1). At Tower,

water level transducers (OnSet HOBO U20 Water Level Logger, MA, USA) were placed in three of the five wells (north, south and west transect arms). At Cutline, an additional three U20 level loggers were installed (north, south and east transect arms). A barometric data logger (OnSet HOBO U20 Water Level Logger, MA, USA) was installed at Cutline for atmospheric water level compensation for all loggers. Atmospheric compensation was corrected for using Onset HOBOware Pro 3.7.12 data processing software. Wells were constructed 3 m in length using Schedule 40 PVC pipe slotted along the entire buried length. Fabric 2" diameter well sock (ESP Well Supply, USA) was used to cover the outside surface and act as a screen for fine sediments.

The vadose zone was instrumented for characterization and understanding of tree water consumption. Three soil moisture stations were installed across both study sites. At Tower, two stations, with one in an open tree clearing and the other a closed tree canopy were installed. At Cutline, the soil moisture station was situated within a closed canopy of trees with ample ground cover vegetation. Each station was instrumented with two Campbell Scientific CS650 Soil Moisture probes, one at a depth of 30cm (parallel to the soil surface) and the other vertically intersecting the end of the horizontally installed probe spanning from ground surface to 30 cm depth. Soil temperature (type K thermocouple, Omega, CT, USA) was also measured in the same pits at 5, 10, 15 and 30 cm depths. Both CS650's and thermocouples were logged on a CR1000 data logger (Campbell Scientific, UT, USA), sampled every 30 seconds and averaged over 30 minutes. Soil tensiometers (SoilMoisture 2725ARL Jet Fill Tensiometer, CA, USA) were setup adjacent to the three existing soil moisture stations, each comprised of three tensiometers at depths of 10, 20 and 30 cm. Tensiometer data was collected in 2017 by a manual visual reading of the gauge 25 times from June 22nd to August 10th, 2017 during the snow-free growing season.

Basic meteorological (MET) data was collected by instrumentation mounted on the 15.5 m forest tower. MET data collected included net radiation (Q^*) via sensors at the top (15 m) and bottom (1.4 m) of the tower (NR Lite2, Kipp & Zonen, VA, USA), relative humidity at a height of 15 m (HMP 155, Vaisala, Finland), two soil moisture probes at depths of 30 cm (CS650, Campbell Scientific Inc., UT, USA), and soil temperature at depths of 5, 10, 15 and 30 cm (type K thermocouple, Omega, CT, USA). Soil moisture, soil temperature and net radiation (1.4 m height) were also collected at Cutline site. P was collected at the Cutline site using an Ott Pluvio^2 (Ott Hydromet, CO, USA) wired to a CR3000 data logger (Campbell Scientific Inc. UT, USA) with wind protection shield and corrected for wind under-catch.

ET data was obtained for both 2016 and 2017 growing seasons from the 15.5 m eddy covariance tower situated above the forest canopy. ET data was obtained using a LI-7500 IRGA Open Path Gas Analyzer (Li-Cor, NE, USA) and a CSAT3 3D Sonic Anemometer (Campbell Scientific Inc., UT, USA) approximately 3 m above average canopy height (Table 2-1) logged onto a CR1000 data logger (Campbell Scientific Inc., UT, USA) and programmed to compute high frequency data instantaneously for raw data storage on the logger. Details on eddy covariance data collection and analysis are described in Petrone et al. (2007), Brown et al. (2010) and Petrone et al. (2015), the methods of which were used in this study. Briefly, data were processed using Eddy Pro software (Li-COR Inc., NE, USA) and bulk averaged over 30 minute periods. Data were corrected and gap filled as outlined in Petrone et al. (2015); Sutherland et al. (2014). Actual evapotranspiration (AET) was calculated from the latent heat flux and the latent heat of vaporization determined from air temperature (Petrone et al. 2007; Brown et al. 2010; Petrone et al. 2015).

2.2.3 Forest Transpiration Measurements

Tree T was obtained using a non-invasive stem heat balance (SHB) sap flow system (Dynamax Flow32-1K, TX, USA). One system was installed at each study site, with 8 sensors at each site totalling 16 sensors overall. The system is designed to estimate sap flow rates through the xylem layer of plants, which in this case were *Picea engelmannii* and *Abies lasiocarpa*. The system was run from early June to late September of each study year. This less invasive method uses only insulated collars with thermopile heaters embedded wrapped around the tree trunks and then insulated from solar radiation. Measurements were collected continuously every 60 seconds and averaged hourly. The data was collected and stored using a CR1000 data logger and multiplexor (Campbell Scientific Inc., UT, USA) connected to all sensors, installed at each study location. To maintain power in a remote location, each system was run using 60 watt solar panels connected to a 12 volt deep-cycle marine battery. The initial amount of sensors installed at each site was 8. After data analysis, 8 sensors from Tower and 6 sensors from Cutline had usable data for scaling-up to stand T (Table 2-3). Measurement and installation locations were established based on canopy cover density and size class distributions, and the proximity of trees to the data logger location due to limitations of sensor cable length. Sensors were proportionately allocated to species based on population information collected by the forest survey (Table 2-1). Installation of the sensors, system programming and data logger setup followed recommendations outlined by the manufacturer (Dynamax Inc., 2007).

Proper installation of the sensors included selecting locations for the sensors compatible with provided sensor sizes, preparing the trees for installation by lightly sanding blemishes to allow the sensor to lay flat and rubbing electrically conductive lubricant G4 gel on the sensor. Once a sensor was installed, a reflective barrier was wrapped around both sensor and trunk to prevent heat loss from sensors and interruptive radiation from the sun (Dynamax Inc, 2007).

Table 2-3. Sap flow sensor installation information for the Flow32-1K systems at Cutline and Tower study sites for 2016 and 2017 study years, Fortress Mountain, Kananaskis, Alberta.

Site	Sensor No.	Sensor Size	Species	DBH (cm)
Tower	1	SGB 25	*Abies lasioscarpa*	1.75
	2	SGB 25	*Picea engelmannii*	3.03
	3	SGB 25	*Abies lasioscarpa*	2.87
	4	SGB 35	*Abies lasioscarpa*	2.55
	5	SGB 25	*Abies lasioscarpa*	3.82
	6	SGB 25	*Picea engelmannii*	3.90
	7	SGB 25	*Abies lasioscarpa*	4.35
	8	SGB 35	*Picea engelmannii*	5.56
Cutline	1	SGB 10	*Abies lasioscarpa*	1.75
	2	SGB 25	*Abies lasioscarpa*	3.19
	3	SGB 25	*Picea engelmannii*	3.82
	4	SGB 25	*Picea engelmannii*	3.19
	5	SGB 35	*Abies lasioscarpa*	3.82
	7	SGB 50	*Abies lasioscarpa*	6.78

2.2.3.1   Stem Heat Balance Theory

The SHB method is minimally invasive to the plants with only a flexible heater being wrapped around the stem. Each sensor is provided a constant voltage, which supplies a constant heat flow to the stem. Different components of the heat flowing in and out of the sensor are combined and partitioned into fluxes that are represented in a heat balance (Steinberg *et al*, 1989). The fluxes of the balance assumes no storage and includes vertical heat conduction (Q_v) (comprised of upward (Q_u) and downward (Q_d) fluxes), radial conduction flux into the heater insulation (Q_r), and heat lost to the sap stream (Q_f).The flux component of the sensor heater is represented as (Q_h), which is equivalent to the power supplied to the system (P_{in})(Steinberg *et al*, 1989). The final heat balance using all components can be represented as,

$$P_{in} = Q_r + Q_v + Q_f \tag{2.1}$$

$$\text{where, } P_{in} = V^2/R \text{ (Ohm's Law)}$$

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where V is the heater voltage and R is the heater resistance value differing between each sensor. Fourier's Law describes the vertical flux components,

$$Q_v = Q_u + Q_d \tag{2.2}$$

$$Q_u = \frac{K_{st} \cdot A \cdot dT_u}{dx}$$

$$Q_d = \frac{K_{st} \cdot A \cdot dT_d}{dx}$$

where K_{st} is the stem thermal conductivity (W m^{-1} k^{-1}), A is the steam area (cm^2), dT_u and dT_d are vertical temperature gradients, and dx is the thermocouple gap, obtained from the Dynagage installation manual (Dynamax Inc, 2007). To determine sap flow, Q_f is divided by the heat capacity of water (4.186 J g^{-1} $^{\circ}$C^{-1}) and the temperature increase of the sap ($^{\circ}$C). Including all variables, the final mass flow rate (F, g hr^{-1}) is determined via (Dynamax Inc, 2007),

$$F = \frac{\frac{Q_f}{4.186}}{dT * 3600s} \tag{2.3}$$

2.2.3.2   Scaling Daily Tree Transpiration to Forest

Single-tree T values are scaled to the stand level using data from a forest survey completed in 2015. Hourly velocity (g/hour) measurements from individual sap flow sensors were processed for gaps, quality and irregularities by controlling for outliers and eliminating faulty values from broken sensors. Poor values originating from errors such as poor sensor-tree connection causing heat loss in vertical or horizontal directions, interference from solar radiation, heater block interference and gaps in data due to weather were analyzed and quality controlled. Of the initial 16 sensors installed, 8 from Tower and 6 from Cutline, were used to create daily flow regression equations.

Linear sap flow regression equations were generated by retrieving the equation for total daily flow vs diameter at breast height for every sensor on each day of measurement during the 2016 and 2017 study period. Separate daily regressions were created for each site. Forest survey data for each site was then applied to the daily regressions (R_D) generated for each day. Total cumulative water (W_C, L) use per plot per day was summed for both sites and followed a series of conversions in order to be represented as a depth (mm/day). In the first step the daily flow regression equations generated from sap flow data are applied to the forest survey data. In equation 2.4, the daily flows of all surveyed trees computed by the regression are summed (L/day). In the following equations, 2.5 – 2.7,

a series of unit conversions occurs to obtain the daily sap flow as a depth. The final equation, 2.8, sees depth in m/day converted to depth in mm/day.

$$W_c \ (L/day) = \Sigma \ R_D \tag{2.4}$$

$$W_c \left(\frac{L}{ha} /day \right) = (\Sigma \ R_D)(100) \tag{2.5}$$

$$W_c \left(\frac{m^3}{ha} /day \right) = \frac{W_c \left(\frac{L}{ha} \right)}{1000} \tag{2.6}$$

$$W_c \ (m/day) = \frac{W_c \left(\frac{m^3}{ha} \right)}{10000} \tag{2.7}$$

$$W_c \ (mm/day) = \ (W_c \ (m))(1000) \tag{2.8}$$

2.3   Results

2.3.1   Subalpine Forest Stand ET Partitioning

ET and T were obtained from eddy covariance and sap flow data for June 5 – Sept 24 in both study years combining both Tower and Cutline sites to capture the representative range in canopy density (2016, 2017) within the footprint of the tower. In 2016 (wet growing season), total ET during the observed growing season was 178.8 mm, while total T was 117.9 mm (Figure 2-3), comprising 66.0 % of total seasonal ET. In 2017 (dry growing season), total ET was 227.1 mm, with 165.1 mm total T. T comprised 72.7 % of total seasonal ET in the dry season (Figure 2-3). P amounts varied by 127.5 mm between the wet and dry seasons, with 282.6 mm falling in the wet season and 155.1 mm falling in the dry; a 45.3 % difference in growing season P between the two years (Figure 2-5, Table 2-4). When considering snow water equivalent (SWE) and its addition to soil moisture stores and available groundwater, total available moisture for 574.7 mm and 537.5 mm for 2016 and 2017 respectively (Table 2-4). With ET and P components considered, the wet season had a 103.8 mm gain of water to the system, contrasted with a net loss of 72.0 mm in the dry season.

The wet growing season daily average T was 58.9 % of total forest ET (Figure 2-3). Comparatively, the dry growing season T was 68.5 % of total forest ET (Figure 2-3). Both seasons had higher magnitude T and ET at the beginning of the season (spring), with a decreasing trend toward senescence in the fall. Magnitude of T and ET remained more stable throughout the wet season with a shallow decrease nearing fall, with the dry season displaying a more prevalent decreasing linear slope, which was double that of dry (wet season slope 0.00925; dry season slope

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Table 2-4. Summary of total available moisture supplied by snowmelt and growing season P over the study period from June 5 – September 25 of both years. Maximum winter SWE values entered in June (snowmelt finished on May 15th in 2016 and June 9th in 2017).

Component	2016				2017			
	June	July	Aug	Sept	June	July	Aug	Sept
SWE	292.1	0	0	0	382.4	0	0	0
Precipitation	45.5	105.4	55.8	76.6	73.2	21.9	16.8	43.2
Total Available Moisture	574.7				537.5			

compared to the dry summer with RH exceeding that of the wet summer for 39 days (34.5 %) (Figure 2-5). Net radiation was variable between the two summers, differing in overall magnitude (W/m^2) but showing similarities in seasonal trends (Figure 2-5). The wet summer tended to reach higher overall magnitudes of net radiation (Q^*) than dry with a higher number of days > 500 W/m^2, but the dry season had more days at magnitudes < 500 w/m^2 (Figure 2-5). When looking at the net radiation (Q^*) and ground heat flux (Q_G) cumulative difference over the snow-free growing season, the dry summer (2017) had a higher total with 110,115 MJ/m^2, compared to the wet summer with 107,329.4 MJ/m^2 (Figure 2-2).
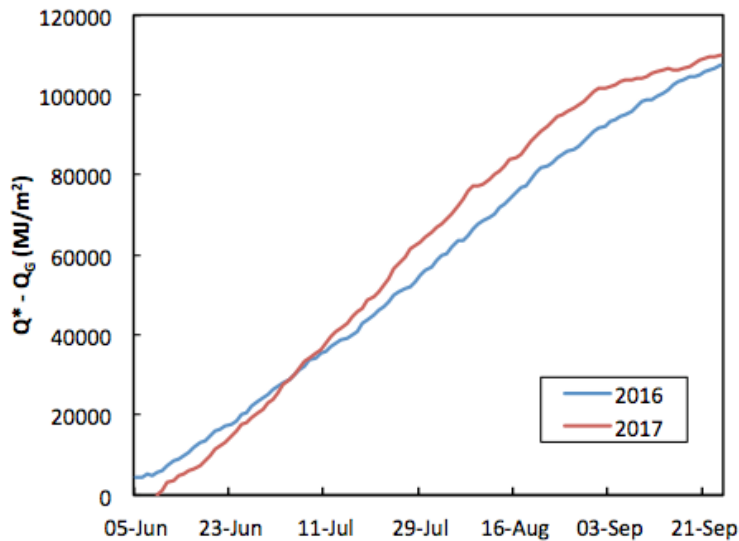
Figure 2-2. Cumulative Q^* - Q_g difference over the snow-free period during the growing season study period from June 5 – September 25 of both study years. 2017 totals start once snow was completely melted on June 9th. 2016 snow was melted by May 15th, so totals start at 0 on June 5th.

16
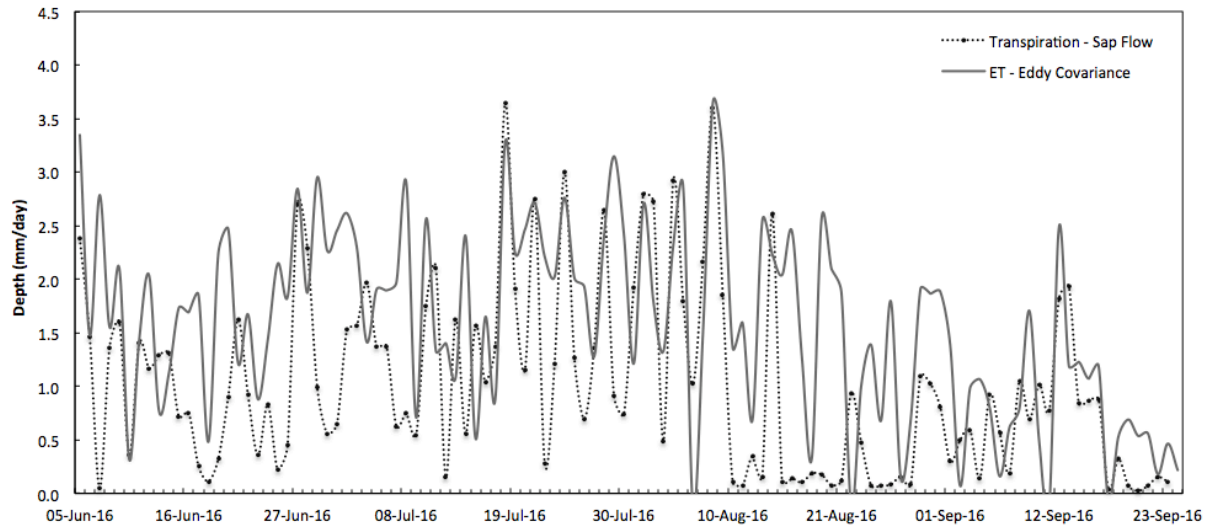
Figure 2-3. Tree T plotted against entire forest ET for the 2016 wet growing season from June 5 – Sept 25 at Fortress Mountain, Kananaskis, AB. Season totals were 178.8 mm and 117.9 mm for ET and T, respectively.
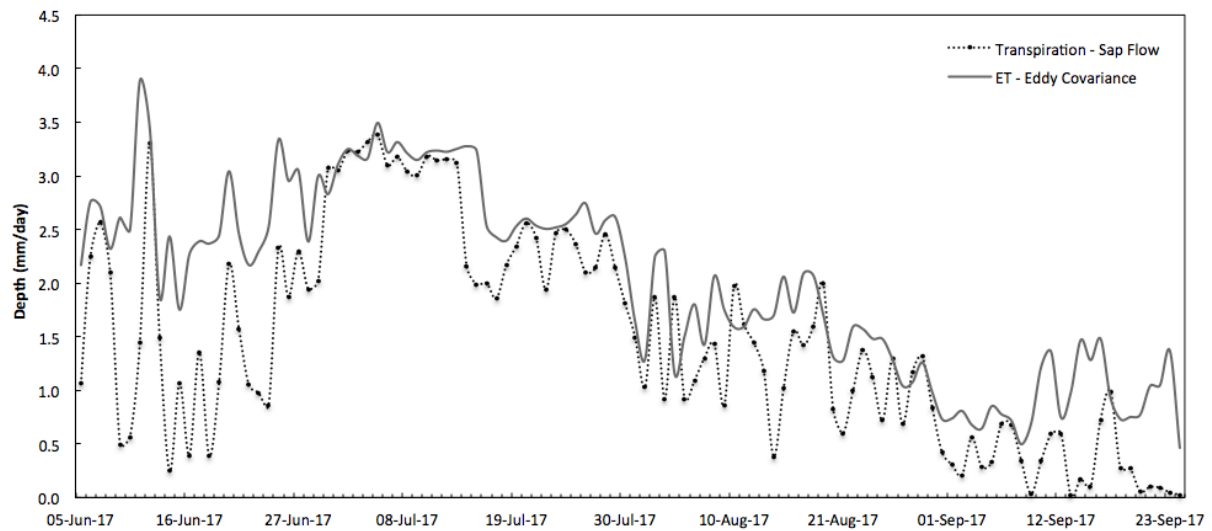
Figure 2-4. Tree T plotted against entire forest ET for the 2017 dry growing season from June 5 – Sept 25 at Fortress Mountain, Kananaskis, AB. Season totals were 227.1 mm and 165.1 mm for ET and T, respectively.

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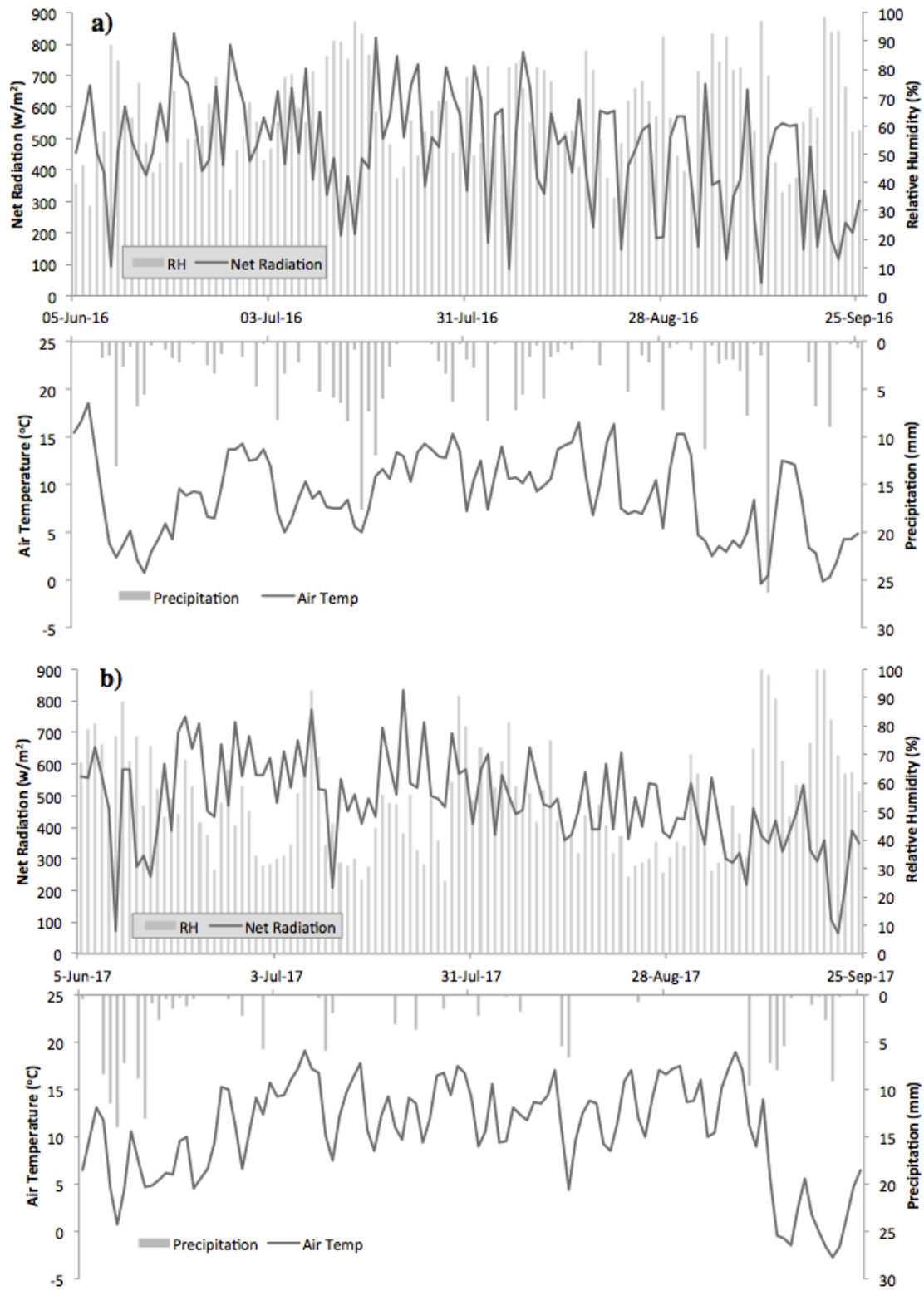
Figure 2-5. Climate plots for (a) 2016 and (b) 2017 from June 5 – Sept 25 growing seasons showing relative humidity, P, air temperature and net radiation, Fortress Mountain, Kananaskis, AB.

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2.3.2   Soil and Climatic Controls on Water Use

Groundwater level and tensiometer data was only available for the dry summer, 2017. Groundwater levels for Tower and Cutline sites showed seasonal variability, with a shallow groundwater table (> 1 m, deepest logged well) persisting only during the snowmelt period starting on May 19 and ending July 1 in 2017 (Figure 2-7). Groundwater did not reappear above 1 m for the rest of the growing season, which is below the typical rooting depth of *Abies lasioscarpa* and *Picea engelmannii*. Small peaks in the water table were recorded on all loggers corresponding to a series of heavy early June P events totalling 63.5 mm, in addition to baseline snowmelt (Figure 2-7). SWE of the winter snowpack within the forest was higher in 2017 (dry summer), reaching 382.4 mm on May 9, while 2016 (wet summer) had a maximum SWE of 292.1 mm on March 21. All level loggers showed similar patterns of water table rise and drop during snowmelt with differences in water table depth likely due to soil and bedrock heterogeneity (Figure 2-6 and 2-7). Two (Cutline 2, Tower 1) of the six installed wells had shallow snowmelt surface ponding at the well locations, leading to a water table value higher than the ground surface (> 0 m). Soil tensiometer nests installed near the end of the snowmelt period (June 22) showed a strong relationship with installed soil moisture probes in the continuing downtrend of a receding groundwater table. Until August 9 (end of manual observations) volumetric water content (VWC) continuously declined with an inverse relationship of increased soil tension shown across all 10, 20 and 30 cm depths (Figure 2-8).
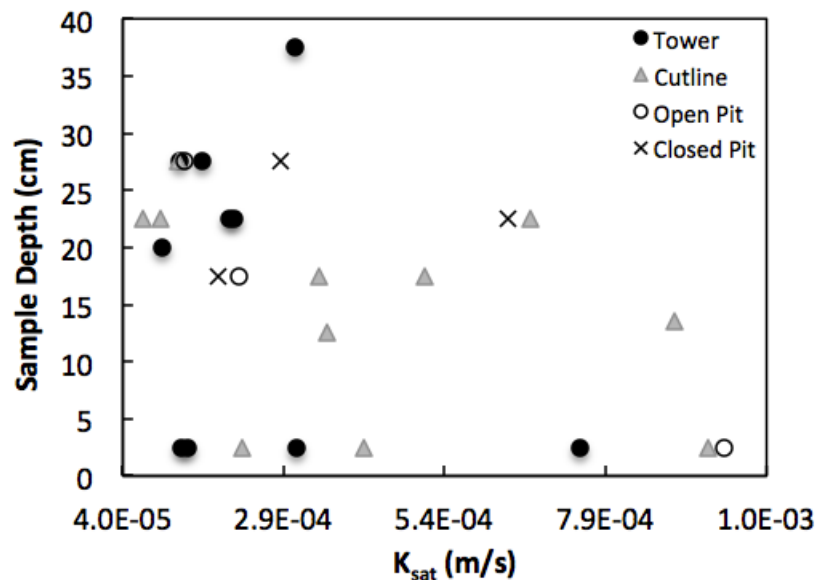
Figure 2-6. Saturated hydraulic conductivity values for soil cores taken from Fortress Mountain study sites. The constant head method was used to determine K$_{sat}$ from incremented sub-sampled cores. Samples obtained from Tower, Cutline and 'open' and 'closed' soil moisture pits.
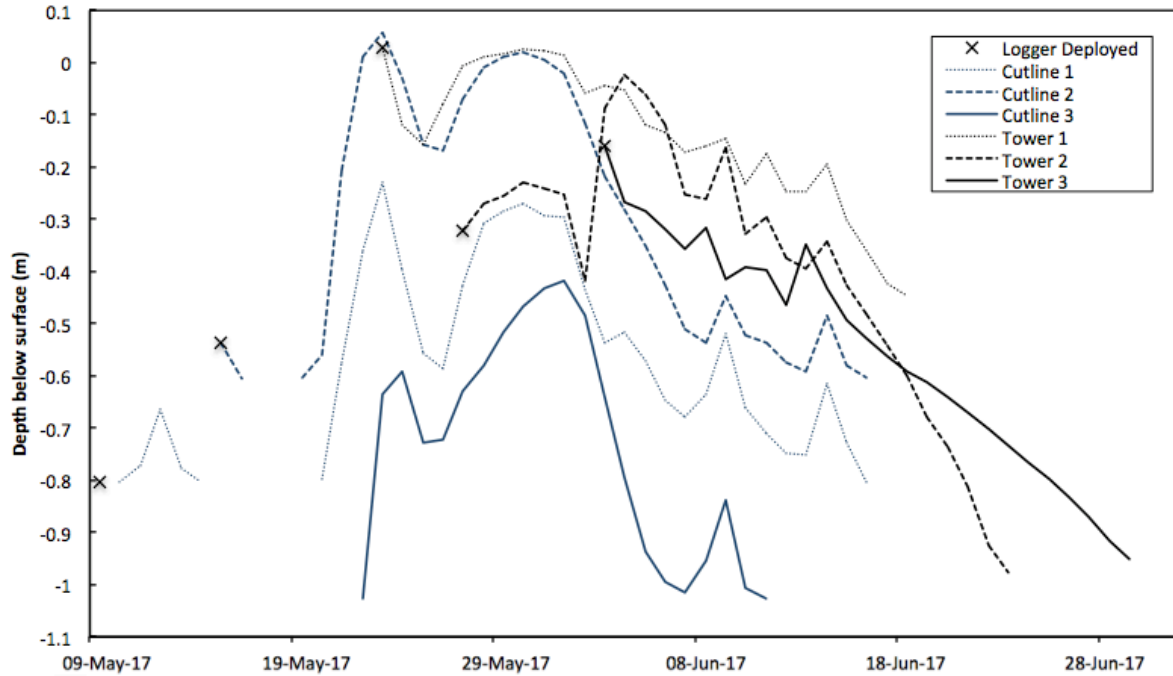
Figure 2-7. Groundwater levels during the snow melt period for Tower and Cutline sites at Fortress Mountain, Kananaskis, AB in 2017. Loggers were deployed as wells were located under the snowpack. Gaps in data are explained by water levels dropping below bottom of installed wells.
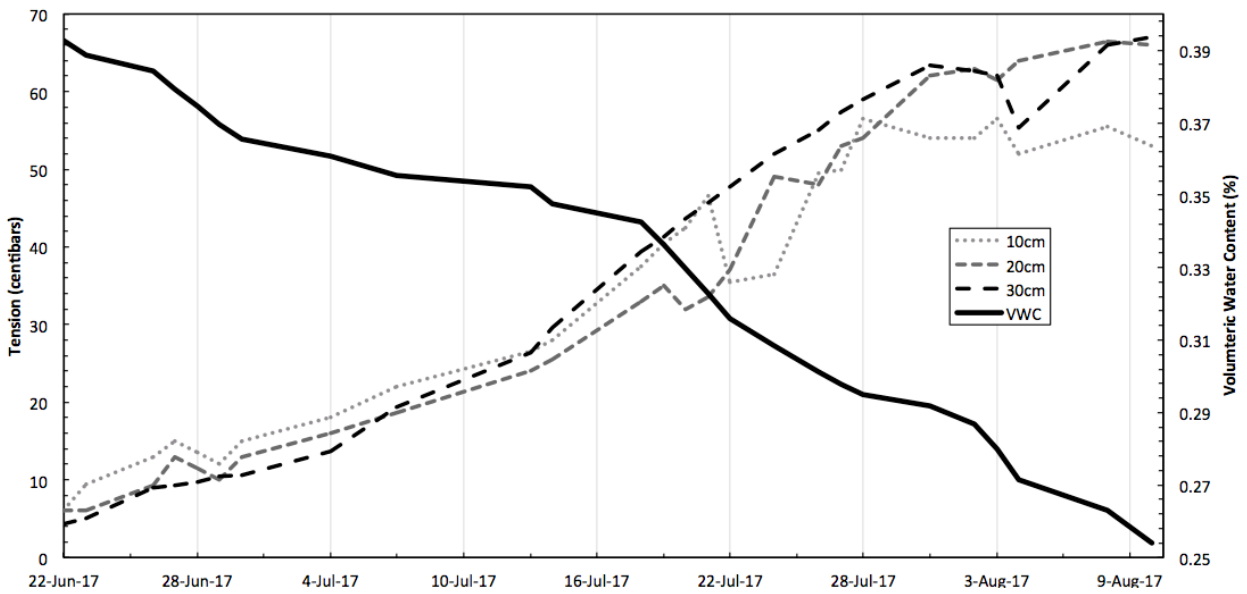
Figure 2-8. Average soil tension values for three depths (10, 20 and 30 cm) from vadose zone stations installed at Tower and Cutline, paired with average volumetric soil moisture values for the 30 cm depth for the same time period. Soil tension values were measured from June 22 – August 9, 2017 at Fortress Mountain, Kananaskis, AB.

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Early season soil tension trends showed shallow depths as drier, which is consistent with the trends observed in soil moisture and water level. Near the middle of the growing season, shallow tensions (10 cm) decreased (increased soil moisture in top 10 cm, not detectable by soil moisture probes) more than deeper depths (20, 30 cm) (Figure 2-8). This trend is explained by periods of P wetting the 10 cm layer of soil without percolating to the deeper 20 and 30 cm depths (Figure 2-5b, Figure 2-8). This is observable from July 6 - 12 as the 30 cm tensiometer depth surpassed the tension of 10 and 20 cm levels (Figure 2-8). During this same period experienced decreased net radiation and a P event (Figure 2-5b). After July 12, 30 cm soil tension stayed higher until Aug 3 where there was a multi-day P event of 3.98 mm, which was enough to saturate the 10, 20 and 30 cm levels.

2.3.2   *Wet and Dry Subalpine Growing Season Trends*

For both study years (2016 and 2017), sap velocity rates (g/hour) were monitored on *Abies lasioscarpa* and *Picea engelmannii* for both Tower and Cutline sites from June – September. Of the data obtained, an 11-day period in the middle (14th – 24th) of each month of the growing season was used for analysis due to completeness and minimal data gaps of the dataset. Dates in June were from the 5th – 15th in order to capture sap velocity and tree response to snow melt. The same dates were compared across both study years. P during the study growing seasons totaled 283 mm, and 155 mm in 2016 and 2017, respectively. These growing season P totals define 'wet' and 'dry' summer used hereafter.

In the wet summer, monthly T values were variable across the growing season with the highest sap velocities and total T occurring in July (34% of season total, 40.1 mm). June was the second highest month (27%, 31.9 mm) with August showing similar quantities of T (24%, 28.3 mm). September was the least productive month (17%, 20.1 mm) as trees moved into senescence (Figure 2-9). Soil moisture in the rooting zone varied month to month, with June being the highest during snowmelt (0.49 VWC) and September being the lowest (0.28 VWC). There was a steady decline of soil moisture throughout the observation period (Figure 2-9). As trees transitioned into senescence in September, trees of DBH less than 4 cm showed higher productivity than older more established trees greater than 4 cm. This was likely due to increased fall season precipitation saturating the rooting zones of younger trees. Comparatively, during early season snowmelt, older more established trees showed higher productivity early on.

In the dry summer, monthly T values were distributed differently due to a prolonged spring snowmelt compared to the wet year. The month with the highest T values and almost half of the total growing season was July (44% of season total, 72.6 mm). During the beginning of snowmelt, June was the second highest (28%, 46.2 mm). August totaled less than half of the T than the month before it (21%, 34.7 mm), and September was the lowest of both wet and dry years (7%, 11.6 mm) (Figure 2-9). Soil moisture in the dry year varied greatly, with highest values in June at the start of snowmelt (0.50 VWV) and lowest in August and September (0.14 VWC). The biggest decrease occurred from June to July, with soil moisture decreasing by more than half (0.50 to 0.21) (Figure 2-9). In the dry year, no DBH class stood out in terms of productivity.

Total tree T was 117.9 mm and 165.1 mm in the wet and dry summers, respectively. In the wet summer, there was a higher total amount of P (282.6 mm) than the dry summer (155.1 mm) in addition to a prolonged period of increased soil moisture and higher overall soil moisture in July, August and September. The dry summer had higher soil moisture levels in June due to a deeper winter snowpack. The proportion of tree T over the growing season varied between years with 61.2% (72.2 mm) in the wet summer occurring in the first half of the growing season and 38.8 % (45.7 mm) occurring in the second half. The dry year differed with 72.0 % (118.5 mm) in the first half and 28.0% (26.2 mm) in the second half. T in the second half of the wet summer (45.7 mm) was almost double that of the dry summer (26.2 mm), which was also reflected in differences in soil moisture (0.35 in 2016 and 0.14 VWC in 2017, respectively). Cumulative T values show similarities in early June, before 2017 T levels surpass that of 2016 due to a prolonged winter snowpack and sustained groundwater table (FIgure 2-10).
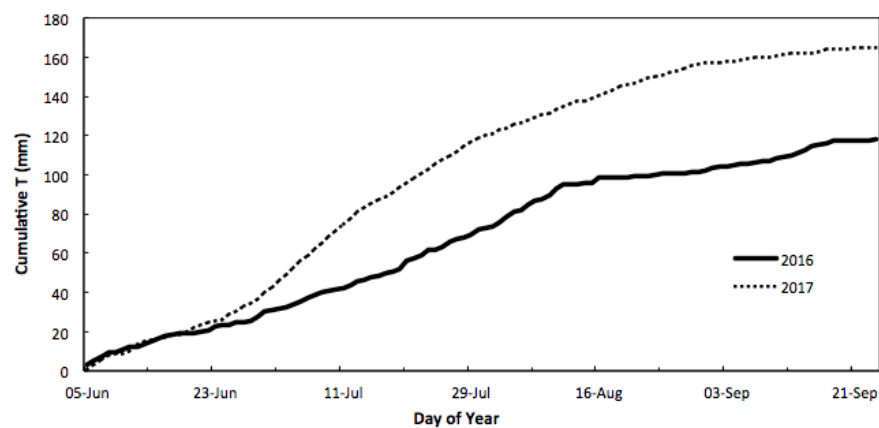
Figure 2-10. Cumulative T over the examined growing season, from June 5 – Sept 24 of both study years, 2016 and 2017. Of importance is the departure from similar early season totals on June 18, where T in 2017 surpasses that of 2016 due to a prolonged and more substantial winter snowpack.

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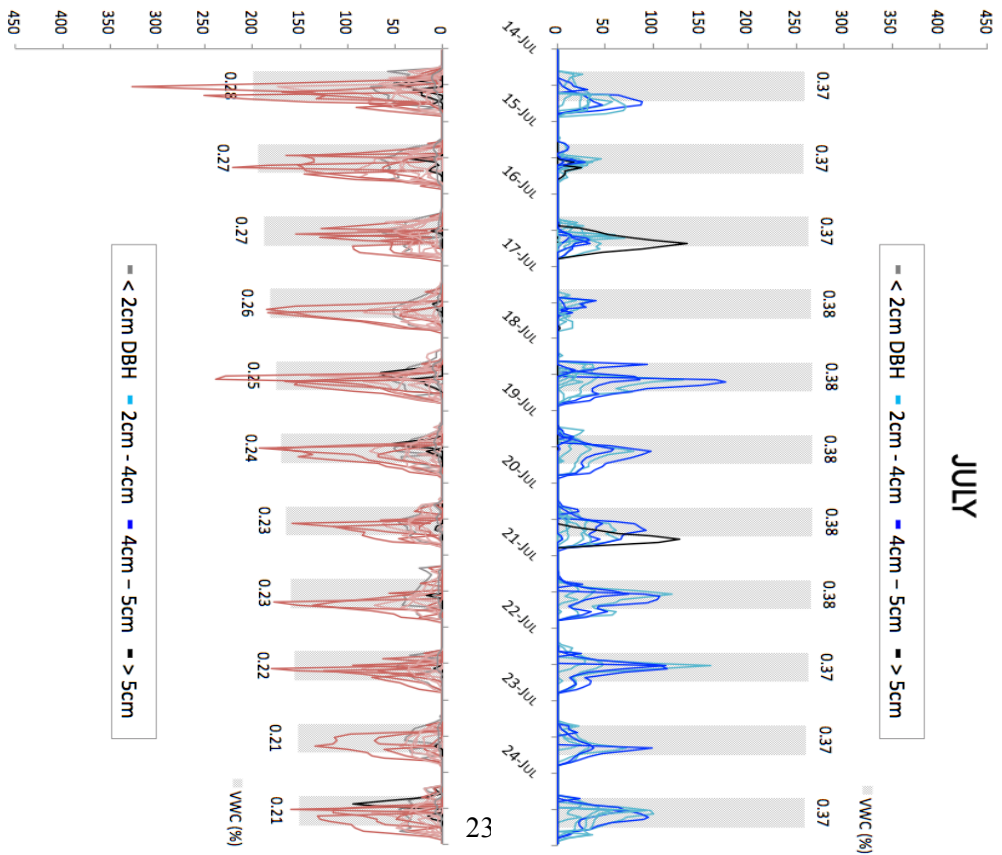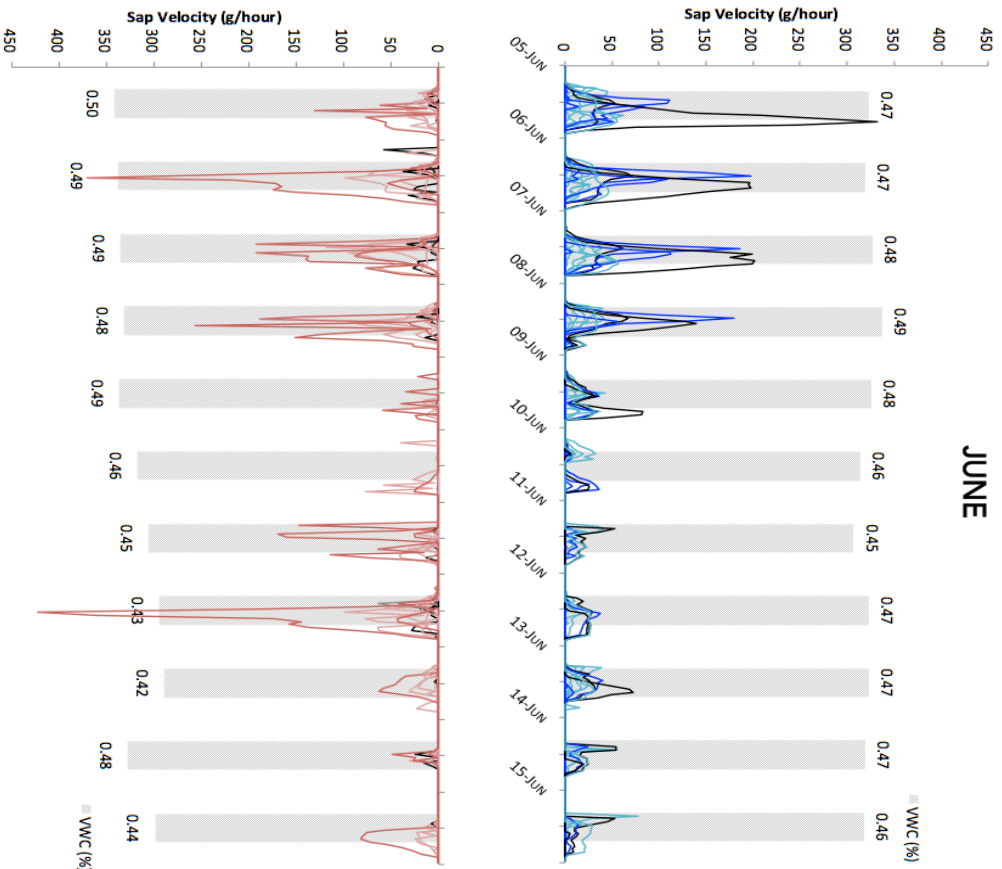
Figure 2-9. 2016 (blue) vs 2017 (red) diurnal coniferous 11-day sap flow comparisons across the growing season from June 5th - Sept 24th. Data was obtained from _Abies lasiocarpa_ and _Picea engelmannii_ coniferous trees at 2100m elevation from _Tower_ and _Cutline_ sites using a Dynamax Flow 32-1K system, Fortress Mountain, Kananaskis, AB.

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AUGUST
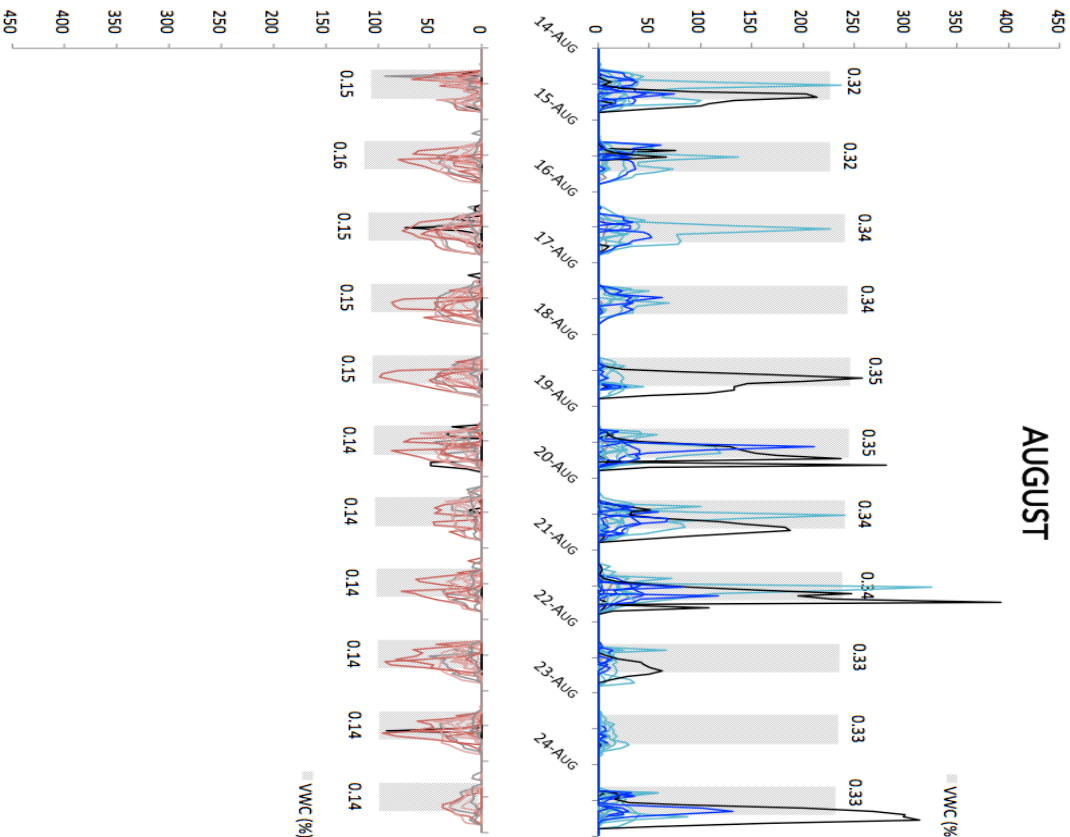
SEPTEMBER
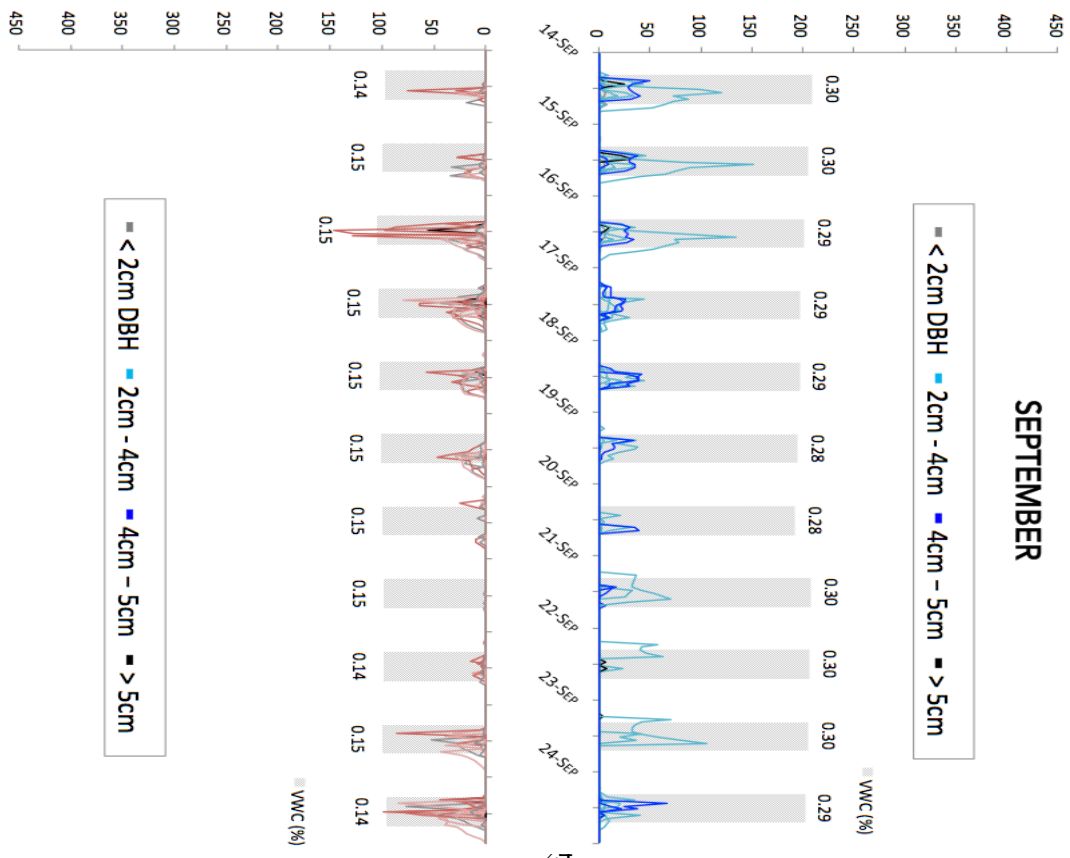
< 2cm DBH   2cm - 4cm   4cm – 5cm   > 5cm

2.4 Discussion

2.4.1 Sub-Alpine Forest Stand ET Partitioning

Both T and ET were higher in the dry summer despite limited water availability throughout the season compared to the wet summer, which had higher total P and soil moisture levels. Reported daily ET (mm/day) averages and T proportions are consistent with those reported in the literature (Lundblad and Lindroth, 2002; Matyssek *et al*, 2009). In the wet summer both tree T and ET were less than that of the dry summer, despite increased P and water availability. Although there was no groundwater level data for 2016, soil moisture within the rooting zone was characterized and provided insight to higher soil water availability for this year. Soil moisture levels in the dry summer were half of the wet summer, suggesting P was the major source of soil moisture after snowmelt as growing season precipitation levels reflected this (45.2% difference). This is evident when compared to trends seen in the tensiometer data and in other sub-alpine forested areas with shallow depth to bedrock and limited groundwater tables (Day *et al*, 1990; Small and McConnell, 2008). Differences in Q* and Q_G also suggest an impact on T and ET, with the wet summer experiencing more days under 500 W/m^2 than the dry summer, which suggests that available energy to drive ET may be more important than availability in soil moisture. Recent literature also supports increases in growing season length and tree productivity, with slight rises in ambient temperature (Teskey and Will, 1999; Slaney *et al*, 2007). This trend is especially noticeable at higher elevations, where coniferous trees respond accordingly to slight changes in ambient temperature (Carroll *et al*, 2017). The wet summer had a lower average air temperature for the growing season compared to the dry summer, which, when coupled with net radiation explains increased T and ET over the dry summer despite lower water availability.

The dry summer showed a slight decrease in T and ET during the beginning of the study season, with a sharp rise as delayed snowmelt followed a winter of higher accumulation. SWE levels were higher in 2017 than 2016, providing the dry summer with a longer growing season and increased water availability at the start of the growing season, which is vital for seasonal vegetation growth in mountainous regions (Kudo *et al*, 1990; Harpold *et al*, 2015; Winkler *et al*, 2018). This later and larger snowmelt explains higher total T and ET values in the dry summer, despite lower season-long moisture availability (considering SWE and P). Individually, T and ET in the dry summer followed similar peaks in magnitude but showed delays in response to P with T lagging slightly behind rises in

ET, suggesting the importance of direct soil and canopy evaporation around periods of P by limiting available soil moisture for T (Feddes *et al*, 1988). There was a slow but constant decline in T and ET after the snowmelt period and as soil moisture decreased until senescence (Lopushinsky and Kaufman, 1984; Penna, 2009; Klein *et al*, 2014). However, in studing spruce T during a wet season, Small and McConnell (2008) found low sap flow velocities even at high soil moisture contents suggesting waterlogged soils will suppress T, supporting the wet season observations here. Although the wet summer results align with Small and McConnell (2008) findings, results from both wet and dry summers in this study showed climate controls did have noticeable effects on T and ET magnitudes.

Interestingly, recent literature has shown contrasts in tree behaviour expected with increasing global temperatures and decreases in regional P. Some models have shown increases in T and ET with rising global temperatures (Rasouli *et al*, 2014; Carroll *et al*, 2017), while others have indicated short-term increases followed by long term declines, regional die-off and increased baseline tree mortality under sustained drought periods (Adams *et al*, 2009; Shafer *et al*, 2015). The results of the dry summer in this study showed increased losses despite a lack of growing season water availability, ultimately leading to an overall loss of water recharging the system. This is similar to the findings of Rasouli *et al* (2014) and Carroll *et al* (2017), although long term behavior such as this with a low snow pack year could cause high moisture stress for trees, similar to that of the trends shown in the tensiometer data where a 'point of no return' for soil tension was exceeded around July 22 of the dry summer growing season. Given the importance of snow pack dynamics, recent studies (Harpold *et al*, 2015; Pomeroy *et al*, 2012; Pomeroy *et al*, 2015) have addressed decreased snow accumulation within forested areas under climate change, further highlighting the potential for decreases in forest productivity with reduced SWE and summer P under long term climate change scenarios.

2.4.2   *Soil and Climatic Controls on Water Use*

Despite having one year of groundwater and tensiometer data (2017), the results clearly show vadose zone processes and their impact on water availability for sub-alpine *Abies lascioscarpa* and *Picea engelmannii*. Most notably is the small window of opportunity where these trees have access to a groundwater table (May 19 – July 1), as the bulk of their rooting systems reach a maximum depth of 1 m due constraints of altitude and surficial geology (Alexander and Shepperd, 1984; Alexander, 1987). For the remainder of the dry summer growing season, trees and vegetation relied upon residual soil moisture from snowmelt and P events large enough to saturate below 30 cm soil depth in order to

sustain new growth and T. In the dry summer, this meant higher T and ET rates at the beginning of the season while a large winter snowpack receded before a slow decline due to limited groundwater access and limited P. Higher SWE values over winter in 2017 helped boost seasonal T values by providing greater soil moisture as the growing season began, in contrast to the dry summer.

Kelsey *et al* (2018) found growth declines in *Abies lasioscarpa* due to recent climate change and associated changes in the water and energy balance, while observing *Picea engelmannii* to have a lower overall decline. *Abies lasioscarpa* are known to be prone to drought stress (Vose and Swank, 1994; Orwig and Abrams, 1997; Sala, 2006; Pichler and Oberhuber, 2007), while *Picea engelmannii* have greater rates of regeneration, are longer-lived and usually more abundant in the canopy (Veblen, 1986). For the Fortress Mountain study area, the more dominant species was *Abies lasioscarpa,* with nearly 70% of the tree population. Much of the rest of the population was composed of the more resilient *Picea engelmannii.* A limitation of this study did not allow for individual species stand-level scaling with eddy covariance and sap flow techniques. Limited numbers (14 between both sites and species) of sap flow sensors did not allow for strong daily T regressions to be developed, and subsequently represent individual species with confidence. However, daily flow regressions developed with both species combined increased the confidence of the regression for daily flow calculations. With this in mind, observing the population dynamics measured and physiological characteristics reported in literature of these species (i.e. likelihood of drought stress) may help infer differences in T response to water availability between, and throughout the two contrasting summers. The majority of Fortress Mountain trees examined consists of a species more sensitive to drought stress, which sheds light on tree behaviour observed in the dry summer while considering growing season water availabilities. Despite increased water availability in 2016, overall T and ET were lower, suggesting the trees were using water conservatively with limited external drought pressures (Small and McConnell, 2008; Wieser *et al*, 2016; Bowling *et al*, 2018). In 2017, despite drought stress for much of the summer, overall T and ET were higher, especially in the first two months of the growing season with access to a sustained winter snowpack. This was not an expected response, as limitations in moisture availability later in the season and resulting drought stress seemed the most likely variable to limit T and ET totals compared to a year with more constant moisture availability (Pataki *et al*, 2000; Adams *et al*, 2009; Matyssek *et al,* 2009; Tague *et al*, 2009; Shafer *et al*, 2015).

The results of the two contrasting summers suggest that warming and summer drought may not impact overall forest health like initially hypothesized, at least over shorter time scales (Sowell

and Spomer, 1986; Day *et al*, 1990; Harder *et al*, 2015; Carroll *et al*, 2017). The dry summer in this study had a net loss of recharge to groundwater during summer months, which over the long-term, may have a greater impact on soil moisture regimes and water availability in consequent summers of continued drought stress. Coupled with knowledge of expected decreases of winter snowpack SWE in forested regions under climate change, subalpine forests could face water scarcity spurring long-term forest die off and mortality as suggested by Adams *et al* (2009).

2.4.3   *Wet and Dry Subalpine Growing Season Trends*

Examining subalpine tree T between two hydrologically different summers showed contrasts in water use. June saw the second highest monthly T rates for both studied years before the highest monthly reported T rates in July, due to larger, mature trees being exposed to radiation by a melting snowpack, allowing frozen xylem to thaw permitting water transport and senescence emergence before the juvenile growth still covered below (Mayr and Charra-Vaskou, 2007; Bowling *et al*, 2018). The 2017 hydrologic data, demonstrates that snowmelt persisted until late June allowing the ephemeral water table to exist until early July. Residual soil moisture contents, exposure of all tree size classes to radiation, and increased ambient temperatures promoted the highest levels of T for the growing season of both study years. The dry summer transpired almost double that of the wet summer in July (72.6 mm and 40.1 mm, respectively), due to a more P falling during June in that summer, promoting higher initial soil moisture values, rather than the lower magnitude but constant frequencies throughout the wet summer. Higher early season P quantities in the dry summer resulted in additions to the existing snowpack and underlying soil in the form of snow and rain, leading to higher overall water availability for trees to be higher, but only during June and July. SWE values also promoted higher T values in the July, while the larger winter snowpack took longer to deplete. There was a 100 mm difference in SWE between study years, allowing trees in the dry summer access to groundwater stores longer into the growing season.

Soil moisture in the dry summer were half that of the wet summer by August, although trees still transpired more, which was contrary to the expected result of higher T levels with higher soil moisture availability, as this was the only source of water for the subalpine trees. This is likely due to the water storage capacity of the trees during drought periods. Preisler *et al* (2016) found that during periods of drought, pine trees stored and used water differently than wet periods. They observed max DBH and tree sap flow in the afternoon, while trees filled their internal water storage during the morning. During wet periods, trees reached max sap flow at midday. Juvenile trees, or trees with less

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or limited water storage capabilities, reach maximum sap flow in the morning using moisture as it is available. At the Tower and Cutline sites, the stand is successively mature. Mature trees and large saplings have water storage capacities, whereas young saplings covered by the early-growing season snowpack and shaded by the canopy showed limited T during the early growing season.

Wet and dry summer data demonstrates noticeable differences in water use by tree class. Wet year saw water use by tree class in the 'water limited period' of the growing season was variable, with the only source being soil moisture. Juvenile trees (< 2 cm DBH) transpired less than 50 g/hour and mature trees (> 5 cm DBH) as much as 350 g/hour. The dry summer experienced more uniform T among all size classes, with trees < 2 cm DBH transpiring almost half that of trees > 5 cm DBH (50 and 100 g/hour, respectively). In dry summers, trees utilize water as it is available to them while additionally being driven by climatic influences. This is especially apparent in the trees of smaller DBH (Preisler *et al,* 2016). In the wet summer, despite water availability, the demand for water use appeared lower. Variations in usage magnitude differed among size class due to climatic controls and limitations on radiation controlling T under sufficient water availability conditions. In other water limited scenarios, especially that of Pomeroy *et al* (2015), decreased snow cover could mean sapling and juvenile trees start to transpire earlier in the growing season, but will also mean less overall water available for mature trees to T and establish growth during the one of most important periods of water availability in the growing season.

2.5   *Conclusions*
This study was designed to understand and quantify subalpine forest T and ET in two climatically contrasting summers (wet vs. dry). Separation and quantification of T and ET, was successfully demonstrated between two hydrologically contrasting summers using a combination of eddy covariance and heat balance sap flow data. T and ET values, compared to other literature, were of magnitudes expected for the species and size classes observed. Examining soil and climatic conditions on water use illustrated that trees strongly relied upon sufficient photosynthetically active radiation and abundant water availability during the beginning of the growing season, more specifically at the tail end of snowmelt. Despite lower season-long moisture availability supplied by both SWE and P, less overall P and lower soil moisture contents during the dry summer, the trees transpired 47.2 mm more than the wet summer. Winter snowpack and higher quantities of early-growing season P were confirmed to be one of the most important sources of available water for subalpine forests throughout the length of the growing season, helping maintain higher T and ET rates

in the dry summer. Net radiation was also seen as a driver for T and ET processes, even with limited water availability. This raises questions of *Abies lasioscarpa* and *Picea engelmannii* physiological processes, and long-term health of subalpine forests if subsequent years were similar to that of the examined dry summer hydrologically.

Stand density and maturity will help project forest health under a changing climate, as it has been shown that forested areas are expected to accumulate less snow while clearings and patched areas show increases, although altitudinal gradients are important with lower elevations receiving less snow overall. Less snow accumulation and SWE could be a determinant to more mature stands, as this moisture is especially important for season-long T totals with a majority occurring during this time. Season long T trends in this study support reliance on a strong winter snowpack and confirm the importance of early season moisture, even in years of decreased summer P and increased net radiation levels. In the wet summer, trees of all size classes had variable T patterns with minimal patterns in magnitude or frequencies. The dry summer showed trees of all size classes utilizing water, as it was available, despite lower soil moisture contents and P levels. In addition to understanding the vital early-season water use behaviours, it is equally important to understand tree response throughout the entire growing season, as there were differences between the two hydrologically different summers examined, which was especially apparent in cumulative T comparisons.

Overall, the sub-alpine forest had very different water use response to differing hydrologic conditions between a wet and dry summer growing season. Insights from tree response in the dry year provide basis for further, long term study in subsequent dry growing seasons to understand subalpine forest health in a changing global climate. In addition, a further understanding of tree physiology in both species of timing and utilization of specific water sources would be beneficial to further understand and quantify subalpine forest water use in the Canadian Rocky Mountains.

Chapter 3:   A δ¹⁸O and δ²H stable water isotope analysis of subalpine forest water sources under seasonal and hydrological stress in the Canadian Rocky Mountains, Kananaskis, Alberta

3.1   Introduction

Freshwater supplies in mountainous regions are at risk as snow and ice stores continue to decline under rising global temperatures, earlier winter snowmelt and changing regional climate regimes (Stewart *et al*, 2005; Whitfield and Cannon, 2000; Rasouli *et al*, 2014). Subalpine forests are of particular importance due to their hydrological connectivity within watersheds, controlling groundwater baseflow fluctuations, influencing basin-wide evapotranspiration (ET) and altering snow storage dynamics. A change in water availability to alpine vegetation could have a drastic effect on the health of these forests, in turn impacting yearly water budgets (Carroll *et al,* 2014; Harder *et al*, 2015; Kelsey *et al*, 2018). Quantifying and conceptualizing these changes is imperative to better inform downstream water management, in addition to providing better quality parameterization for climate models. Thus, understanding how subalpine forests are obtaining and using water during the short mountain region growing seasons must be improved.

Past research has conceptualized vegetation water use by a reservoir of simple well-mixed subsurface storage, which is refilled by growing season precipitation (P) and always available for transpiration (T) and growth (Wigmosta *et al*, 1994; Lawrence *et al*, 2011). In reality, recent research has proven water transport through soils to vegetation more complicated, with preferential pathways via macropores and water storage occurring in the finer pore spaces within the soil matrix (Barbeta and Peñuelas, 2017; Sprenger *et al*, 2018; Allen, 2019). Plant water use then becomes a more dynamic system involving soil pore spaces, preferential pathways and rooting depth of vegetation (Brooks *et al*, 2010). In subalpine vegetation systems, this complexity intensifies with high heterogeneity and anisotropy within the subsurface soil and bedrock geology. Often, there are large differences in soil depths and storage capacities further limiting available water during the growing season, represented in surficial discontinuities and glacially formed landscape features (Hood and Hayashi, 2015; Christensen *et al*, 2016; Harrington *et al*, 2017). Rooting structures of subalpine forests are also highly dependent on subsurface structure, with limitations in rooting depth due to shallow soils or limited access to groundwater tables as a consequence of fractured bedrock. Many

studies have explored the relationship of rooting depth and water uptake in generalized landscapes (Schenk and Jackson, 2002; West *et al*, 2012; Fan *et al*, 2017; Dubbert *et al*, 2019), but few have focused on these processes in subalpine landscapes at higher altitudes (Jia *et al*, 2017).

With stable water isotopes $\delta^{18}O$ and δ^2H, it is possible to determine the origin of water held within the xylem of plants, which is later transpired (Bertrand *et al*, 2014; Allen *et al*, 2019). These tracers have been used to show that plants draw water from a variety of sources, visible through the isotopic signatures unique to each source. Studies have shown that, despite being situated next to streams, many plants were using an unidentified source with isotopically different signatures than the 'obvious' source they were located next to (Brooks *et al*, 2009; Good *et al*, 2015; Bowling *et al*, 2017). McDonnell (2014) described this as the 'two water worlds' hypothesis, where streams and trees appear to evaporate different pools of water back to the atmosphere. He called upon more research and isotope-based tracer studies to be completed in forested catchments in order to understand the tightly bound soil water and more mobile water as sources for vegetation.

In mountainous environments that have limited growing seasons and water availabilities, subalpine forests strongly rely upon soil moisture stores to sustain growth (Day *et al*, 1990; Small and McConnell, 2008). Study sites located at Fortress Mountain in Kananaskis, Alberta are composed of coniferous tree stands of *Abies lasiocarpa* and *Picea engelmannii*. Current research of these species has focused on physiological and biological differences by elevation and climate (Sowell and Spomer, 1986; Sala, 2006; Kueppers *et al*, 2017), and species management (Alexander, 1987). However, there are limited studies of ET and water use (Brodersen, 2006). Most Rocky Mountain forest research has been conducted in the United States, with limited research programs conducted in the Canadian Rocky Mountains, highlighting a gap in knowledge of these species in northern latitudes. Determining the water sources of these Canadian Rocky Mountain species is important to understand tree growth and T throughout the shoulder and growing seasons in order to understand the hydrological connectivity of mountain watersheds (Kräuchi *et al*, 2000; Matyssek *et al*, 2009), and how these behaviours could be altered under long-term climate change. This study aims to identify and characterize subalpine forest water use at an elevation of 2100 m in the Canadian Rocky Mountains. Three main objectives will be addressed through a $\delta^{18}O$ and δ^2H stable water isotope analysis on trees at the Fortress Mountain study sites: I) determine subalpine forest source water during pre-, mid- and end- of the growing season; II) partition relative source water contributions of xylem water within *Abies lasioscarpa* and *Picea engelmannii* using a simple two component mixing

model; and III) evaluate which source waters are most important for subalpine tree T, and how long term climate pattern changes could affect forest health.

3.2   Materials and Methods

3.2.1   Study Site Description

The data for this study was collected at Fortress Mountain in the Kananaskis River Valley of the Canadian Rocky Mountains, Alberta. A research campaign was conducted from May - September 2017, from the beginning of snowmelt until end the of the growing season in order to obtain hydrometric and isotopic data. Fortress Mountain has a highly variable climate depending on season, but typically has long cold winters and cool wet summers, falling in the humid continental category (Beckstead & Veldman, 1985; Alberta Environment and Sustainable Resource Development, 2014).
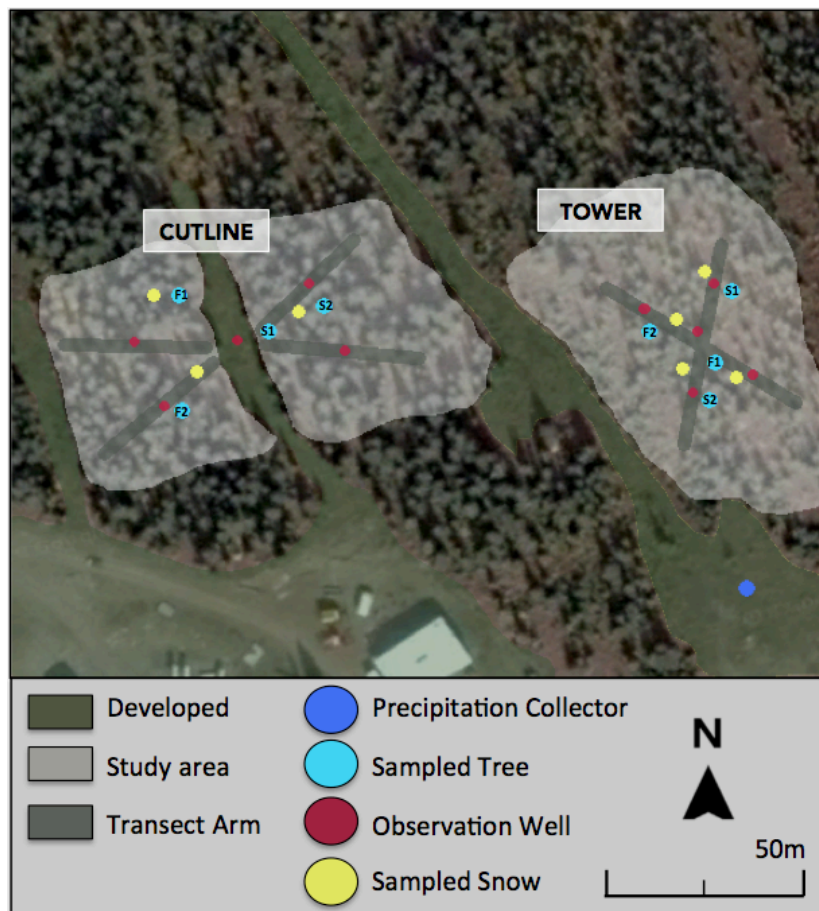
Figure 3-1. Study site map of Tower and Cutline study sites at Fortress Mountain, Kananaskis, AB. Isotopic sampling locations are highlighted, with labels S# representing *Engelmann spruce* and F# representing *Subalpine fir*.

Two adjacent subalpine sites at Fortress Mountain were used in this study in order to accurately represent the diverse forest structure at this elevation, hereafter referred to as 'Tower' and 'Cutline'. They are close in proximity (115 m apart) and sit on a low gradient rolling bench at elevations of 2079 m and 2083 m, respectively (Figure 3-1). They differ primarily by tree age and community composition, with Tower having the younger and higher population density and Cutline the older and sparser population (Table 2-2). The subalpine forest at this elevation consists of coexisting tree species subalpine fir (*Abies lasioscarpa*) and Engelmann spruce (*Picea engelmannii*). Species proportions are similar between both sites, with subalpine fir being the dominant species and Engelmann spruce making up the remainder (71.9 % and 29.5 %, respectively). There are only coniferous tree species at this elevation, with the remaining 1.4 % of the population consisting of lodgepole pine (*Pinus contorta*) and alpine larch (*Larix lyalli*). A transect system with arms spanning approximately 50 m in each cardinal direction, and 10 sampling locations along each segment was established at each site (Figure 3-2) and used to collect forestry inventory and leaf area index (LAI) values.

3.2.2   Hydrometric Data Collection

Groundwater wells were installed at both study sites to understand early season snowmelt and the ephemeral water table it generates. A total of five wells were installed at each site (10 total); along each transect, a well was placed in the middle of each arm with an additional well at the centre point, where transect arms meet. At Tower, water level transducers (HOBO U20 Water Level Logger; OnSet, MA, USA) were placed in 3 of the 5 wells (north, south and west transect arms). At Cutline, an additional three U20 level loggers were installed (north, south and east transect arms). A barometric data logger (HOBO U20 Water Level Logger; OnSet, MA, USA) was installed at Cutline for atmospheric water level compensation for all loggers. Atmospheric compensation was corrected for using Onset HOBOware Pro 3.7.12 data processing software. Monitoring wells were constructed using Schedule 40 PVC pipe slotted along the entire buried length. Fabric 2" diameter well sock (ESP Well Supply, USA) was used to cover the outside surface and act as a screen for fine sediments.

The vadose zone was instrumented for characterization of moisture dynamics after P events. Three soil moisture stations, split between the two study sites were used and monitored throughout the entire study duration. At Tower two stations were installed, with one in an open tree clearing and the other within a closed canopy. At Cutline, the soil moisture station was situated within a semi-open tree canopy with ample ground vegetation. Each station was instrumented with two CS650 Soil

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Moisture probes (Campbell Scientific Inc., UT, USA) at depths of 30 cm (parallel to the soil surface) and vertically intersecting the end of the horizontally installed probe reaching a depth of 30 cm. Soil temperature (type K thermocouple; Omega, CT, USA) was also measured in the same pits at 5, 10, 15 and 30 cm depths. Both CS650's and thermocouples were logged on a CR1000 data logger (Campbell Scientific Inc., UT, USA), sampled every 30 seconds and averaged over 30 minutes. Soil tensiometers (2725ARL Jet Fill Tensiometer; SoilMoisture, CA, USA) were setup adjacent to the three existing soil moisture stations, each comprised of three tensiometers at depths of 10, 20 and 30 cm. Tensiometer data was collected by manual measurement 25 times from June 22nd to August 10th, during the snow-free growing season.

Basic meteorological (MET) data was collected by instrumentation mounted on a 15.5 m tower, above the forest canopy. MET data collected included net radiation via sensors at the top (15 m) and bottom (1.4 m) of the tower (NR Lite2; Kipp & Zonen, VA, USA), relative humidity at a height of 15 m (HMP 155; Vaisala, Finland), and wind speed and direction using a CSAT3 sonic anemometer. P was collected at the Cutline site using an Ott Pluvio^2 (Ott Hydromet, CO, USA) wired to a CR3000 data logger (Campbell Scientific Inc. UT, USA) with a wind protection shield, and was additionally corrected for wind under catch.

3.2.3   Isotope Sample Collection

All potential sources for tree water use, including snow, P and groundwater, were sampled for analysis of δO^{18} and δH^2. There was no surface water at the study site to sample. Water samples were collected during pre-, mid- and post growing seasons from May-September in 2017 whenever the sources were available. Water samples were bottled with minimal headspace and stored at room temperature (never refrigerated or frozen to limit phase changing) before processing.

Snow samples were collected for both the pre- and post- growing season sampling periods due to availability. In the pre- period, the spring snowpack was approximately 1.2 m deep at the time of sampling. Snow pack cores were taken with a 4.1 cm diameter PVC pipe, and melted at room temperature to ensure complete mixing and no phase changing before being sub-sampled into 20 mL glass poly-seal sampling bottles. A total of 6 cores were taken on two different dates, May 23rd and June 3rd. Snow was additionally sampled during the post- growing season collection period due to an early season snowfall just prior to September 26th, the sampling date. Snow was collected in a plastic

sampling bag and melted at room temperature before sub-sampling into a 20 mL glass poly-seal container.

P (in the form of rain) was measured throughout the entire study period (May-September) after every major storm event when possible, and less frequently during July-September due to extremely dry conditions and minimal major P events. Samples were collected a total of 9 times, and were sub-sampled from the collector into 20 mL glass poly-seal containers. A P collector was built to collect and limit evaporation of samples between sampling periods. A plastic hose was watertight sealed to the bottom of a funnel, which was then sealed to the top of a water reservoir container. The hose was cut with enough length to coil on the bottom of the reservoir to ensure the water level of collected samples topped over the hose, limiting evaporation and phase changing of the sample. A Ping-Pong ball was placed in the top of the funnel to limit evaporation further.

Groundwater was sampled during the snowmelt period starting in May until the snowmelt groundwater table dissipated. The geology at this site consists of fractured bedrock and glacial till, and no constant groundwater table persists during the growing season (Christensen *et al*, 2016). All groundwater samples were taken from 10 wells ranging from 71-132.5 cm in depth, which falls within the maximum rooting depth of *Abies lasioscarpa* and *Picea engelmannii.* Sampling procedure consisted of purging the entire well volume 3 times before sampling into a 20 mL glass poly-seal container. Groundwater was sampled a total of 13 times from May 15th to June 19th.

Soil water samples were taken at every tree sampled for stem water. Two samples were taken at each tree during every pre-, mid- and post- growing season sampling campaign totaling 48 overall samples. Samples were taken with a 1-inch soil auger at a depth of 35 - 45 cm and stored in a thick poly-plastic bag. Soil samples were refrigerated during storage and transportation in order to ensure no evaporation or phase changing occurred before azeotropic distillation analysis occurred

Eight trees were sampled for each pre-, mid- and post- growing season sampling period for a total of 24 tree stem water samples. Trees were sampled from the Tower and Cutline sites, which contributed 4 samples each to a single sampling period. Each set of 4 trees was selected first by species division and then by size class (Figure 3-1). At both Tower and Cutline, two *Abies lasioscarpa* and two *Picea engelmannii* were sampled. The two trees from each species were sampled according to the forest survey conducted in 2015, ensuring trees from above and below the median DBH and height of a species were sampled. The same trees were sampled during each sampling event.

Site	Tree Species	Sample Code	DBH (cm)	Height (m)
Tower	*Abies lasioscarpa*	T-F1	6.7	4.27
	Abies lasioscarpa	T-F2	18.7	8.76
	Picea engelmannii	T-S1	6.3	4.13
	Picea engelmannii	T-S2	30.5	10.64
Cutline	*Abies lasioscarpa*	C-F1	10.3	6.68
	Abies lasioscarpa	C-F2	18.6	10.43
	Picea engelmannii	C-S1	7.9	5.88
	Picea engelmannii	C-S2	28.6	12.22
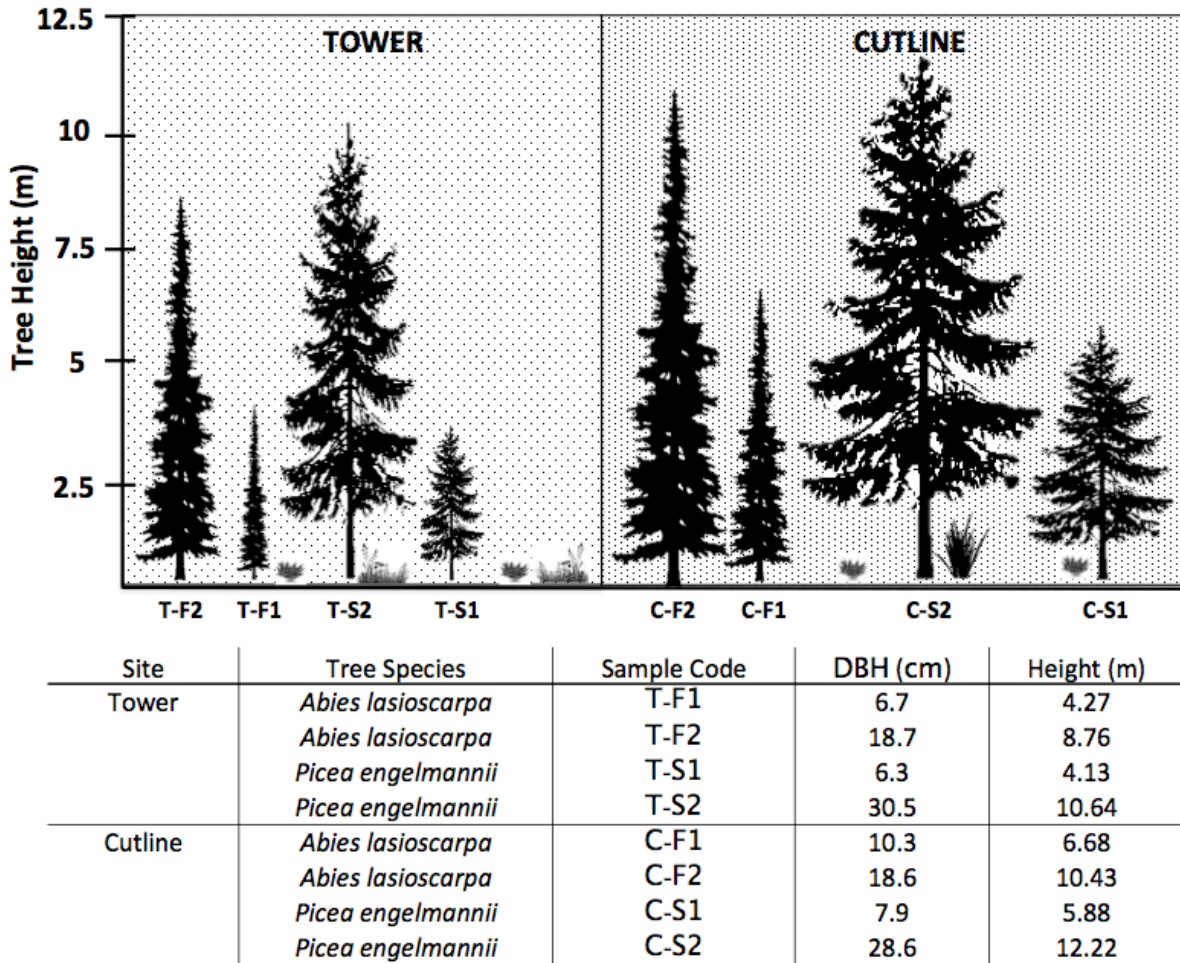
Figure 3-2. Schematic of class and size distribution of selected trees for stable water isotope sampling of δO^{18} and δH^{2} at both Tower and Cutline study sites.

Tree water was sampled from *Abies lasoscarpa* and *Picea engelmannii* by harvesting older growth (no current year growth) from stem sections by cutting branch sections off from the top, middle and bottom of each tree. Small stem sections were snipped from the mid point of the branches, taking care not to sample new growth of the current growing season. Needles were stripped from the stem samples before being placed in 30 mL vaccutainers for storage. As many stems as possible were stored in the containers to limit headspace for storage until azeotropic distillation analysis occurred. For each tree, 10 vaccutainers were filled in order to obtain an adequate sample size for distillation. All samples were harvested with nitrile gloves to limit contamination during handling. After sampling, samples were placed in the freezer for storage and transport until analysis in order to limit evaporation or phase changes from occurring, compromising sample integrity.

3.2.4 Isotope Sample Processing and Distillation

All samples collected were submitted and processed by the Environmental Isotope Laboratory (EIL) at the University of Waterloo, Ontario. Snow, groundwater and P water samples were processed using the δO^{18} and δH^2 LGR-OA-ICOS Laser System as described in the methods used by EIL, University of Waterloo (LGR, 2010; Penna, 2012; Berman *et al*, 2013). Soil and tree samples were first processed by azeotropic distillation (Dewar and McDonald, 1961; Revesz and Woods, 1990) using toluene to extract pure water from organic sample. The soil water samples were then run on the LGR-OA-ICOS Laser System at EIL, University of Waterloo (2013), while tree water samples were run using the EA/HT Mircomass IsoPrime system as described in the methods by EIL, University of Waterloo (Drimmie *et al* 2001; Morrison, 2001). The EA system was used over the LGR-OA-ICOS Laser System due to better accuracy and analysis of organically derived water contents (Drimmie *et al*, 2011).

3.2.5 Data Processing

3.2.5.1 Isotopic Framework Development

Table 3-1. Framework parameters calculated for the Fortress Mountain isotopic framework used in development of the LEL and the LMWL for 2017. Where, steady state isotopic composition of a terminal basin is δ_{ssl}, limiting isotopic enrichment of a water body is δ^*, equilibrium liquid-vapour fractionation factor is α^*, equilibrium is ε^*, and kinetic separation is ε^*_κ, mean weighted isotopic composition of P δ_P(‰).

Variable	Value	
h (%)	62.8	
T (°C)	9.4	
LEL slope, intercept	4.49, -0.064	
	^{18}O	^2H
α^* (^{18}O, ^2H)	1.0	1.1
ε^* (^{18}O, ^2H)(‰)	10.8	97.8
ε^*_κ (^{18}O, ^2H)(‰)	6.3	5.6
δ_{AS} (^{18}O, ^2H)(‰)	-27.5	-209.3
δ^* (^{18}O, ^2H)(‰)	3.4	-46.0
$\delta\varepsilon_{\delta SSL}$ (^{18}O, ^2H)(‰)	-39.2	-370.3
δ_{ssl} (^{18}O, ^2H)(‰)	-7.3	-99.7
δ_P (^{18}O, ^2H)(‰)	-20.0	-154.0
δ_{Ps} (^{18}O, ^2H)(‰)	-17.0	-132.0

An isotopic framework for the 2017 study year was developed in order to generate a local meteoric water line (LMWL) and local evaporation line (LEL) specific to the Fortress Mountain, Kananaskis,

AB region (Table 3-1). This local framework is necessary to analyze the stable water isotope samples obtained. In order to properly develop a framework, past climate normals for relative humidity and temperature were determined from long-term Environment Canada data in conjunction with meteorological stations that have been situated at Fortress Mountain since 2014 (Environment Canada, 2015). In addition to relative humidity and temperature constraints, individual network parameters were calculated specific to the Kananaskis region. Using Brock *et al.* (2007) as a guide, the following baseline network parameters were calculated: isotopic composition of ambient atmospheric moisture, δ_{AS} (Gibson and Edwards, 2002); steady state isotopic composition of a terminal basin δ_{ssl} (Gonfiantini, 1986); limiting isotopic enrichment of a water body, δ^* (Gonfiantini, 1986); equilibrium liquid-vapour fractionation factor, α^* (Horita and Wesolowski, 1994); the equilibrium, ε^*, and kinetic separation, ε^*_κ (Gonfiantini, 1986); and the mean weighted isotopic composition of P δ_P(‰)(Bowen and Revenaugh, 2003; IAEA/WMO, 2015; Bowen, 2017). Once calculated, the LEL was determined as the intersection of the calculated δ^*, δ_{ssl} and δ_P points in δ^{18}O and δ^2H space. The LMWL for the framework was determined by plotting all sampled source water on the δ^{18}O and δ^2H
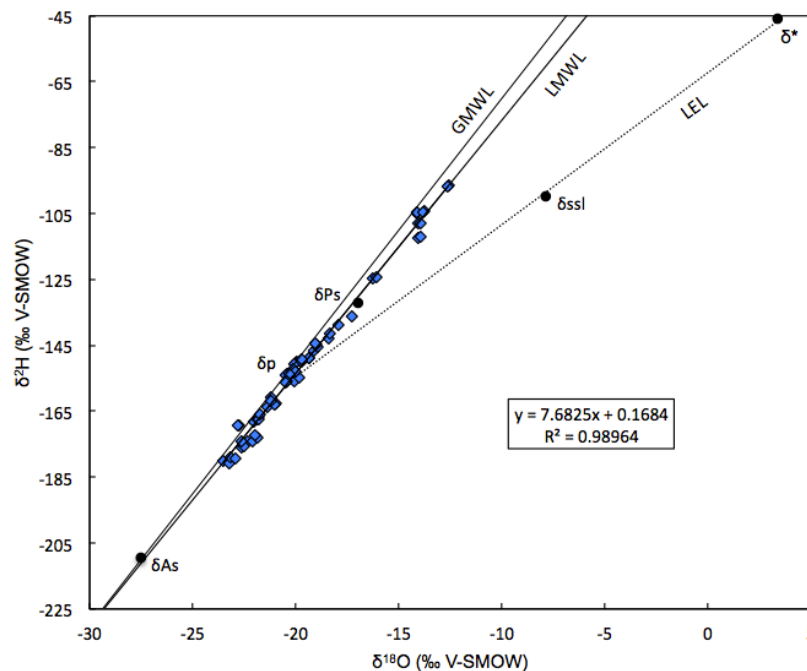
Figure 3-3. δ^{18}O and δ^2H isoplot with developed Fortress Mountain isotopic framework and associated parameters. LMWL created by regression is shown along with source water (P, groundwater, snow) plotted along the line. Generated R^2 value was .99 with an equation of δ^2H = 7.78δ^{18} + 0.17. Calculated GMWL shown as δ^2H = 8δ^{18} + 10 (Craig, 1961). LEL for the local climate is also shown.

Plot (P, groundwater, snow), then obtaining the R^2 value generated by a linear regression. The LMWL generated had an R^2 value of 0.99, and equation of $\delta^2H = 7.78\delta^{18} + 0.17$ (Figure 3-3), which indicates a strong relationship adequate for LMWL representation of the Fortress Mountain, Kananaskis area. All calculated parameters, LEL, LMWL, Global Meteoric Water Line (GMWL) and all isotope samples collected and analyzed were all subsequently plotted on a $\delta^{18}O$ and δ^2H plot.

3.2.5.2   *MixSIAR Bayesian Mixing Model*

In order to partition the relative source water contributions of sub-alpine forest xylem water, the R package MixSIAR, a Bayesian mixing model (BMM) that runs the Markov Chain Monte Carlo (MCMC) method, was used. MixSIAR is the latest iteration of a series of mixing models (MixSIR, SIAR) designed to analyze biotracer and isotope data to determine relative proportions of a mixture and its sources (Stock and Semmens, 2016). MixSIAR successfully incorporates the uncertainties associated with stable water isotope compositions, multiple sources, error terms, priors and varying data structures allowing for analysis of covariates and multiple variables at once. For this study, the GUI version of MixSIAR was used within R console (Stock and Semmens, 2016; R Core Team, 2019). MixSIAR was chosen over simple linear mixing models and previous versions of compartment mixing models due to its performance partitioning source water from multiple sources while including error terms and statistical checks for competency (Evaristo *et al*, 2017; Wang *et al*, 2019). Importantly, the BMM assumes uncertainty and variability associated with stable water isotope sources are normally distributed. Along with the residual error term, the model will find a solution even if it is nonsensical. This was avoided by ensuring the proper checks and $\delta^{18}O$ and δ^2H biplot analysis was followed as suggested by MixSIAR (Stock and Semmens, 2016).

Two separate model runs were completed, analyzing the covarying effects of: time of season and species and time of season and tree age. Each run was setup with the same parameters. Time of season was always considered a 'random' variable, while age and species were always considered 'fixed' (Semmens *et al*, 2009). Run lengths were set at a chain length of 1,000,000 iterations to ensure the Gelman-Rubin and Geweke statistical diagnostic checks were met and the MCMC chains had converged (Gelman and Ferguson, 2012). The error structure used in the model was residual * process (Parnell *et al*, 2010). Both tropic enrichment factor and concentration dependence were set to 0. A non-informative prior (uniform) distribution was chosen based on insights of the MCMC method and observations drawn from the $\delta^{18}O$ and δ^2H biplot (Newsome *et* al, 2007; Evaristo *et al*, 2017).

3.3   Results

3.3.1   Isotopic Characteristics of Sub-alpine Trees and their Source Waters

The isotopic compositions of tree source water (excluding soil water) varied extensively between P, snow and groundwater throughout the three seasonal sampling periods (pre-, mid-, end-) (Figure 3-4). The $\delta^{18}O$ value of P ranged from -19.99 to -12.59 ‰ with a mean (± 1 SD) of -15.28 (± 2.38) ‰. $\delta^{2}H$ value of P ranged from -150.44 to -96.49 ‰ with a mean (± 1 SD) of -177.31 (± 17.93) ‰. Both $\delta^{18}O$ and $\delta^{2}H$ P values varied significantly between the 8 sampling periods over the growing season (p = 0.040 for both when $p <$
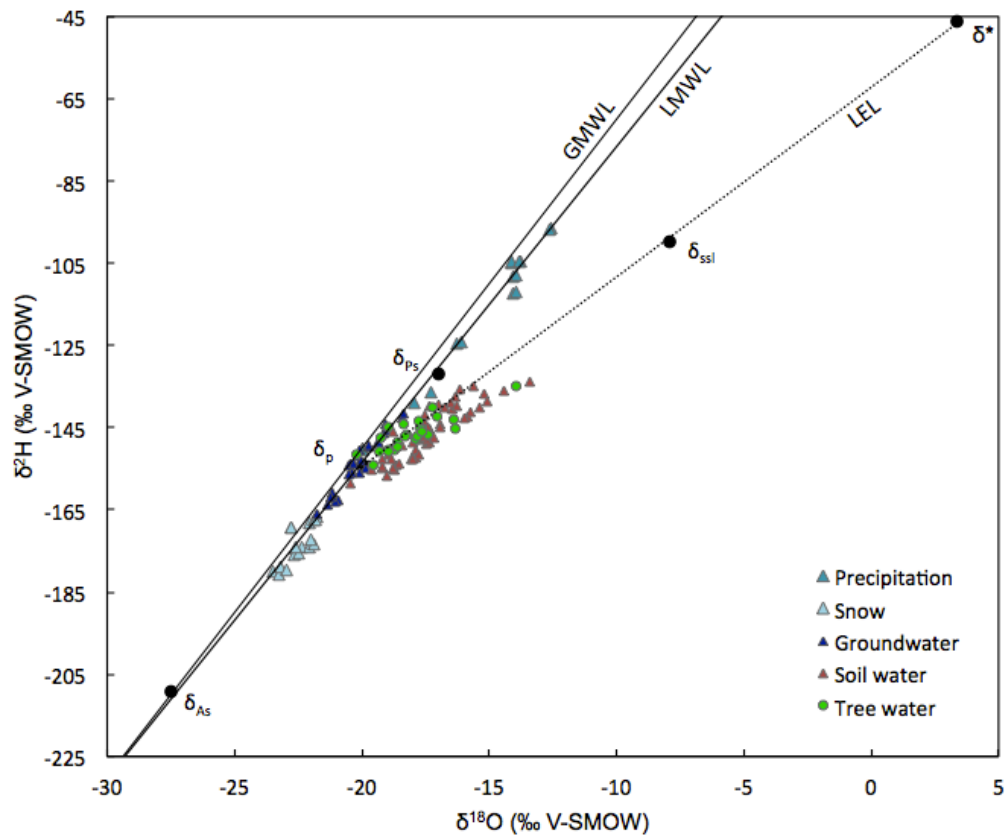
Figure 3-4. $\delta^{18}O$ and $\delta^{2}H$ isoplot showing all sampled source waters (P, snow, groundwater, soil water) across three sampling periods in 2017 (pre-, mid- end- growing season) plotted with tree xylem water. LMWL generated shown with an equation of $\delta^{2}H = 7.78\delta^{18} + 0.17$. GMWL shown as $\delta^{2}H = 8\delta^{18} + 10$ (Craig, 1961). Calculated LEL for the local climate is also shown.

0.05 at 95% confidence). P isotopic signatures typically vary greatly, influenced by the temperature of P condensation, and the ratio of P being condensed to the P already condensed in the air mass. Successful creation of a LMWL specific to the Kananaskis region (R^2 0.99, Figure 3-3) was dependent on the variation in P signatures over the growing season, from snow melt to the end of senescence, in order to provide confidence and a strong linear relationship. The δ^{18}O value of snow water ranged from -23.52 to -21.79 ‰ with a mean value (± 1 SD) of -22.48 (± 0.54) ‰. Where the δ^2H value of snow water ranged from -180.83 to -166.67 ‰ with a mean value (± 1 SD) of -173.40 (± 4.59) ‰. Both δ^{18}O and δ^2H snow water values varied significantly between the 3 sampling periods in May, June and September (p = 0.021 and p = 0.003 when p < 0.05 at 95% confidence, respectively). Like rain, snow isotope signatures also varied due to similar atmospheric processes governing particle formation. The δ^{18}O value of groundwater ranged from -21.75 to -18.33
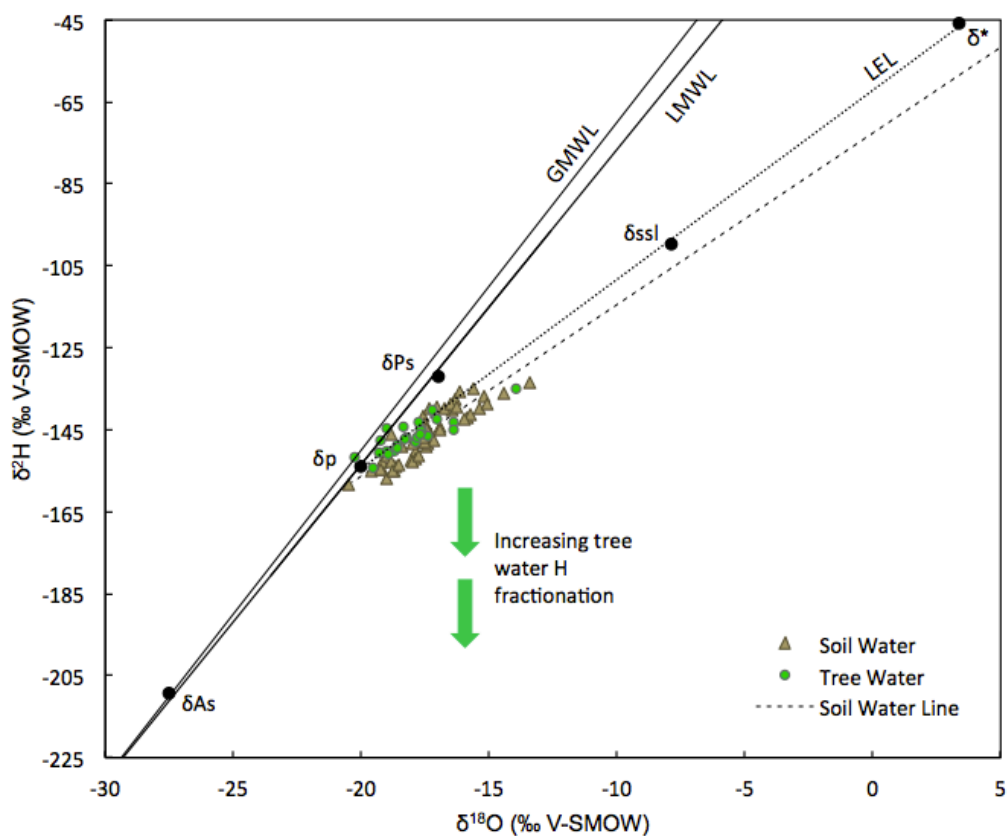
Figure 3-5. δ^{18}O and δ^2H isoplot with soil water and tree xylem water for all sampling periods in 2017 (pre-, mid-, end-) plotted. Soil water regression line δ^2H = 4.22 δ^{18} – 72.95, R^2 = 0.81. Tree water plotted below this line indicates δ^2H fractionation. LMWL created by regression shown as δ^2H = 7.78δ^{18} + 0.17. GMWL shown as δ^2H = 8δ^{18} + 10 (Craig, 1961). Calculated LEL for the local climate is also shown.

‰ with a mean value (± 1 SD) of -20.03 (± 0.91) ‰. The δ^2H value of groundwater ranged from - 166.08 to -141.56 ‰ with a mean value (± 1 SD) of -153.08 (± 6.91) ‰. The δ^{18}O and δ^2H groundwater values did not vary significantly during the snowmelt period, while a groundwater table was present and accessible to trees ($p > 0.05$). There was no significant difference due to the groundwater pool being generated from the spring snowpack melt over a concentrated time period.

Soil water and tree xylem water were analyzed separately, as they both had potential for species and growing season variation and were sampled concurrently during each of the three sampling periods. The δ^{18}O value of soil water ranged from -20.47 to -13.40 ‰ with a mean value (± 1 SD) of -17.40 (± 1.38) ‰, where the δ^2H value ranged from -158.44 to -133.63 ‰ with a mean value (± 1 SD) of -146.30 (± 6.48) ‰. There was no statistically significant difference in the δ^{18}O and δ^2H isotopic signature obtained from soil water samples of different tree species ($p > 0.05$). There was, however, a significant difference in the δ^{18}O values in soil water obtained over the growing season ($p = 0.037$ when $p < 0.05$, 95% confidence interval). Small differences between δ^2H in sampled soil water indicates minimal evaporative influence causing isotopic enrichment during the sampling process. However, the soil water line plotted below the LMWL (δ^2H = 4.22 δ^{18} – 72.95, R^2 = 0.81) indicating soil water experiences evaporative enrichment naturally, before collection (Figure 3-5). Differences in δ^{18}O values indicate replenishment from a variable source, in this case P as there was no groundwater present, which was isotopically variable over the growing season.

The δ^{18}O value of tree xylem water ranged from -20.22 to -13.94 ‰ with a mean value (± 1 SD) of -18.04 (± 1.27) ‰. The δ^2H value of tree xylem water ranged from -154.31 to -134.82 ‰ with a mean value (± 1 SD) of -146.55 (± 4.08) ‰. There was no statistically significant difference in xylem water δ^{18}O and δ^2H values between species ($p > 0.05$). Additionally, there was no significant difference ($p > 0.05$,) in xylem water δ^{18}O distribution between sampled growing season stages, but statistically, there was a seasonal difference ($p = 0.025$ when $p < 0.05$, 95% confidence interval) in δ^2H values. Differences in δ^2H between soil and xylem water are indicative of evaporative influence causing isotopic enrichment, where δ^2H fractionation was displayed in 8 of 25 tree xylem water samples (Figure 3-5). δ^2H fractionation in vegetation is calculated as δ^2H$_{SOIL}$ - δ^2H$_{TREE}$. A positive difference indicates fractionation, where a negative, or 0 difference indicates no fractionation. Most vegetation are assumed to not H^2/H^1 fractionate when using and transpiring water, although it has been observed in some cases (Dawson and Ehleringer, 1992; Evaristo *et al*, 2017). When partitioned over the growing season incorporating soil and groundwater, δ^2H values of tree xylem water showed seasonal variation in sources used (Figure 3-6). Although a large overlap between soil water and

groundwater signatures were observed, (δ^2H -158.44 to -143.56 ‰), a pattern was noticeable between the three sampling periods. Pre- season trees appeared to use a mixture of sources, having access to the groundwater table during spring snowmelt, while mid- season used predominantly soil water, with some retention and storage of groundwater from the beginning of the growing season. End- season xylem water δ^2H values again incorporated more groundwater, while lessening dependencies on soil water only. The increase δ^2H signatures similar to groundwater may be explained by an increase in P and snow near the end of the growing season, replenishing soil moisture and deep groundwater stores after a summer season of no recharge (Chapter 2). Snow δ^2H values during the end- period were -169.29, helping to support the recharge utilization theory. End- season was the only sampling period to observe a trend in tree age and water source, with smaller trees utilizing more soil water than larger trees.
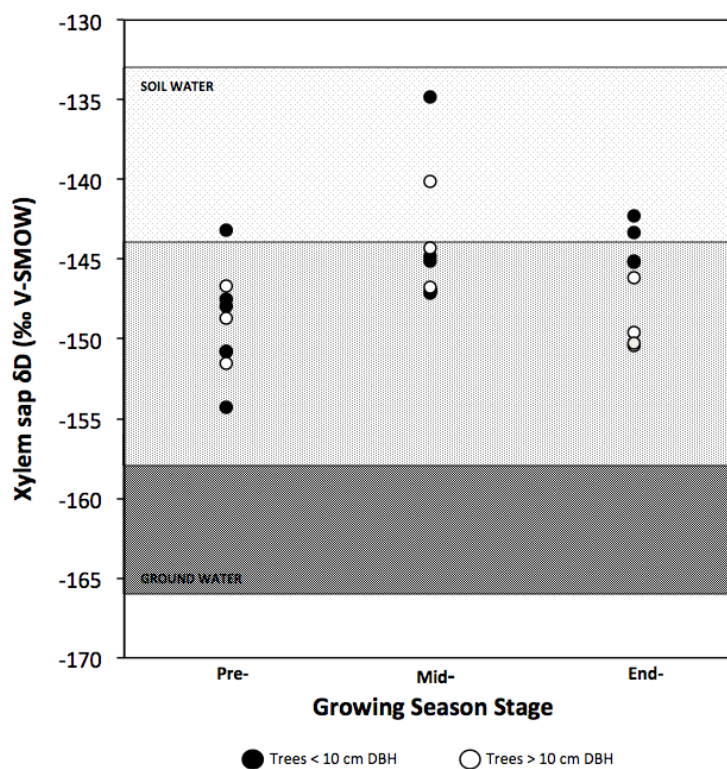
Figure 3-6. δ^2H xylem sap plotted by sampling period (growing season stage) and by tree size class (> 10 cm <). Lightest gray band at top of plot is the δ^2H space occupied by soil water only. The dark gray band on the bottom of the plot is the δ^2H space occupied by groundwater only. The band in between soil water and groundwater δ^2H signatures is the extent of overlap between the two sources.

3.3.2   Quantifying Relative Source Water Partitioning

Results for the MixSIAR BMM are sectioned into growing season stage and species (spruce and fir), and growing season stage and tree age. Tree age is based on the size class separations chosen for initial tree xylem isotope sampling. The lower size class of both species is hereafter the 'young' category, and the upper size of both species the 'old' category. Growing season stage is partitioned by the three major sampling events of tree xylem and soil water, pre-, mid- and end- growing season. The MixSIAR R package is not able to concurrently run more than two constraining variables at one time, although specializing in multiple source partitioning, which is why runs of species and age were separated.

The growing season stage and species BMM analysis showed differences across time and within spruce and firs (Figure 3-7). Although both species had different source water proportions, they both followed similar water use and source trends. For firs, the proportions of water sources during the pre- period were as follows: 36.5 % groundwater (SD ± 23.0 %), 6.6 % P (SD ± 7.2 %), 6.8 % snow (SD ± 8.9 %) and 50.1 % soil water (SD ± 20.5 %) (Figure 3-7, a). The mid- period proportions were: 11.3 % groundwater (SD ± 11.5 %), 13.4 % P (SD ± 7.9 %), 4.3 % snow (SD ± 5.9 %) and 71.0 % soil water (SD ± 17.6 %) (Figure 3-7,a). Finally, the end- period proportions were comprised of: 28.5 % groundwater (SD ± 20.6 %), 7.6 % P (SD ± 7.3 %), 6.3 % snow (SD ± 8.1 %) and 57.6 % soil water (SD ± 20.7 %) (Figure 3-7, a). In spruce, the proportions of source waters during the pre- period were: 20.5 % groundwater (SD ± 14.6 %), 5.5 % P (SD ± 5.6 %), 4.8 % snow (SD ± 6.6 %) and 69.3 % soil water (SD ± 15.2 %) (Figure 3-7, b). Mid- period proportions were: 6.5 % groundwater (SD ± 8.4 %), 11.5% P (SD ± 7.8 %), 2.8 % snow (SD ± 4.4 %) and 79.2 % soil water (SD ± 14.4 %) (Figure 3-7, b). Lastly, end- period proportions were comprised of: 14.7 % groundwater (SD ± 12.3 %), 6.5 % P (SD ± 6.1 %), 4.0% snow (SD ± 5.5 %) and 74.7% soil water (SD ± 15.1 %) (Figure 3-7, b).

BMM confidence proportion plots for both species are shown in Figure 3-8. Fir trees used the highest proportion of groundwater in the pre- period, utilizing increased groundwater tables due to spring snowmelt (Figure 3-7). Soil water and P proportions were highest in the mid- period, due to tree reliance on soil moisture as the groundwater table receded and was eventually no longer available. What little P fell recharged shallow soil moisture layers allowing access for the trees. There was a slight increase in proportion of groundwater used, due to late growing season P recharging deeper soil moisture stores (Figure 3-7). As highlighted earlier, the δ^2H signatures of late growing season snow likely influenced the increase in groundwater signatures observed the xylem water. With

similar source usage throughout the growing season as fir, spruce relied upon soil water more heavily with a minimum difference of 8.2 % at the mid- sampling points and a maximum spread of 19.2 % at the pre- growing season sampling point (Figure 3-7). Spruce relied less upon initial groundwater stores and end of season recharge with differences of 16.0 % and 13.8 %, respectively (Figure 3-7).

The BMM analysis of growing season stage and ages showed minimal water source differences across time, but similarities in behaviour between age groups (Figure 3-9). Slight differences between young and old were noticeable in the overall source partition spreads, in the mid- and end- period specifically. In the young group, proportions for Pre- season were: 15.0 % groundwater (SD ± 14.4 %), 4.4 % P (SD ± 5.0 %), 4.6 % snow (SD ± 6.0 %) and 76 % soil water (SD ± 16.9 %) (Figure 3-9, a). In the mid- period, proportions were: 8.6 % groundwater (SD ± 9.4 %), 11.5 % P (SD ± 6.0 %), 3.4 % snow (SD ± 4.4 %) and 76.4 % soil water (SD ± 13.5 %) (Figure 3-9, a). Finally, the end- period proportions were: 12.1 % groundwater (SD ± 11.0 %), 5.4 % P (SD ± 5.6 %), 4.1 % snow (SD ± 5.1 %) and 78.4 % soil water (SD ± 14.7 %) (Figure 3-9, a). For the older tree group, pre- period proportions were as follows: 24.1 % groundwater (SD ± 19.2 %), 7.0 % P (SD ± 7.2 %), 7.1 % snow (SD ± 8.9 %) and 61.8 % soil water (SD ± 21.4 %) (Figure 3-9, b). In the mid- period, proportions were: 15.3 % groundwater (SD ± 15.2 %), 20.7 % P (SD ± 8.3 %), 5.3 % snow (SD ± 6.6 %) and 58.7 % soil water (SD ± 18.2 %) (Figure 3-9, b). Lastly, end- period proportions were: 23.2% groundwater (SD ± 18.8 %), 8.1 % P (SD ± 7.6 %), 7.8 % snow (SD ± 9.9 %) and 60.8 % soil water (SD ± 20.7 %) (Figure 3-9, b).

BMM confidence proportion plots for both age groups are shown in Figure 3-10. The young group, showed a very slight increase of soil water use over the growing season (2.4 %) while relying upon this source for over 75 % of its water needs (Figure 3-9). Interestingly, despite an available groundwater table at the beginning of the growing season, this only slightly influenced the groundwater source portion compared to the other growing season stages (15 % in the pre- stage and 8.6 % during mid-), but most reliance remained on soil water (Figure 3-9). This may be explained by less established rooting systems of younger trees, which do not have as much access to the groundwater table as their larger counterparts. Like the young group, the old tree group had a steady proportion of soil water use throughout the growing season, although of a smaller magnitude (16.5 % less on average) (Figure 3-9). In this age group, groundwater reliance was 7.8 % more on average, with higher values at the start and end of the season, during snowmelt and end of growing season recharge (Figure 3-9). Both age groups utilized P more during the mid- period, while there was no
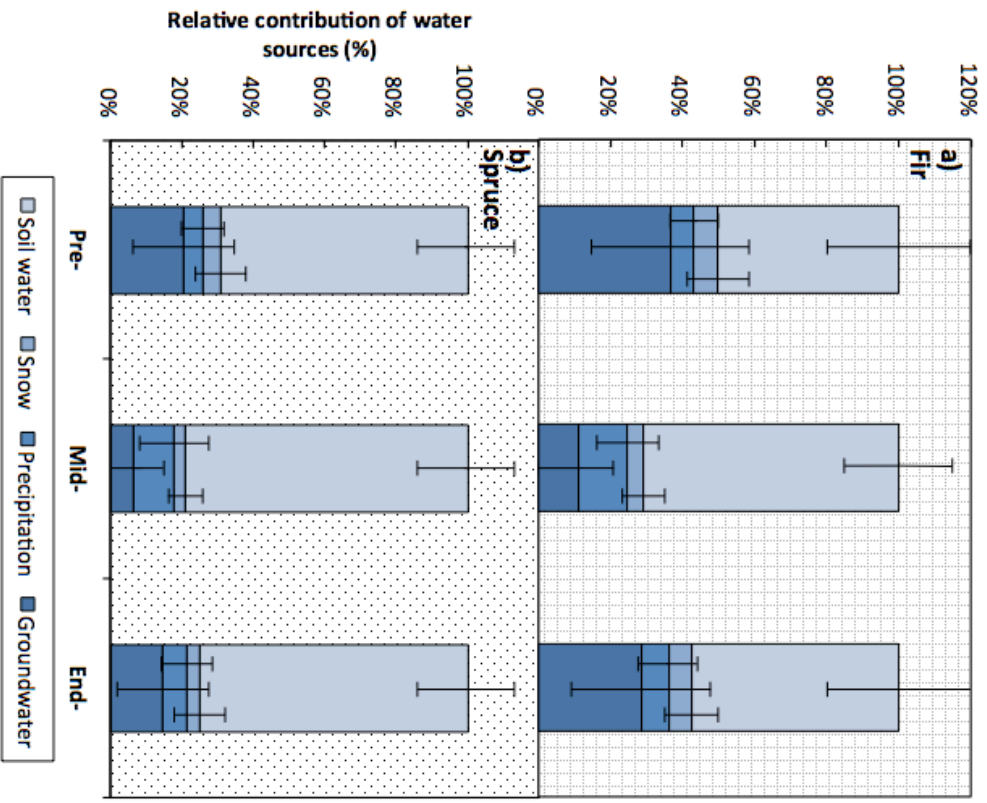
Figure 3-7. Relative source water contributions to xylem water generated by MixSIAR BMM partitioned by sampling period and growing season stage (pre-, mid- end) and tree species (a) fir, b) spruce). Standard deviations for each source depicted by error bars.
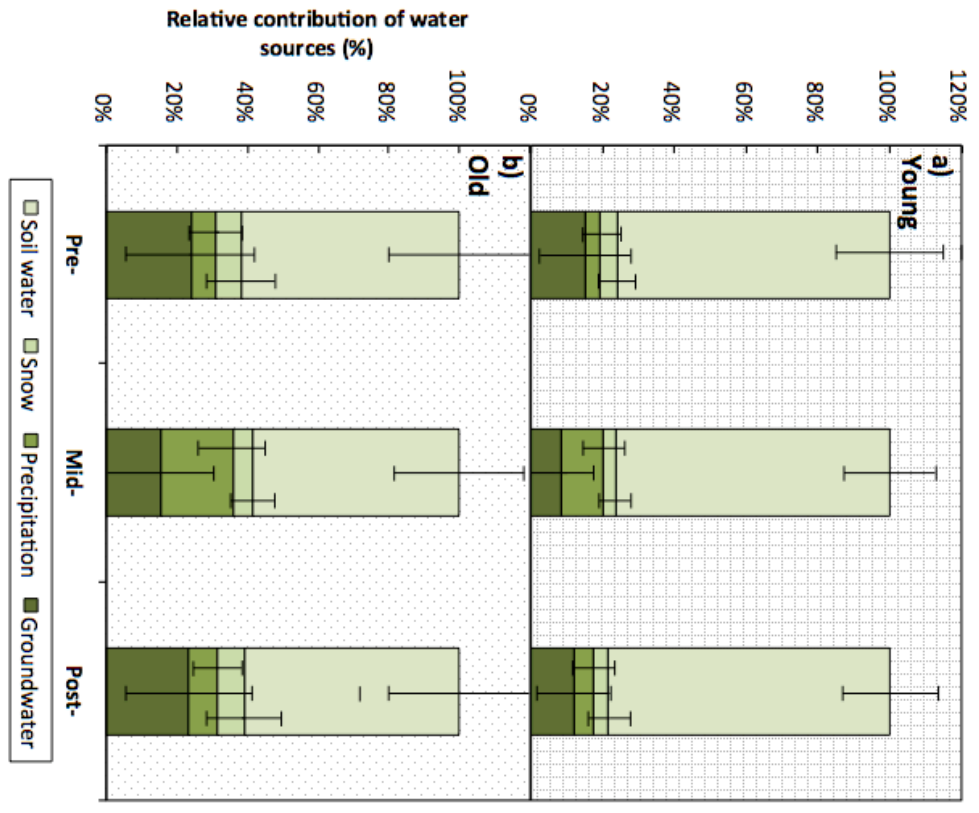
Figure 3-9. Relative source water contributions to xylem water generated by MixSIAR BMM partitioned by sampling period and growing season stage (pre-, mid- end) and tree age (a) young, b) old). Standard deviations for each source depicted by error bars.

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groundwater table present, with older trees using twice as much P as younger trees during this period (20.7 % vs 11.5 %) (Figure 3-9). Generally, older trees used more groundwater when it was available than younger trees, but both relied mostly upon soil moisture.

The MixSIAR BMM also generated source water proportions for the entire season, with runs also split into species and age based groups (Figure 3-11). For spruce, season long proportions were: 15.4 % groundwater (SD ± 14.1 %), 15.7 % P (SD ± 15.4 %), 8.8 % snow (SD ± 12.5 %) and 60.1 % soil water (SD ± 21.8 %) (Figure 3-11, a). For fir: 26.5 % groundwater (SD ± 16.9 %), 16.3 % P (SD ± 12.9 %), 11.3 % snow (SD ± 11.8 %) and 45.9 % soil water (SD ± 18.6 %) (Figure 3-11, a).
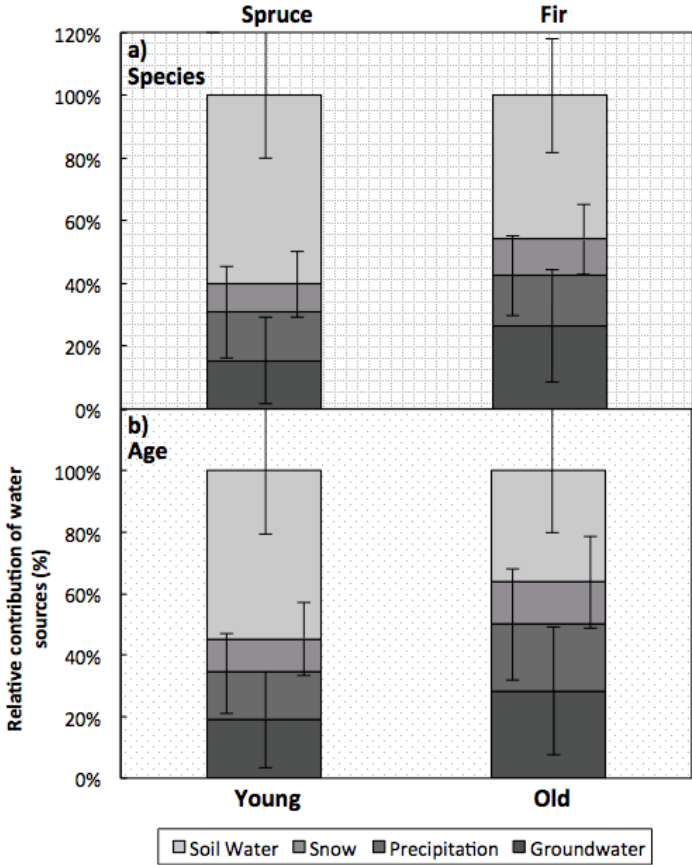
Overall, fir had a larger reliance on groundwater with almost 10 % more of water used coming from this

Figure 3-11. Relative source water contributions to xylem water for entire growing season length generated by MixSIAR BMM, partitioned by a) species (spruce, fir) and b) tree age (young, old). Standard deviations for each source depicted by error bars.
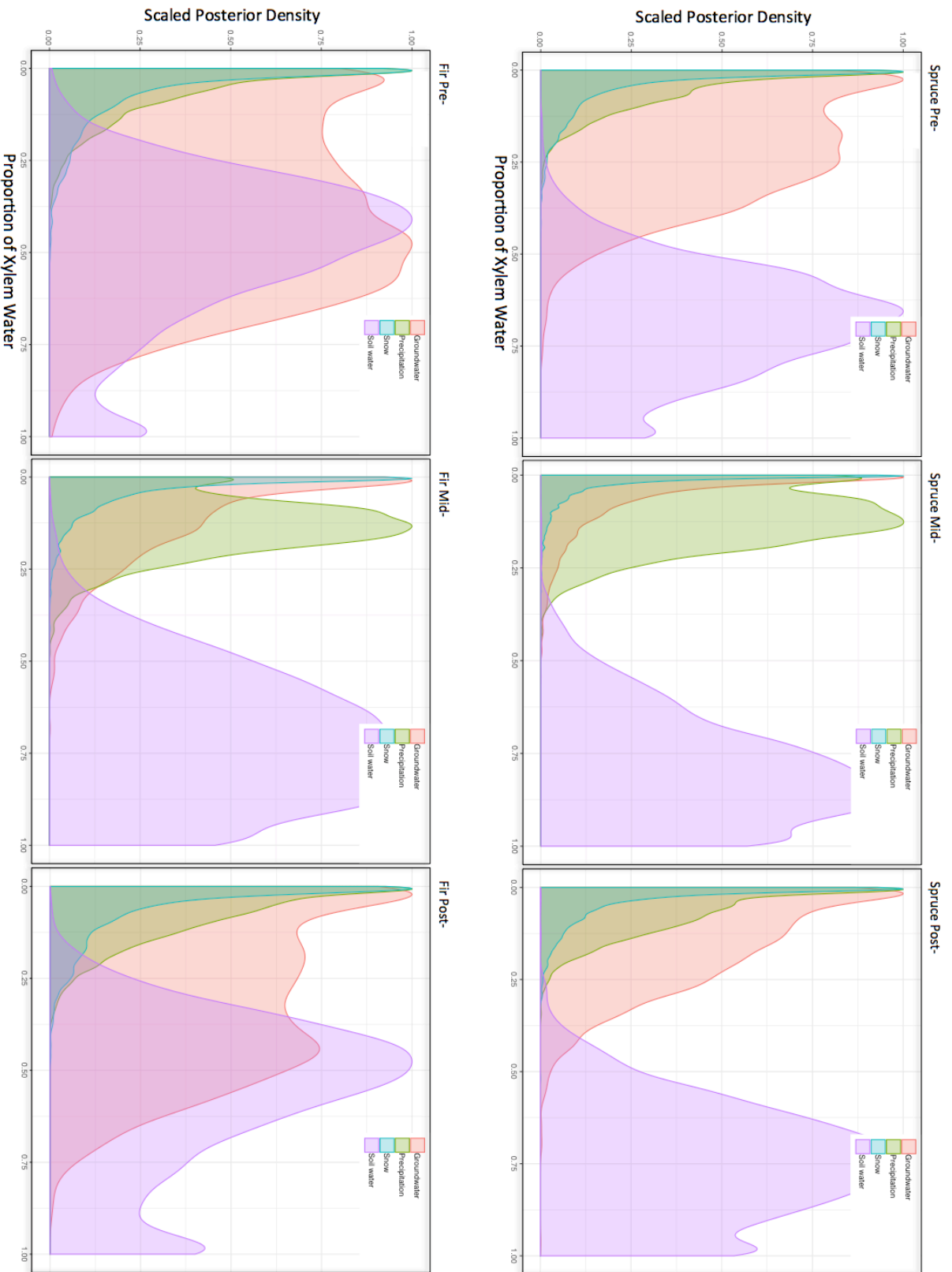
Figure 3-8. Density and proportion spread plots of xylem source water contributions generated by MixSIAR Bayesian Mixing Model runs for time of growing season (pre-, mid-, end-) and species.
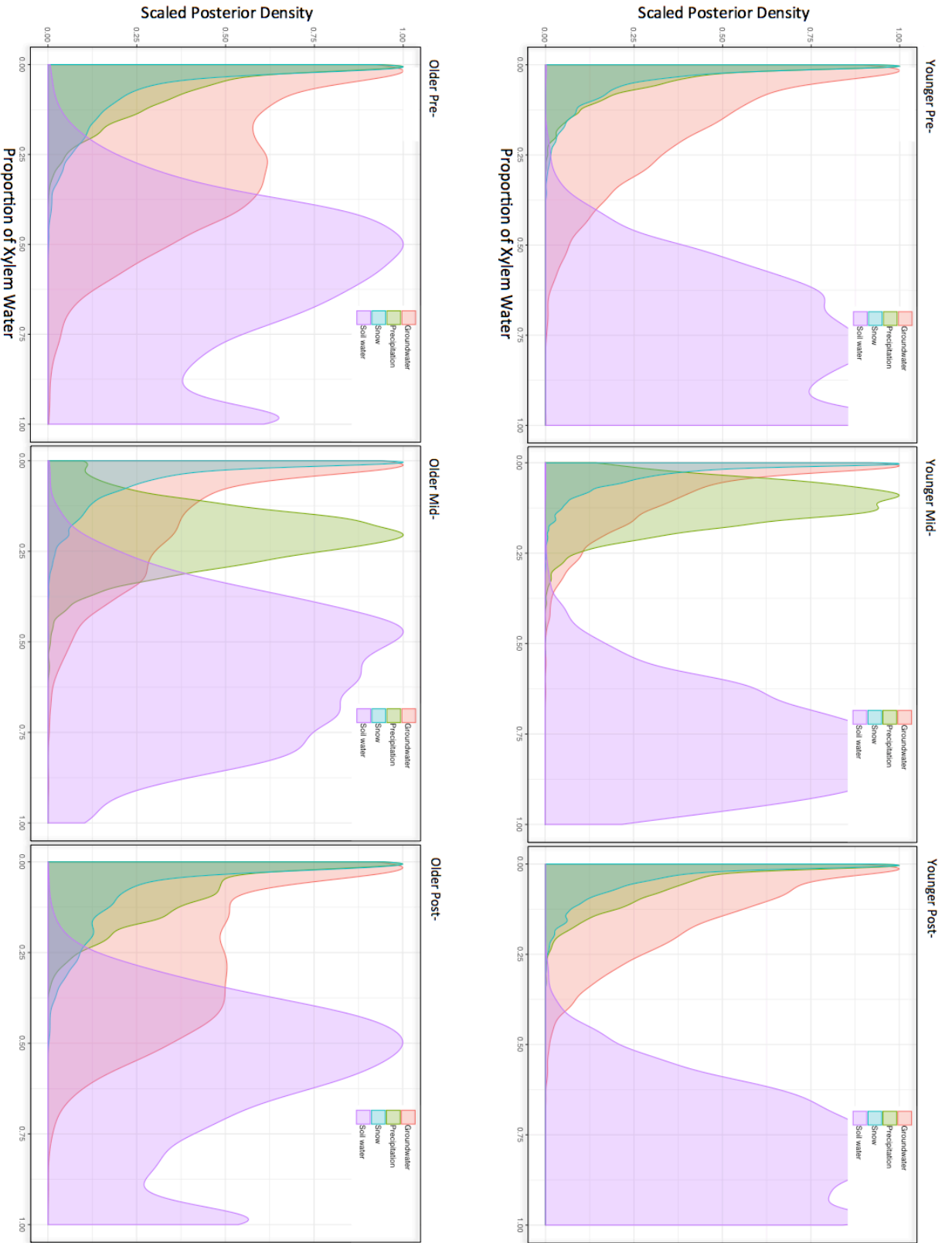
Figure 3-10. Density and proportion spread plots of xylem source water contributions generated by MixSIAR Bayesian Mixing Model runs for time of growing season (pre-, mid-, end-) and tree age (DBH based).

source. Soil water was equally important to both species, being the highest proportion of sources, but spruce placed a higher reliance upon this source with almost 15 % more (Figure 3-11). Both species used P and snow sources similarly. When examining season long trends in water source among tree age, the proportions for the young group were: 19.3 % groundwater (SD ± 15.1 %), 15.2 % P (SD ± 13.5 %), 10.8 % snow (SD ± 11.9 %) and 54.8 % soil water (SD ± 21.5 %) (Figure 3-11, b). For the old group: 28.4 % groundwater (SD ± 21.6 %), 21.6 % P (SD ± 13.8 %) and 36.2 % soil water (SD ± 20.8 %) (Figure 3-11, b). As the individual growing season point analysis showed, older trees are less reliant upon soil water, with a proportion of only 36.2 %, a 18.6 % difference between the young group (Figure 3-11). Older trees appear to pull similarly from many different sources, while younger trees are much more reliant on soil moisture stores.

3.4   Discussion

3.4.1   Effectiveness of MixSIAR BMM

With the emergence of $\delta^{18}O$ and δ^2H use in vegetation water sourcing, there are many active discussions regarding collection and processing of organic materials (soil and tree xylem water) (Orlowski, 2016; Barbeta *et al*, 2018; Millar *et al*, 2018) in addition to results presentation and data analysis related to partitioning models (Evaristo *et al*, 2017; Wang *et al*, 2019). With stable water isotopes, care must be taken to prevent evaporation and subsequent phase changing of sampled organic materials in order to prevent isotopic enrichment and fractionation viewable in δ^2H results. It is generally believed that trees do not fractionate water during uptake (Dawson and Ehleringer, 1992), although it has been observed in trees within a few studies (Lin & da Sternberg, 1993; Evaristo *et al*, 2017). Magnitude of isotopic separation between H^2/H^1 can be tested in comparison to soil water isotopic signatures (Ellsworth & Williams, 2007). A total of 8 (of 25) subalpine trees sampled in this study displayed potential H^2/H^1 fractionation, when compared against soil water values. This discrepancy could also be a product of difficulty sampling, with tree stem segments experiencing evaporation or phase changing before analysis. Primarily, H^2/H^1 fractionation is most important when considering linear mixing models. Fractionation can cause discrepancies when only considering δ^2H in calculations, skewing relative source water proportions incorrectly. As addressed by Evaristo *et al* (2017), when using two isotopes together in analysis, such as a BMM, the potential fractionation of δ^2H does not hinder outputs. The authors further suggest that if uncertainties exist in sources and mixtures (xylem water), the BMM approach is the most appropriate method. With this in mind, for

this study the MixSIAR BMM was the most suitable method to capture relative source contributions with multiple source inputs and one mixture (xylem water).

3.4.2   *Relative Source Water Partitioning*

Stable water isotope identification of source water in vegetation is becoming a more commonly utilized method in ecohydrology (Goldsmith *et al*, 2012; Bertrand *et al*, 2014; Barbeta and Peñuelas, 2017; Liu *et al*, 2017; Allen *et al*, 2019). In this study, $\delta^{18}O$ and $\delta^{2}H$ stable water isotopes were used in order to help determine subalpine source water during three points in the growing season (pre-, mid-, end-), and to partition the relative contributions of sources to tree xylem composition using the MixSIAR BMM. Recently, several studies have analyzed the efficiency and adequacy of using the MixSIAR BMM package in order to answer questions similar to the aim of this study (Evaristo *et al*, 2017; Wang *et al*, 2019). Wang *et al* (2019) found that MixSIAR and SIAR had better source water appointment performances due to inclusion of error terms and uncertainties associated with varying isotopic compositions. Evaristo *et al* (2017) discussed uncertainties in the models and source water predictions, while indicating that in study sites similar to theirs the BMM approach may prove useful to quantify source water appointment, especially between the vadose and saturated zones. BMM results in this study indicate that between both tree species and age classes, subalpine trees switched reliance on source water throughout the growing season, mainly between the two subsurface compartments (saturated/ unsaturated).

Largely, groundwater supplied via snowmelt was an important source, primarily at the beginning of the growing season. This source additionally replenished early season soil water supplies by increasing soil moisture levels before receding below a tree-attainable level during the growing season. Towards the end of the growing season, nearing senescence, both fir and spruce saw increases in groundwater isotope signatures, likely due to increased P levels at the end of the growing season in 2017. This increased P allowed recharge, compared to a drought-like summer, which inhibited recharge of P, which was instead evaporated or transpired within a few days (Chapter 2). End of season snowfall also influenced source water proportions, appearing isotopically distinct in tree xylem water. Soil water was the most important water source for both subalpine tree species, regardless of age class, although there were distinct differences when examining species and tree age relating to source water proportion. Overall, spruce were more reliant on soil water, with fir trees using less soil water and utilizing more groundwater. Interestingly, subalpine fir have been reported to show greater levels of drought stress while spruce are more resilient (Veblen, 1986; Kelsey *et al*,

2018). Observing seasonal water source partitioning of fir, it appears that in the mid- season they retain, or store, more groundwater than their counterparts. This highlights differences in physiology and rooting structures between fir and spruce, with fir rooting deeper and relying less upon vadose zone water compared to spruce at the study area. Subalpine fir and spruce rooting systems vary extensively with dependencies on subsurface geology and soil structure. Both species in subalpine environments more commonly have shallow rooting systems, with deeper taproots more commonly in well draining deep soils (Alexander, 1987). Is it possible that with fir being more abundant at the study location (70 % of population), their rooting systems are more established and reach deeper depths due to successional dominance.

The summer growing season studied experienced drought with no groundwater recharge during July and August. Soil moisture values were half of the values observed the year before at the end of the growing season (Chapter 2). Despite small differences in source water spread, limitations in soil water could affect both fir and spruce tree T, and long-term health if there are successive summer drought seasons (Pataki *et al*, 2000; Adams *et al*, 2009; Matyssek *et al,* 2009; Tague *et al*, 2009; Shafer *et al*, 2015). Based on BMM results showing spruce placing more reliance on soil water, spruce may show effects of drought stress before fir, despite spruce having been observed to be a more resilient species in past studies (Veblen, 1986). As indicated previously, this may be site specific and based on the succession of species proportion, with fir being the dominant species at this study location. Results also highlighted different water source proportions with tree age, regardless of species. Older trees, overall, tended to use more groundwater compared to younger. A direct relationship is observed with rooting depth and age, with younger spruce and fir typically displaying lateral root spread and weak taproots (Alexander, 1987). These differing behaviours may provide more physiological resilience to drought for older subalpine trees, allowing them to use an additional water source. Age and maturity also corresponds to increased storage, allowing trees contain source signatures obtained earlier, throughout the length of the growing season.

3.4.3   Species Differences in Seasonal Water Sources

Through creation of an isotopic framework and generation of the LMWL and LEL for the Fortress Mountain, Kananaskis area, δ^{18}O and δ^2H stable water isotopes provided an understanding of subalpine forest water sources. The δ^{18}O and δ^2H isoplot in addition to the seasonal δ^2H xylem water plot highlighted that overall, soil water was the most utilized resource. Groundwater was also an important resource, utilized primarily during the beginning of growing season snowmelt period.

Numerous studies have sought to understand physiological characteristics behind tree water use in co-occurring fir and spruce subalpine forests (Kaufmann, 1982; Boyce and Saunders, 2000; Sala, 2006; Andrus *et al*, 2018; Davis and Gedalof, 2018), but limited studies have considered season long source water identification in conjunction with physiological processes such as T.

The isoplot produced here, in addition to the source water-partitioning model, identified subalpine tree source water for three parts of the growing season. The three sampling periods were able to highlight the progression of water use as snowmelt finished and soil moisture stores lessened toward senescence during the dry summer of 2017. The percentages developed also indicate relative importance of these sources to the tree species examined. Mid summer, 71 and 79.5 % of total xylem water for fir and spruce, respectively, contained soil water signatures. Recent studies examining the constraints on seedling and sapling growth in the Rocky Mountain identified soil moisture as an important limiting factor in successful establishment (Andrus *et al*, 2018; Davis and Gedalof, 2018). In particular, Davis and Gedalof (2018), who had a study site located at Fortress Mountain, found treeline advance and establishment of co-occurring fir and spruce is unlikely considering earlier snowmelt and longer snow-free growing seasons depleting soil moisture are expected to become more frequent (Fang *et al*, 2013). Hydrological conditions of the growing season examined in this study were representative of summer drought conditions, with no summer P recharging subsurface storage. Only the first 30 cm of soil received percolated water before being utilized by vegetation or evaporated within a few days (Chapter 2). Results showed younger trees relied upon soil moisture stores more than their counterparts, who incorporated groundwater more into their overall source use. These results, in conjunction with research indicating poor success of sapling establishment and forest health with lower soil moisture reliability (Cul and Smith, 1991; Harpold *et al*, 2014; Lazarus *et al*, 2017; Andrus *et al*, 2018; Davis and Gedalof, 2018), could indicate younger trees show more signs of stress in addition to potential die back if drought conditions become more frequent in subsequent summer growing seasons (Adams *et al*, 2009). The ability of older trees to spread their water source allocations differently, likely due to more established rooting structures, may give them an edge in resilience to less than favourable growing season conditions under a changing climate. A growing season experiencing an extended snowmelt period due to a large winter snowpack may help established subalpine forests experience less drought stress by providing an extended groundwater source for longer, despite drought conditions occurring later in the summer, such as in 2017. This was evident in the MixSIAR model results, with groundwater signatures being maintained throughout the

entire growing season despite the groundwater depletion after snowmelt (after the pre- sampling period).

3.5   *Conclusions*

The aim of this study was to understand and partition subalpine forest water sources during a growing season experiencing a drought period in the Canadian Rocky Mountains. Development of an isotopic framework, LMWL, and LEL were integral to the successful identification of tree water sources. The LMWL was generated with an R^2 value of 0.99, indicating a successful relationship and potential for use in future $\delta^{18}O$ and δ^2H stable water isotopes studies occurring on the eastern slopes of the Rocky Mountains. Subsequent use of the MixSIAR BMM with source and xylem water samples provided an understanding of water use behaviour at three points throughout a growing season at 2100 m of elevation.

Tree species and age both displayed differences in water source allocations, although all categories placed a higher reliance on soil water. Groundwater supplied by snowmelt was highlighted as an important source during the beginning of the growing season, and closer to the end of the growing season with increased P in the fall. The results highlighted the importance of soil moisture reserves to the health of subalpine forests, and shed light upon future behaviours should years of successive drought periods occur. These findings help support established literature that have indicated future success of co-occurring fir and spruce forests could be limited should soil moisture stores decrease. This moisture limitation has the ability to limit tree line progression, which has the potential to further limit forest population growth as valley bottoms experience die backs with faster rates of change due to higher baseline temperatures than the alpine. Successionally, these forests could be nudged off balance as older trees, able to utilize groundwater, will have a higher survival rate compared to their counterparts who may experience increased levels of drought stress. Although soil moisture was determined to be the most important source, extended snowmelt periods supplied by large winter snowpacks could offset summer droughts by supplying subalpine forests with an additional source for a limited period of time. Extended growing seasons with rising temperatures could cancel this effect, as trees will need to rely on soil moisture stores for longer periods of time. A multi-year $\delta^{18}O$ and δ^2H stable water isotope study could help provide further understanding of these co-occurring subalpine forests under hydrologically variable mountain growing seasons.

Chapter 4:   Summary

4.1   Overall Summary & Future Recommendations

While it is understood that subalpine forests will experience change under altered global climate regimes, the magnitude of these changes is not clear. In addition, forest water use behaviours have not been extensively explored in co-occurring species *Abies lasioscarpa* (subalpine fir) and *Picea engelmannii* (Engelmann spruce), of the Canadian Rocky Mountains. This is the first study to quantify fir and spruce water use in the same stand for two growing seasons, in 2016 and 2017. The two study years were contrasting hydrologically, one experiencing wetter conditions and the other drought. The contrasts in years allowed for insight into fir and spruce water use behaviour, showing that trees transpired more throughout the drier summer. Results indicate the sustained, large spring snowpack in 2017 helped encourage early growing season transpiration (T) of a higher magnitude than 2016, the wet summer. This research also helps quantify the relative proportion of T to total evapotranspiration (ET), helping to understand the contribution of forests in this water balance term. In 2016, there was a positive gain of water to the system, replenishing groundwater and soil moisture stores. In 2017, there was a net loss of water to the system, allowing no recharge during July and August. Gaining this hydrological understanding has implications for predicting future forest health and response to climate change. If there are successive years of summer drought, younger trees may struggle to get enough water to sustain growth due to limited internal storage capacities and shallower rooting systems. This may alter the natural succession of forests in the Canadian Rocky Mountains, and could place further stress on these species in the event of a wildfire or biological pests.

In conjunction with the hydrometeorological-based tree investigation, stable water isotopes (δ^{18}O and δ^2H), were used to partition subalpine tree water sources were partitioned using a Bayesian mixing model, MixSIAR, for three points of the growing season. It was found that soil moisture was the most important water source for all trees, across both species and between two age classes (young, old), throughout the entire growing season. Groundwater was the second most important source, being most valuable during spring snowmelt and the beginning of the growing season as trees emerged from senescence. Like the hydrometeorological study, it was found that younger trees rely more on soil moisture than older trees. There were minimal differences between species, although it was found that fir trees utilized more groundwater across the growing season, compared to spruce. This suggests that rooting structure of fir may be better adapted to decreases in soil moisture during summer drought periods, allowing them to access deeper groundwater. Population abundance and

succession may play a part in their successful adaption to access varied water sources, as fir were the most populous at the research location with 70% of local forest population.

The insights this research provides insights on water use behaviour, in addition to filling gaps in the regional water budgets by informing ET processes, will also refine current modeling approaches. From this research, we can update current models for forest structure and tree water use dynamics. A better understanding of multi-year forest hydrology is necessary to inform downstream decision-making. Thus, this process-based research is essential to inform models looking to forecast changes in mountain hydrology not only under climate change, but also during environmental impact such as pine beetle infestation, wildfire and resource harvesting.

4.2   Project Limitations & Challenges

Within this study, there were limited, but important project limitations and challenges. For the T and ET investigation of subalpine forests, a limitation to the separation of T into species-specific variables occurred due to poor linear relationships caused by missing or erroneous data. For this reason, both species were combined in order to create daily linear regressions to scale-up individual tree sap flow to stand level T. This method was found suitable for representation of the forest, and was representative of greater ET values, as captured by eddy covariance.

For the $\delta^{18}O$ and δ^2H stable water isotope study, although results were representative (compared with Chapter 2) of subalpine tree water use behaviour across a growing season, challenges occurred in sample collection which may hinder result outputs if using linear based mixing models. Linear mixing models rely upon use of stable isotopes individually to calculate source water proportions, which, if organic samples experienced evaporation or phase changes would cause fractionation especially evident in δ^2H values. This fractionation could cause erroneous model results. The mixing model used in this study used the stable water isotopes combined, which eliminates the bias and error associated with calculating mixing individually. In order to avoid evaporation of water from organic samples, great care should be taken to ensure proper collection practices. This includes selecting a container with no air space, and proper transport such as a cooler with ice for tree xylem samples.

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