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Subalpine forest water use behaviour and evapotranspiration during two hydrologically contrasting growing seasons in the Canadian Rockies

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Abstract

Hydrological processes in mountain headwater basins are changing as climate and vegetation change. Interactions between hydrological processes and subalpine forest ecological function are important to mountain water supplies due to their control on evapotranspiration (ET). Improved understanding of the sensitivity of these interactions to seasonal and interannual changes in snowmelt and summer rainfall is needed as these interactions can impact forest growth, succession, health, and susceptibility to wildfire. To better understand this sensitivity, this research examined ET for a subalpine forest in the Canadian Rockies over two contrasting growing seasons and quantified the contribution of transpiration (T) from the younger tree population to overall stand ET. The younger population was focused on to permit examination of trees that have grown under the effect of recent climate change and will contribute to treeline migration, and subalpine forest densification and succession. Research sites were located at Fortress Mountain Research Basin, Kananaskis, Alberta, where the subalpine forest examined is composed of *Abies lasiocarpa* (Subalpine fir) and *Picea engelmannii* (Engelmann spruce). Seasonal changes in water availability from snowmelt, precipitation, soil moisture reserves yielded stark differences in T and ET between 2016 and 2017. ET was higher in the drier year (2017), which had late snowmelt and lower summer rainfall than in the wetter year (2016) that had lower snowmelt and a rainy summer, highlighting the importance of spring snowmelt recharge of soil moisture. However, stand T of the younger trees (73% of forest population) was greater (64 mm) in 2016 (275 mm summer rainfall) than 2017 (39 mm T, 147 mm summer rainfall), and appears to be sensitive to soil moisture decreases in fall, which are largely a function of summer period rainfall. Relationships between subalpine forest water use and different growing season and antecedent (snowmelt period) hydrological conditions clarify the interactions between forest water use and alpine hydrology, which can lead to better anticipation of the hydrological response of subalpine forest-dominated basins to climate variability and change.

KEYWORDS

Canadian Rocky Mountains, eddy covariance, evapotranspiration, forest health, sap flow, subalpine forest, transpiration, water use

1 | INTRODUCTION

Subalpine forests within the Canadian Rockies experience very short growing seasons, typically spanning only 3 months, from June to August. Heavily influenced by altitudinal gradients, orography and flow directions of frontal systems, the hydrometeorology of mountain headwater basins is complex, with the majority of annual runoff generated by the seasonal melt of deep snowpacks. These snowpacks accumulate about 70%–75% of annual precipitation, *P*, (Storr, 1967) and are vital to recharging the soil water supplies that support early growing season vegetation transpiration (*T*). Under a changing climate, this region is expected to experience earlier snowmelt (Cayan et al., 2001; Stewart et al., 2005) and changes in regional *P* patterns and quantities (Groisman et al., 1994; Stewart et al., 2005; Whitfield & Cannon, 2000), 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 & Johnson, 2006, 2008), harvesting (Swanson & 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 water use and resilience of forests in response to these disturbances are of particular importance, due to the coupled relationship between forests and runoff generation (Harder et al., 2015; Pomeroy et al., 2012; Swanson & Bernier, 1986). Thus, there is a need to understand how stand evapotranspiration (*ET*) is influenced by snowmelt and growing season precipitation regimes. Further, quantifying water use by the population of trees that have grown under recently changing climatic conditions will enable better predictions of how mountain headwater water yield may respond to further climatic change (Pomeroy et al., 2012; Swanson & Bernier, 1986).

Previous studies have examined changes in runoff-generating hydrological processes due to clear cutting or forest harvesting treatments (Pomeroy et al., 2012; Swanson & Bernier, 1986; Whitaker et al., 2002), but few have highlighted forest resiliency and productivity in response to these disturbances in the Canadian Rockies (Harder et al., 2015). It is also unclear how the impacts of these disturbances may change with climate change. Harder et al. (2015) examined the long-studied Marmot Creek Research Basin in the Canadian Rockies of Alberta and found its streamflow regime to be insensitive to changing climate, extreme weather and forest clearcutting, which is in contrast to what has been found in mountain headwater basins further south in Colorado and Idaho. Research has shown that recent growth acceleration of small/young needleleaf trees have coincided with the establishment of trees outside the forest range, reflecting a connection between the physiological performance of dominant species and shifts in forest distribution, with a changing climate (Silva et al., 2016). Further, younger needleleaf trees have exhibited a more strained stem water status and higher sensitivity to environmental conditions than mature trees, such that an increase in evaporative demand with climate change may impair regeneration and long-term stability of drought-prone forests (Oberhuber et al., 2015). However, other work has suggested that younger trees are more capable of adapting to water stress with climate change (Bassiman et al., 2003).

High altitude zones are considered sensitive indicators of climate change and are expected to respond to increasing global temperatures more rapidly than lower elevations (Breshears et al., 2009; Kirschbaum, 1995; Tague et al., 2009). To date, there are limited studies on forest *ET* and transpiration (*T*) at higher elevations (>1500 m) in the Canadian Rockies (Leets et al., 2009). While *T* has been quantified for some locations in the American Rocky Mountains, studies undertaken under differing study site elevations and climate regimes may produce results that are not representative of vegetation-atmospheric interactions further north (Barnard et al., 2017; Hu, Moore, Burns, & Monson, 2010; Hu, Moore, Riveros-Iregui, et al., 2010; Moore et al., 2008). Other high elevation studies have been completed in mountainous regions outside of North America, but have vastly different forest compositions and climates, providing poor comparison for forest water consumption (Kräuchi et al., 2000; Matyssek et al., 2009; Tenhunen et al., 1998). This knowledge gap limits the current understanding of mountain forests on high altitude water balances in Canada and introduces uncertainty into the modelled water budgets of these regions and their response to disturbance (Fang et al., 2013; Matyssek et al., 2009; Rasouli et al., 2019).

Given the anticipated shifts in snowmelt and growing season precipitation regimes, there is a need to understand how such shifts will impact mountain headwater water yields in the Canadian Rockies by changing patterns in *T* and *ET*. Thus, this study was designed to understand and quantify subalpine forest *ET* under contrasting hydrological conditions with particular attention to *T* from the younger population of trees that may already be responding to climate warming in the region. Younger trees that have developed during this period of changing climatic conditions are important to examine as they may elucidate important ecohydrological adaptive processes. Thus, the objectives of this study are to: (1) observe how interannual and seasonal hydrometeorological variations linked to snowmelt and summer rainfall and associated soil water availability control *ET* in a subalpine forest; and (2) understand how *T* from young trees in subalpine forests are impacted by evolving soil water availability. Contextualizing how subalpine *ET* and younger tree *T* respond to hydrometeorological variability allows this study to address how mountain forests may respond to future climate change.

2 | MATERIALS AND METHODS

2.1 | Study site

The observations for this study were made in the Fortress Mountain Research Basin (FMRB), Kananaskis River Valley, Alberta. Research campaigns and data collection occurred from May–September in 2016 and 2017. FMRB is Crown forestry land in the heart of the Canadian Rockies that is leased to Fortress Ski Area. The cool humid continental climate in the Kananaskis Valley is highly variable seasonally and inter-seasonally, experiencing long cold winters interrupted by winter Chinook thaws and cool wet summers interrupted by summer snowfalls (Alberta Environment and Sustainable Resource Development, 2014; Beckstead & Veldman, 1985).

Observations from the nearby (25 km away), valley bottom Kananaskis Field Station from 1981–2010 (Environment and Climate Change Canada, 2015) show 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 minimums and maximums ranging from –45.6 to 34.5°C. Chinook winds are also common in this area of the Canadian Rockies, 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 for climate and hydrology patterns experienced in the valley (Longley et al., 1967; MacDonald, Pomeroy & Essery, 2018). Summer P during the study observation period (May–Sept. inclusive) totaled 275.0 mm in 2016 and 146.9 mm in 2017. The 2016 and 2017 summer snow-free seasons were hydrologically contrasting due to a 47% difference in summer P across both study years and higher levels of seasonal soil moisture availability due to greater snowpacks and higher P in 2016. Average monthly temperatures were within the range of monthly normals by 2°C (Environment and Climate Change Canada, 2015).

Two adjacent subalpine sites were used at FMRB to ensure proper representation of the diverse forest structure at the elevation examined. The sites used in this study were composed of co-occurring tree species *Abies lasiocarpa* (subalpine fir, hereafter *fir*) and *Picea engelmannii* (Engelmann spruce, hereafter *spruce*), which are representative of the subalpine as the dominant species of this area and elevation. The first site, hereafter referred to as Tower, is described as a well-populated shorter growth (relative to Powerline) forest patch at 2079 m of elevation (50.825746 N, 115.196725 W). The second site, hereafter referred to as Powerline, 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 was established at each site and used for spatial variation in water table sampling (Figure 1). The two sites are approximately 115 m apart, as defined by the centres of each transect.

2.1.1 | Vegetation and forest surveys

Vegetation and forest surveys were conducted to characterize the forest structure for scaling of transpiration. The forest inventory followed guidelines of the *Reforestation Standard of Alberta* (Alberta Environment and Sustainable Resource Development, 2012). Circular plots of 100 m² (5.6 m radius) were established at each end point and centre of the cross-transect arrangements, totaling five sampling areas at each study site (Figure 1). Diameter at breast height (DBH), height, basal area, and tree species identification were collected from each 100 m² plot. Trees with a DBH greater than the smallest tree being monitored for sap flow measurements (2.5 cm at Powerline, 2 cm at Tower) were catalogued for the 100 m² plot. Tree height was measured using a telescoping tree measuring pole, or a clinometer (Suunto, Vantaa, Finland) where necessary. DBH was measured using

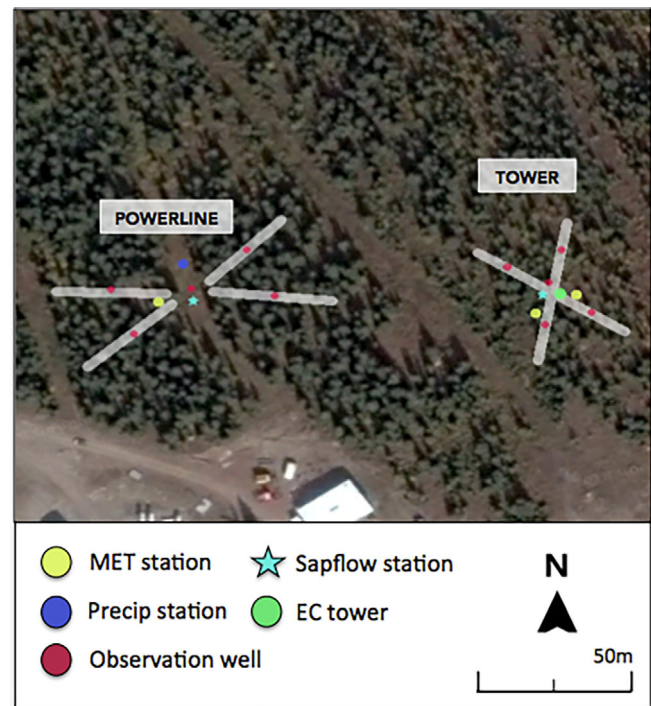


FIGURE 1 Instrumentation distribution and transect locations at the tower and Powerline sites at Fortress Mountain Research Basin, Kananaskis, AB

a 60 cm tree calliper. Tree species were identified using the field guide by Alberta Parks for Kananaskis Country (Parks, 1999).

Leaf area index (LAI) values were obtained with a LAI-2200 plant canopy hand analyser (Li-Cor, NE, USA) weekly for the growing season duration (June–August). Values obtained at each site included understory vegetation (LAI_U), canopy (LAI_C), and stand total (LAI_S) at 40 points along the transect arms (Figure 1). Due to the needleleaf tree populations of the study areas, a needleleaf 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 needleleaf-correction factors were combined based on tree species by weighting the relative abundance of species among surveyed trees (Davidson et al., 2000; Liu et al., 2015).

2.1.2 | Tower stand characteristics

The Tower site is the most easterly of the two sites (Figure 1). The tree population is comprised mainly of fir and spruce (Table 1). Average diameter at DBH for *Fir* is 6.7 cm (±5.5), while the average height is 4.4 m (±2.3) (Table 1). The average DBH of spruce was 6.2 cm (±4.2) with an average height of 4.0 m (±1.7). Of the species examined at this site, fir is the most common (73.2%) and spruce was the second most common (25.5%, Table 1). Compared to the Powerline site, trees at the Tower site 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 of the

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

Note: Data collected in August 2015.

Site	Mean canopy LAI	Mean understory LAI	Mean stand LAI
Tower	2.64	1.72	4.36
Powerline	3.25	1.32	4.56
Combined	2.95	1.52	4.46

TABLE 1 Forest inventory data for tower and Powerline sites, Fortress Mountain Research Basin, Kananaskis, Alberta, from completed forest characteristic survey

TABLE 2 Mean LAI values for tower and Powerline sites, Fortress Mountain Research Basin, Kananaskis, Alberta, collected weekly over the summer growing season from May–August in 2016

canopy (LAI_C) at Tower was 2.64, with a mean stand total LAI_S of 4.36 (including understory), which is smaller than that of the Powerline site for the same year (Table 2).

2.1.3 | Powerline stand characteristics

The Powerline site is located west of the Tower site (Figure 1). This site is characterized as having a smaller population, but a higher canopy density than Tower, which can be seen in the tree survey statistics (Table 1) and reported LAI values (Table 2). Similar to the Tower site, the Powerline site is dominated by fir and spruce; however, the DBH and average heights of trees at this site are more than double those at the Tower site. For example, fir trees have an observed average DBH of 14.4 cm (± 6.4) and height of 8.75 m (± 2.54) and spruce have an average DBH of 20.3 cm (± 9.2) and an average height of 9.49 m (± 3.3) (Table 1). Although fir and spruce dominate both the Tower and Powerline sites, population compositions differ slightly between the sites. There was a lower fir population, totaling 70.6% (compared to 73.2% at Tower) and a higher spruce population of 29.4% (compared to 25.5%) at Powerline (Table 1). In 2016, LAI_C for Powerline was 3.25, with a mean LAI_S of 4.56, both higher (denser vegetation) than Tower (Table 2).

2.2 | Hydrometeorological sampling and field instrumentation

The vadose zone was instrumented for characterising the relationship between soil moisture and tree water consumption. Three soil moisture stations were installed across both study sites and used during both growing seasons. At Tower, two stations, one in an open tree clearing and the other a closed tree canopy were installed. At Powerline, the soil moisture station was situated within a closed canopy of trees. Each station was instrumented with two Campbell

Scientific CS650 Soil Moisture probes, one at a depth of 30 cm (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. The CS650's were logged on a CR1000 data logger (Campbell Scientific, UT, USA), sampled every 30 s 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 below the surface. Tensiometer data were only collected in 2017 by a manual visual reading of the gauge 25 times from June 22nd to August 10th during the snow-free growing season.

Groundwater observation wells were installed for snowmelt and growing season water table characterization in 2017. Five wells were placed at each site (10 total) following transect arm placement (Figure 1). Water level transducers (OnSet HOB0 U20 Water Level Logger, MA, USA) were placed in six of the 10 installed wells, three at each site. A barometric data logger (OnSet HOB0 U20 Water Level Logger, MA, USA) was installed at Powerline for atmospheric pressure compensation. Wells were installed as deep as possible (obstructions by fractured bedrock and heterogeneous rocky soils), with a maximum depth of 1.5 m, capturing water table prevalence below the known tree-rooting zone.

Snow water equivalent (SWE) was determined through manual snow survey transects situated in the forest cover between Tower and Powerline sites. An ESC-30 snow sampling tube paired with a weigh scale was used for measurement, in addition to a snow probe for depth measurements. SWE was measured once monthly throughout the snow season from October to June, evenly spaced along the northwest transect from the Powerline site. Continuous snow depth measurements were additionally collected by an SR50A snow depth sensor located at Powerline (Campbell Scientific Inc., UT, USA)

Basic meteorological data were collected by instrumentation mounted on the 15.5 m forest tower. Meteorological data 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), in addition to the previously described soil moisture and temperature. P was collected at the Powerline site using an Ott Pluvio² (Ott Hydromet, CO, USA) with wind alter shield and corrected for wind under-catch.

ET data were obtained from the 15.5 m eddy covariance tower, with instruments situated above the forest canopy. The flux measurements from this tower contained both the Tower and Powerline sites within its footprint. ET data were obtained using a LI-7500 IRGA Open Path Gas Analyser (Li-Cor, NE, USA) and a CSAT3 3D Sonic Anemometer (Campbell Scientific Inc., UT, USA) approximately 3 m above average canopy height (Table 1) logged on a CR1000 data logger (Campbell Scientific Inc., UT, USA) and programmed to compute high frequency data instantaneously for raw data storage on the logger. The IRGA was calibrated at the beginning and end of the study period, using a zero gas and two-point span calibration to account for any drift in sensor sensitivity, which remained 5% over the duration of the study period. Raw EC data were processed internally by the data logger, using the Easy Flux software provided by Campbell Scientific (Campbell Scientific Inc., Logan, UT, USA), which accounted for density correction for open path sensors (Webb et al., 1980). EddyPro software (version 5.2.1; Li-COR Inc., Lincoln, NE, USA) and a custom R-Software script were used to further process EC data output from the data logger. This analysis included corrections for coordinate rotation (double rotation), time lag and sensor separation, density effects and periods of low turbulence based on the inflection point of frictional velocity (u^*) and energy balance closure (Aubinet et al., 2012; Kaimal & Finnigan, 1989; Burba et al., 2012; Brown et al., 2010; Foken & Leclerc, 2004; Petrone et al., 2015). The Kljun et al. (2015) footprint analysis was used to constrain water fluxes to within the desired site boundaries, using their flux footprint prediction R-functions. All fluxes were then filtered to be from within 80% of the calculated footprint. Fluxes located within the chosen footprint were processed further. ET was gapfilled using the Bowen ratio method and Priestly Taylor calculated potential evapotranspiration, following Petrone et al. (2015).

2.3 | Forest transpiration measurements

In recent years, methods to quantify tree T have improved, with the introduction of minimally invasive techniques such as the stem-heat balance (SHB) technique (Cermak et al., 1973), based on the original thermal dissipation probe method (Steinburg et al., 1989). 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 (Grime et al., 1995; Smith & Allen, 1996; Steinburg et al., 1989). This method has been successfully used to quantify the T of forests at various altitudes and ages (Matyssek et al., 2009) in addition to providing insights on tree health and physiology (Steppe et al., 2015).

Tree T was obtained using a non-invasive SHB sap flow system (Dynamax Flow32-1K, TX, USA) at two study sites of similar

needleleaf tree compositions (*Abies lasiocarpa* and *P. engelmannii*) but differing in main physical characteristics (tree height, diameter at breast height and population density). One system was installed at each study site, with eight sensors at each site totaling 16 sensors overall. As the younger tree population was of interest, the sensors were placed on trees of this target population. The tree size classes observed in this study account for 73% of the forest population at this study site. The system was run from early June (4th) to late September (25th) of each study year. This less invasive method uses insulated collars with thermopile heaters embedded wrapped around the tree trunks and additionally insulated from solar radiation. Measurements were collected continuously every 60 s and averaged hourly. The data from all 16 sensors were collected and stored using a CR1000 data logger and multiplexor (Campbell Scientific Inc., UT, USA). Measurement and installation locations were established based on the 2015 tree survey of 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 1). Installation of the sensors, system programming and data logger setup followed recommendations outlined by the manufacturer (Dynamax Inc., 2007).

2.3.1 | Scaling daily tree transpiration to forest stand contributions

Single-tree T values were scaled to the stand level using data from the forest survey conducted. Hourly velocity (g/h) measurements were processed for gaps, quality and irregularities by managing outliers and eliminating faulty values. Poor values originating from errors such as poor sensor-tree connection causing erroneous heat balances, interference from solar radiation, thermopile heater interference and gaps in data due to weather were additionally analysed and quality controlled. Of the initial 16 sensors installed, 8 from Tower and 6 from Powerline, were used to create daily flow regression equations after initial data analysis and quality checks (Table 3).

Linear sap flow regression equations were generated by retrieving the equation for total daily flow versus DBH 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) (Ford et al., 2007; Vertessy et al., 1995). In the first step the daily flow regression equations generated from sap flow data were applied to the forest survey data. In Equation (1), daily flows sums are calculated using the tree survey applied to the daily regression equation are summed (L/day). In the following Equations (2)–(5), a series of unit conversions occur to obtain the daily sap flow as a depth (mm). The final Equation (5) converts depth in m/day to in mm/day, for comparison to obtained daily ET data.

TABLE 3 Sap flow sensor installation information for the Flow32-1K systems at tower and powerline sites for 2016 and 2017 study years, in the Fortress Mountain Research Basin, Kananaskis, Alberta

Site	Sensor no.	Sensor size	Species	DBH (cm)
Tower	1	SGB 25	<i>Abies lasiocarpa</i>	1.75
	2	SGB 25	<i>Picea engelmannii</i>	3.03
	3	SGB 25	<i>Abies lasiocarpa</i>	2.87
	4	SGB 35	<i>Abies lasiocarpa</i>	2.55
	5	SGB 25	<i>Abies lasiocarpa</i>	3.82
	6	SGB 25	<i>Picea engelmannii</i>	3.90
	7	SGB 25	<i>Abies lasiocarpa</i>	4.35
	8	SGB 35	<i>Picea engelmannii</i>	5.56
Powerline	1	SGB 10	<i>Abies lasiocarpa</i>	1.75
	2	SGB 25	<i>Abies lasiocarpa</i>	3.19
	3	SGB 25	<i>Picea engelmannii</i>	3.82
	4	SGB 25	<i>Picea engelmannii</i>	3.19
	5	SGB 35	<i>Abies lasiocarpa</i>	3.82
	6	SGB 25	<i>Abies lasiocarpa</i>	3.82
	7	SGB 50	<i>Abies lasiocarpa</i>	6.78

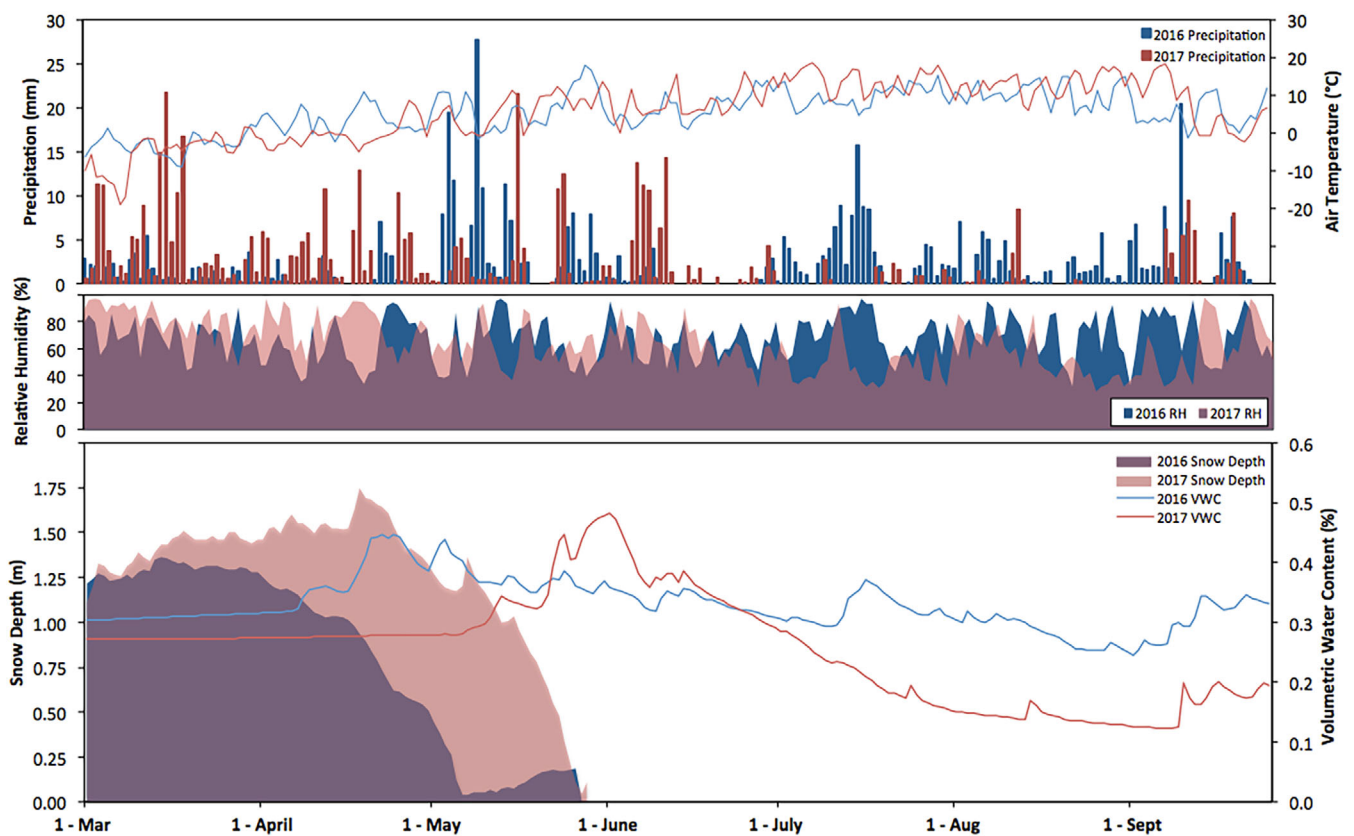


FIGURE 2 Climate plots for 2016 and 2017 from Mar 1 to Sept 25 growing seasons showing relative humidity, P, air temperature, VWC and snow depth for Fortress Mountain Research Basin, Kananaskis, Alberta. Data are shown from Mar to provide context on moisture availability and pre-growing season moisture trends prior to the data collection of T and ET starting on June 4

$$W_c (\text{L/day}) = \Sigma R_D \quad (1)$$

$$W_c (\text{L/ha/day}) = (\Sigma R_D)(100) \quad (2)$$

$$W_c (\text{m}^3/\text{ha/day}) = \frac{W_c (\text{L/ha})}{1000} \quad (3)$$

$$W_c (\text{m/day}) = \frac{W_c (\text{m}^3/\text{ha})}{10000} \quad (4)$$

$$W_c (\text{mm/day}) = (W_c (\text{m}))(1000) \quad (5)$$

3 | RESULTS

3.1 | Soil and climatic controls on water use

In the summer of 2016, average air temperature was 8.1°C (minimum –1.5°C to maximum 15.1°C) and average relative humidity was 69% (Figure 2). In summer 2017, average air temperature was higher at 10.8°C (minimum –2.4°C to maximum 18.6°C) and average relative humidity was much lower, at 56% (Figure 2). Cumulative available energy ($Q^* - Q_G$) over the snow-free growing season was slightly higher at 110115 MJ/m² in 2017 compared to 107329 MJ/m² in 2016 (Figure 3). Precipitation received over the two study years differed both in volume received as well as the seasonal distribution of precipitation received. The 2016 season had a smaller snowpack (292.1 maximum SWE on March 21) and earlier snowmelt, with larger summer rainfall (252.8 mm), whereas the 2017 season had a larger snowpack (382.4 mm maximum SWE on May 9), later snowmelt but less summer rainfall (149.3 mm) (Table 4). Thus, while the annual sum of snowmelt and P are almost identical for the 2 years, at 545 and 532 mm, seasonal P accumulations varied by 127.5 mm between 2016 and 2017 (47% difference in growing season P between the 2 years) (Figure 2, Table 4).

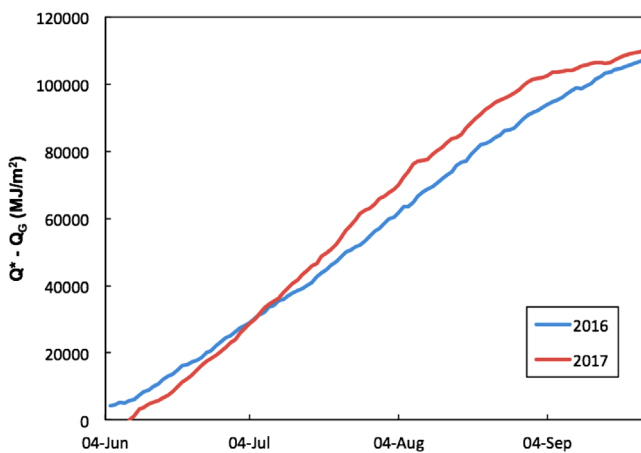


FIGURE 3 Cumulative $Q^* - Q_g$ difference over the snow-free period during the growing season study period from June 4 to September 25 of both study years for the Fortress Mountain Research Basin, Kananaskis, Alberta. 2017 totals start once snow was completely melted on June 9th. 2016 snow was melted by May 15th so totals start at 0 on June 5th

Water table depth and tensiometer data were only available for 2017. Water table depths for Tower and Powerline sites showed seasonal variability, with a shallow depth (<1 m deepest logged well) persisting only during the snowmelt period starting on May 19 and ending July 1 in 2017 (Figure 4). The water table did not reappear above a depth of 1 m for the rest of the growing season, which is below the typical rooting depth of fir and spruce species in this study (Alexander, 1987; Alexander & Shepperd, 1984). Small peaks in the water table were recorded on all loggers corresponding to a series of heavy early June P rain events totaling 78.0 mm, in addition to baseline snowmelt (Figure 2, Figure 4). 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 (Figures 4 and 5). Two (Powerline-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 soil moisture probes in the continuing downtrend of a receding water table. Volumetric water content (VWC) continuously declined with an inverse relationship of increased soil tension shown across all 10, 20 and 30 cm depths (Figure 5) until August 9 (end of manual observations).

Early season soil tension trends showed the shallow measured depths as drier, which is consistent with the trends observed in soil moisture and water levels. 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 6). This trend is explained by periods of P recharge wetting the 10 cm layer of soil without percolating to the deeper 20 and 30 cm depths (Figure 2, Figure 6). This is observable from July 6–12 as the 30 cm tensiometer depth surpassed the tension of 10 and 20 cm levels (Figure 6). This same time period experienced decreased net radiation and a P event (Figures 2 and 3). After July 12, 30 cm soil tension stayed higher until August 3 where there was a multi-day rain event of 3.9 mm, which was enough to saturate the 10, 20 and 30 cm levels.

3.2 | Subalpine forest stand ET

ET was estimated using eddy covariance between June 4 and Sept 25 for both study years (2016, 2017). Total growing season ET was smaller (178.8 mm) during the 2016 season that had more summer rain (275 mm) than in 2017 (227.1) which had less summer rain (146.7 mm) (Figure 7). Total available moisture (considering the SWE contribution to soil and groundwater available moisture) for the growing season was 544.9 mm and 531.7 mm for 2016 and 2017, respectively (Table 4). With ET and P components considered as the only inputs and outputs during the study period, 2016 provided 96.2 mm of water recharge to the system, contrasted with a net loss of 135.7 mm evaporated out in 2017. Both seasons had higher ET at the beginning (spring), with a decreasing trend toward senescence in fall (Figure 6). ET remained more stable throughout 2016 with a shallow decrease nearing fall, and 2017 displaying a more prevalent decreasing linear slope, which was double that of 2016 (Figure 7).

Component	2016				2017			
	June	July	Aug	Sept	June	July	Aug	Sept
SWE	292.1	0	0	0	382.4	0	0	0
Precipitation	18.2	103.5	53.8	77.3	78.0	13.4	14.6	43.3
Total available moisture	544.9				531.7			

Note: Maximum winter SWE values entered in June (snowmelt finished on May 15th in 2016 and June 9th in 2017).

TABLE 4 Summary of total available moisture supplied by snowmelt and growing season P over the study period from June 4 to September 25 of both years, Fortress Mountain Research Basin, Kananaskis, Alberta

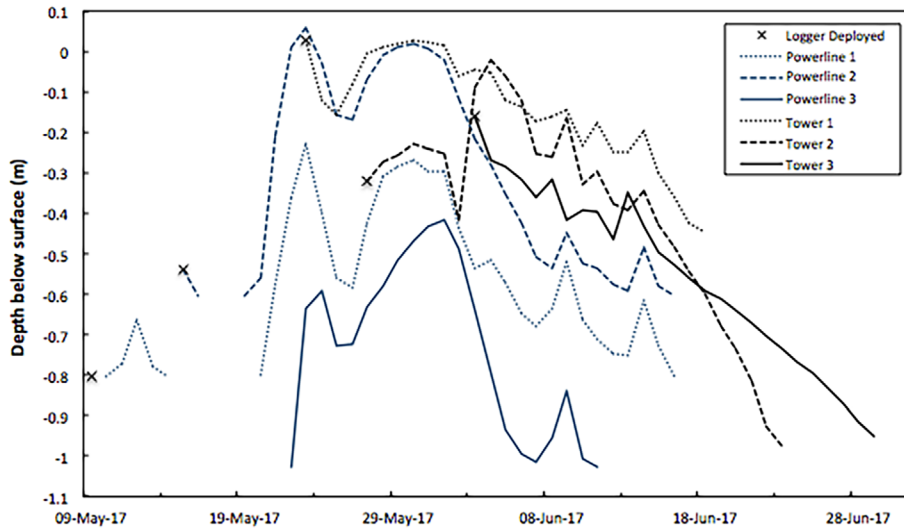


FIGURE 4 Groundwater levels during the snow melt period for tower and Powerline sites in 2017, Fortress Mountain Research Basin, Kananaskis, Alberta. Loggers were deployed as wells were located under the snowpack. Gaps in data are explained by water levels dropping below bottom of installed wells

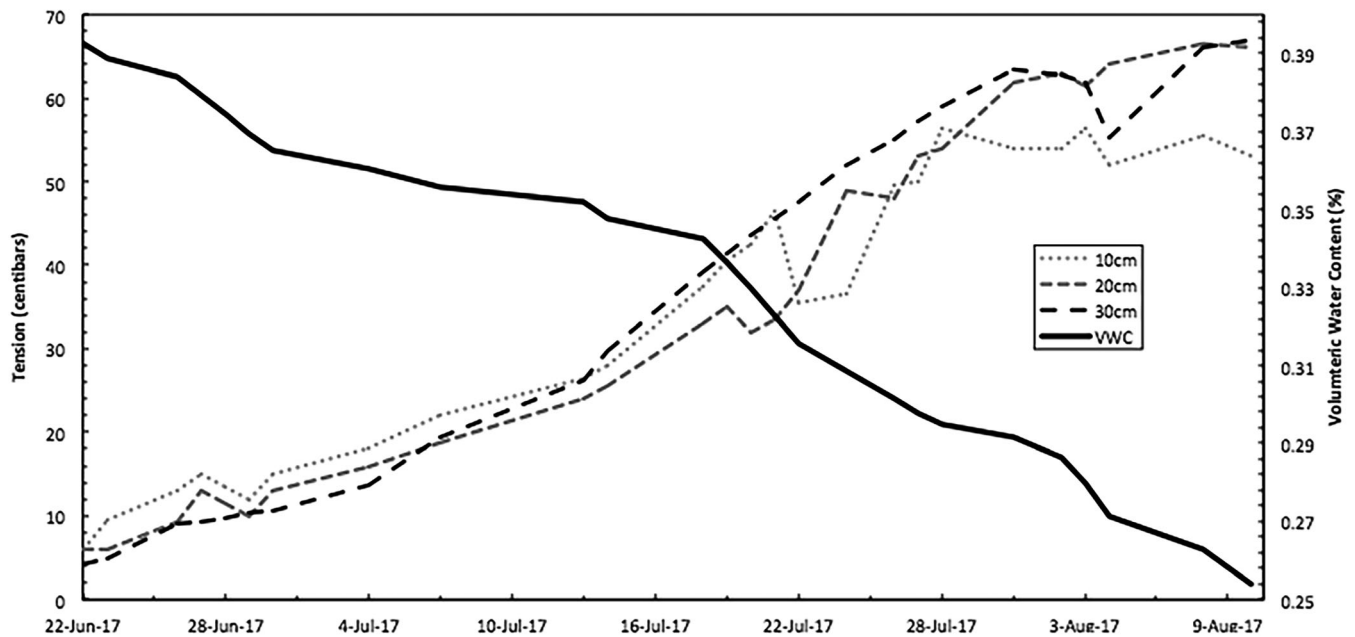


FIGURE 5 Average soil tension values for three depths (10, 20 and 30 cm) from vadose zone stations installed at tower and Powerline, paired with average volumetric soil moisture values for the 30 cm depth for the same time period. Soil tension values were measured from June 22 to August 9, 2017 in the Fortress Mountain Research Basin, Kananaskis, Alberta. VWC is shown here for comparison over the same time period. VWC was measured for longer, and appears in Figure 2

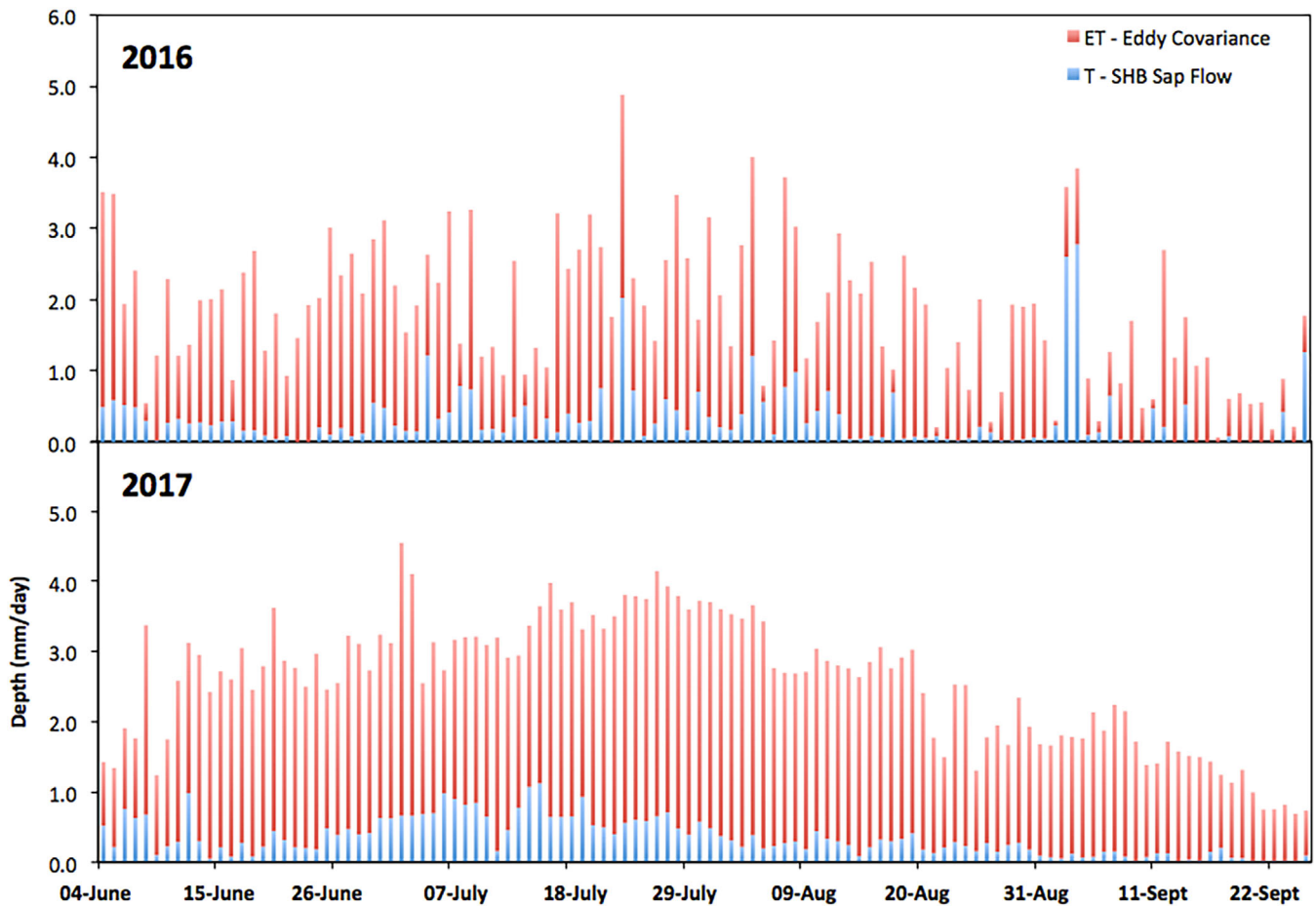
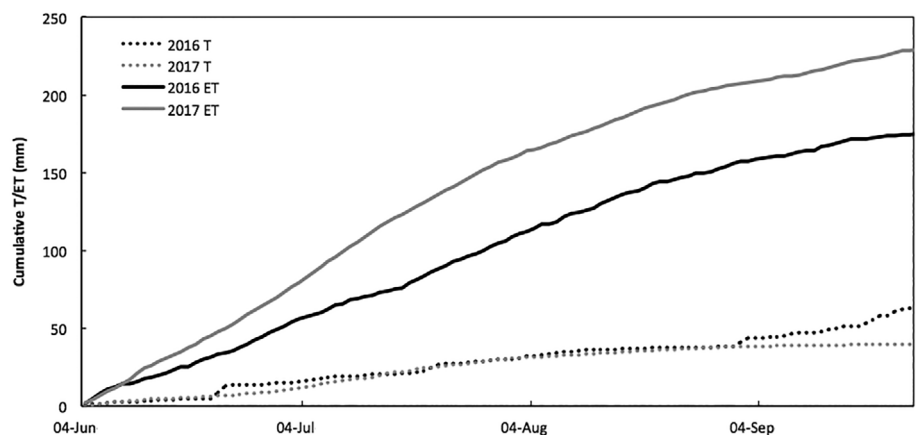


FIGURE 6 Young tree transpiration (T) plotted with forest stand evapotranspiration (ET) for the (a) 2016, and (b) 2017 growing seasons, from June 4 to Sept 25, for the Fortress Mountain Research Basin, Kananaskis, Alberta

FIGURE 7 Cumulative young tree transpiration (T) and forest stand evapotranspiration (ET) over the examined growing season, from June 4 to Sept 24 of 2016 and 2017, Fortress Mountain Research Basin, Kananaskis, Alberta. 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



3.3 | Subalpine tree T growing season trends

For both study years (2016 and 2017), sap velocity rates (g/h) were monitored on younger populations of fir and spruce for both Tower and Powerline sites from June to September. T rates were obtained from sap flow data for June 5 to Sept 24 in both study years combining both Tower and Powerline sites to capture the representative

range in canopy density (2016, 2017) within the footprint of the tower. In 2016 (rainy summer), total T of the young tree population was 63.8 mm (36% of total seasonal ET, Figure 7). In contrast, in 2017 (dry growing season), 41.0 mm total T comprised only 15% of total seasonal ET (Figure 7).

The distribution of the tree T over the growing seasons also differed between the two study years. For example, in 2016 (low

snowpack, higher summer rainfall), 47% (30.1 mm) occurred in the first half of the season, and 53% (33.7 mm) occurred in the second half of the season. In contrast, in 2017 (larger snowpack, smaller summer rainfall), 76% (31.3 mm) occurred in the first half of the season, and only 24% (9.7 mm) occurred in the second half of the season. These seasonal T distributions coincided with a prolonged period of increased soil moisture and higher overall soil moisture in July, August and September in 2016 (seasonal mean VWC 0.35) relative to 2017, but higher soil moisture levels in June 2017 due to a deeper winter

snowpack (2017 seasonal mean VWC 0.14). Cumulative T values showed similarities in early June, before the 2017 T levels surpassed those of 2016 due to a prolonged winter snowpack and sustained groundwater table (Figure 7).

A subset of the dataset (11-day period in the middle of each month of the growing season across both study years) was selected for closer analysis to compare seasonal trends between the 2 years (Figure 8). Data selected were between 14th–24th of July–Sept and May in each year, but between 5th–15th in June to show sap velocity

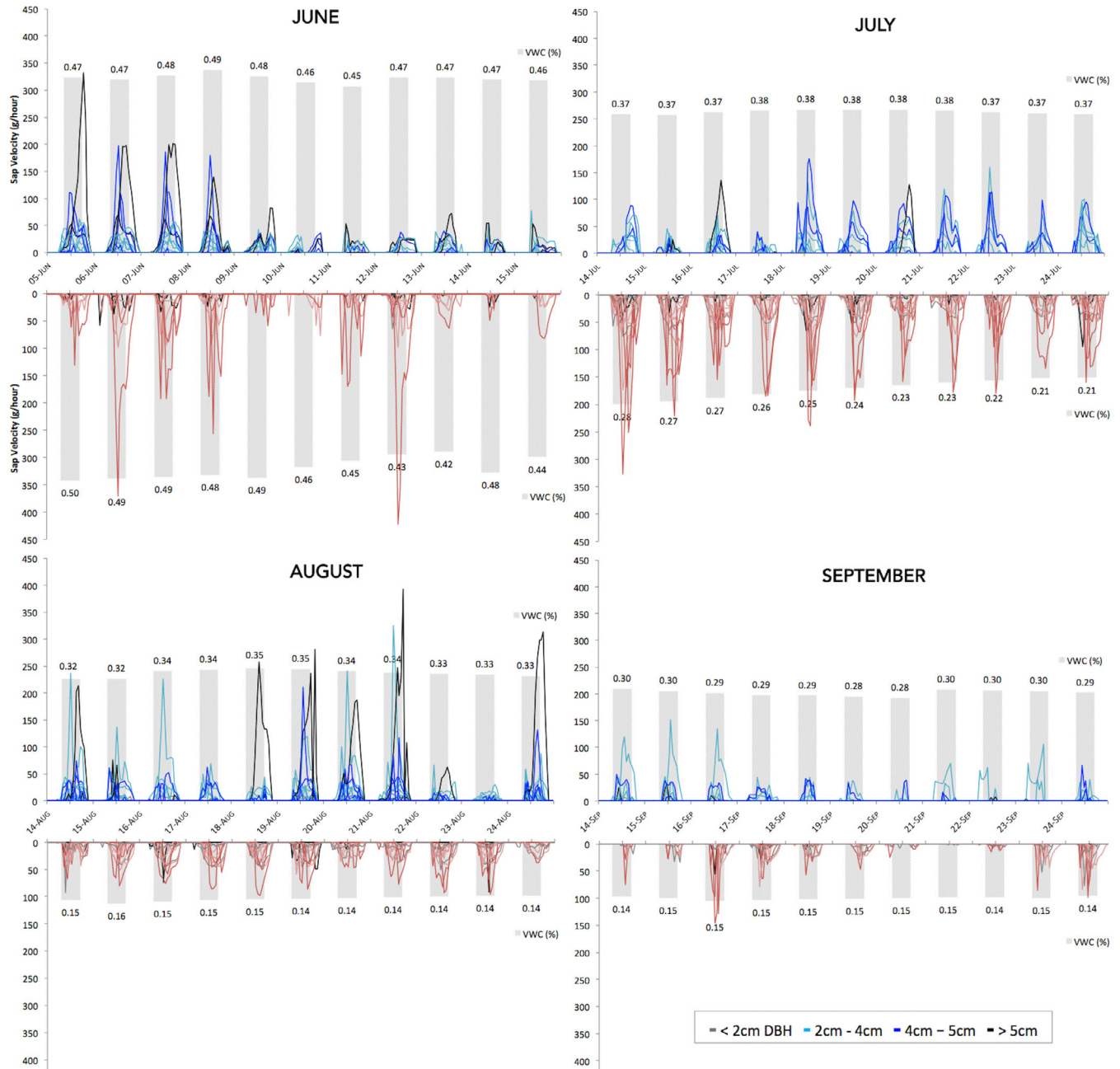


FIGURE 8 2016 (blue) versus 2017 (red) diurnal coniferous 11-day sap flow comparisons across the growing season from June 4 to Sept 24. Data were obtained from *Abies lasiocarpa* and *Picea engelmannii* coniferous trees at 2100 m elevation from tower and Powerline sites using a Dynamax flow 32-1K system, in the Fortress Mountain Research Basin, Kananaskis, Alberta

response to snowmelt. Although sap velocity rates were obtained during the entire growing seasons for both years and used for T scaling and ET partitioning, the smaller time periods (11 days) highlighted here are for trend analysis with higher quality continuous data and minimal data gaps and would thus not be affected by interpolation.

In 2016, monthly T values for the younger tree population were variable across the growing season with the highest sap velocities and T rates occurring in September (41% of season total, 26.0 mm). July was the second highest month (24%, 15.2 mm) with June showing similar quantities of T (23%, 14.9 mm), while August had the least T (12%, 8.1 mm) (Figure 8). Soil moisture in the rooting zone varied month to month, with June being the highest during snowmelt (0.49 VWC) and a steady decline of soil moisture throughout the observation period to the lowest (0.28 VWC) in September (Figures 2 and 8). As trees transitioned into senescence in September, trees of DBH less than 4 cm showed higher T than trees greater than 4 cm. This was likely due to more summer rain and increased fall season precipitation saturating the surface rooting zones of the younger trees observed. Comparatively, during early season snowmelt, more established trees with deeper rooting zones showed higher productivity early on with the presence of the snowmelt groundwater table. The more established young trees would also be above the snowpack sooner than their less mature counterparts, allowing T to occur earlier in the season.

In 2017, monthly T values were distributed differently due to a prolonged spring snowmelt compared to 2016 (Figure 2). July had the highest T values, and half of the total growing season (50% of season total, 20.5 mm). During the beginning of snowmelt, June was the second highest (26%, 10.8 mm). T then progressively decreased, with August totaling less than half of the T of July (19%, 7.9 mm), and September the lowest (4%, 1.8 mm) (Figure 8). Soil moisture in 2017 varied greatly, with highest values in June at the start of snowmelt (0.50 VWC) 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 (0.50–0.21) (Figure 9). Vapour pressure deficits (VPD) did not have strong correlations with the T values obtained ($R^2 < 0.2$, Figure 9).

4 | DISCUSSION

4.1 | Subalpine forest stand ET and the role of young trees

ET was higher in 2017 summer despite limited water availability throughout the later growing season compared to the 2016, which had higher total P, especially in late summer, and slightly higher overall water availability. The T of younger trees was higher in 2016, with reported daily ET (mm/day) totals and proportions of T consistent with those reported in the literature (Lundblad & Lindroth, 2002; Matyssek et al., 2009). Although there was no groundwater level data for 2016 (with more summer rain) higher levels of soil moisture within the rooting zone suggest increased soil water availability. Soil moisture levels in the 2017 were half of those in 2016, due to decreased precipitation throughout the growing season. P was the major source of soil moisture after snowmelt which was evident in the tensiometer data in the current study, and has been shown in other studies within subalpine forested areas with shallow depth to bedrock and limited groundwater tables (Day et al., 1990; Small & McConnell, 2008). Although there was greater moisture supply in 2017, greater Q^* and Q_G in 2017 may have also increased T and ET. Recent literature also shows increases in tree water use with increased growing season lengths under climate change, with additional slight increases in ambient temperature and available energy (Slaney et al., 2007; Teskey & Will, 1999). This trend is especially noticeable at higher elevations, where needleleaf trees respond accordingly to slight changes in ambient temperature (Carroll et al., 2017). The 2016 season had a lower average air temperature during the growing season, which when coupled with available energy further explains the smaller ET in 2016, despite having more summer rainfall and greater water availability throughout the snow-free season.

VPD appeared to have little correlation with T throughout the growing season (daily timescale). This indicates that the young tree population may be less sensitive to climate parameters, instead placing priority on available moisture to drive T. Similar results were found in a study of other needleleaf trees in Sweden, with VPD having poor

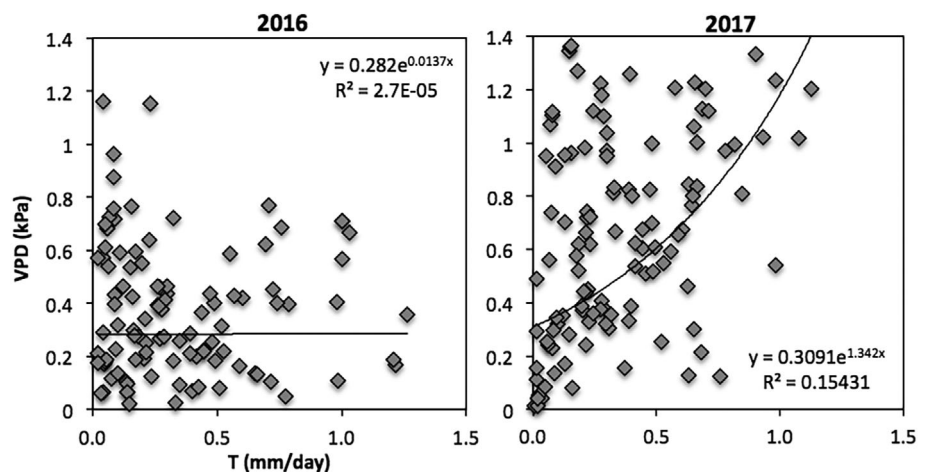


FIGURE 9 Daily VPD vs young tree T plots for both 2016 and 2017, for the Fortress Mountain Research Basin, Kananaskis, Alberta. Poor correlations are noted for both years, with the dry summer (2017) having a slightly better relationship, in comparison

correlations with T obtained from sapflow and canopy conductance (Lundblad & Lindroth, 2002). By examining total available moisture for both summers, it is clear the younger trees were less productive without growing season rains replenishing their shallow rooting zone soil layer. Despite evaporative demand being higher in 2017, these trees appeared to reduce their rates of transpiration, photosynthesizing less in periods of drought or higher VPD (Massmann et al., 2019). Comparatively, examining ET totals of the whole forest stand for both summers showed that mature trees may be responding differently, as ET rates were 37% higher in the dry summer, despite drought conditions. The drivers for T for mature trees may be more reliant on climate parameters and be more influenced by evaporative demand, than soil moisture replenishment as a result of their more developed and extensive root systems (Marques et al., 2020). These results highlight a potentially important physiological difference between young trees and more mature trees within the same population (Thompson et al., 2011).

At the beginning of the study seasons, 2017 showed lower T and ET than 2016, with a sharp rise as delayed snowmelt followed a winter of higher accumulation. SWE levels were higher in 2017 than 2016, providing the drier summer with increased water availability at the start of the season, which is vital for seasonal vegetation growth in mountainous regions (Harpold et al., 2014; Kudo et al., 1999; Tague et al., 2009; Winchell et al., 2016; Winkler et al., 2018). This later and larger snowmelt explains higher total ET values in the dry summer, despite lower season-long moisture availability (considering SWE and P). Comparatively, T of the younger trees in the drier late summer of 2017 was lower than 2016. Individually, T and ET in 2017 follow similar peaks in magnitude but show delays in response to P with T lagging slightly behind rises in ET. There was a slow but constant decline in T and ET after the snowmelt period and as soil moisture decreases until senescence in both years (Klein et al., 2014; Lopushinsky & Kaufmann, 1984; Penna et al., 2009). However, while studying spruce T during a rainy summer, Small and McConnell (2008) found low T even at high soil moisture contents suggesting waterlogged soils will suppress T, supporting the rainy summer ET observations here. Although young tree T values are higher in the summer with more continuous moisture available, this is likely due to the rooting structure of young fir and spruce trees. Fir and spruce roots are more surficial and shallower than their larger, older counterparts (Nicoll et al., 2011). Although the 2016 ET results align similarly with Small and McConnell (2008), this study shows that climate controls had noticeable effects on T and ET magnitudes observed in the rainy and drier summers.

Recent literature has shown contrasts in tree behaviour expected with increasing global temperatures and decreases in regional P. Some models show increases in T and ET with rising global temperatures (Carroll et al., 2017; Rasouli et al., 2014), while others indicate 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 drier summer (2017) in this study showed greater water use despite a lack of mid-growing season water inputs, ultimately leading to an overall loss

of water recharging the system. This is similar to findings of Rasouli et al. (2014) and Carroll et al. (2017), although long term behaviour such as this with a lower snowpack year than 2017 could cause high moisture stress for trees, especially younger cohorts. This is suggested in the trends in tensiometer data where a 'point of no return' for soil tension was exceeded around July 22 of the drier summer growing season. Given the importance of snowpack dynamics, recent studies (Harpold et al., 2015; Pomeroy et al., 2012, 2015) have addressed decreased snow accumulation within forested areas under climate change, further highlighting the potential for decreases in forest water use with reduced SWE and summer P under long term climate change scenarios. Although the importance of winter snowpack totals to forest water use has been well studied, this paper furthers understanding of hydrological conditions promoting water use and how varying seasonal climate conditions affect gains and losses to the water budget of young fir and spruce forests of the Canadian Rockies. The quantification of subalpine forest ET and young tree T results in this forest provide insights to understanding water use of Canadian Rockies subalpine forests over longer time periods, in a changing climate. Building on established knowledge of hydrological processes in a system promoting increased water use, the impact of varying hydrological conditions and summer climates on younger forest populations is important for beginning to understand how future forest health could be impacted. These results help address the hypothesis of dependence on available moisture, or opportunistic behaviour, for the younger population of trees affected by climate change showing increased water use occurring during periods of availability and limited use during periods of drought.

4.2 | Soil and climatic controls on water use

This study demonstrates the importance of vadose zone processes and water availability on the T of young alpine fir and spruce. There is a notable small window of opportunity during which 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 to constraints of altitude and surficial geology (Alexander, 1987; Alexander & Shepperd, 1984). Following the lowering of the water table, trees and vegetation rely upon residual soil moisture from snowmelt and P events large enough to saturate the rooting zone to sustain new growth and T for the remainder of the growing season (Langs et al., 2020). Although P events large enough for groundwater recharge are apparent in the tensiometer and moisture probe data at 30 cm soil depth, for smaller events, P quickly evaporates within a few days.

Differences in seasonal patterns in T and ET from trees may also be partially explained by the snowpack accumulation and melt. In 2017, ET rates at the beginning of the season were greater due to a large receding winter snowpack contributing to moisture availability in the rooting zone and groundwater recharge, for both young and old trees. Early in the season, the snowpack partially (in some cases fully) covered younger trees and they did not contribute largely to ET and T totals during this period (most of June). This may help explain, in

addition to the smaller moisture storage in surface soils caused by a smaller number of P events, why a larger snowpack in 2017 did not contribute to higher young tree T volumes than the 2016 season.

Kelsey et al. (2018) found population growth declines in fir (*A. lasiocarpa*) due to recent climate change and associated changes in the water and energy balance, while observing spruce (*P. engelmannii*) to have a lower overall decline. *A. lasiocarpa* are known to be prone to drought stress (Orwig & Abrams, 1997; Pichler & Oberhuber, 2007; Sala, 2006; Vose & Swank, 1994), while *P. 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 is fir, representing nearly 70% of the tree population. The rest of the population is composed of the more resilient spruce. A limitation of this study on water use over two contrasting summers was that it did not allow for individual species stand-level scaling with eddy covariance and sap flow techniques. However, daily flow regressions developed with both species combined increase 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) helps infer differences in T response to water availability between, and throughout the two contrasting summers. The majority of FMRB trees examined consist 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, ET overall was lower, whereas young tree T was higher, suggesting the forest is using water conservatively with limited external drought pressures (Bowling et al., 2018; Small & McConnell, 2008; Wieser et al., 2016). When observing the young tree population, these trees took advantage of the water available for T. In 2017, despite drought stress for much of the summer, overall ET was higher, especially in the first 2 months of the growing season with access to a sustained winter snowpack. Comparatively, younger tree T in this summer was lower than the wet summer, clearly showing the effect drought stress has on this population. Higher ET 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 totals compared to a year with more constant moisture availability (Adams et al., 2009; Matussek et al., 2009; Pataki et al., 2000; Shafer et al., 2015; Tague et al., 2009). However, greater available energy and more clear conditions in 2017 allowed the more mature trees to continue to transpire due to their more extensive root systems being able to still access moisture (Langs et al., 2020). The younger tree T response in the drier summer, is indicative of their shallow rooting and limited access to deeper water sources limiting photosynthesis rates. With this understanding, this indicates that the younger forest population examined here has developed physiological sensitivity and adaptation to less than ideal growing conditions, focusing photosynthesis and T during periods of water availability. This may also explain the overall forest population proportion of 70% for the more drought stressed species, despite reports of population growth declines due to recent climate changes (Kelsey et al., 2018). Results of the two contrasting summers suggest that

warming and summer drought may not impact overall forest health, or survival, as hypothesized by other studies, at least over shorter time scales (Carroll et al., 2017; Day et al., 1990; Harder et al., 2015; Sowell & Spomer, 1986). The dry summer in this study shows 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. The apparent adaptation and response seen in the dry summer examined may not be sustainable under continued long-term drought like conditions. This is especially important 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). The sensitivity to water availability hypothesized here may be sustaining population dynamics and forest health of current subalpine forests, but projected decreases in their most important water source may spur higher rates of mortality and die-off.

4.3 | Rainy and dry subalpine growing season trends

Examining subalpine stand ET and young tree T between two hydrologically different summers shows 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. Before the snowpack has completely melted, larger, mature trees are 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 (Bowling et al., 2018; Mayr & Charra-Vaskou, 2007). This is evident in the dry summer, with the larger snowpack. Young tree T rates are lower overall due to some of their population being buried until the snowpack has finished melting. The 2017 hydrological data demonstrates that snowmelt persisted until late June allowing the ephemeral water table to exist until early July. Residual soil moisture contents, exposure to radiation, and increased ambient temperatures promoted the highest levels of ET for the growing season of both study years. In the drier summer (2017), younger trees transpired substantially more than that of 2016 in September (26.0 mm and 1.8 mm, respectively), due to more P in the fall as the vegetation moved into senescence. Higher early season P quantities in 2017 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 July, while the larger winter snowpack took longer to deplete (15.2 mm and 20.5 mm, in 2016 and 2017 summers respectively). There was a 100 mm difference in SWE between study years, allowing trees in 2017 access to groundwater stores longer into the growing season, boosting overall ET values but hindering young tree T values as discussed previously. Soil moisture in 2017 was half that 2016 by August, which impacts young tree T. Overall ET was not as affected due to mature, older trees utilising the large influx of a melting winter snowpack, driving ET values to be

higher in this year than in 2016, further enforcing the importance of winter snowpack contributions to ET.

Rainy and drier summer precipitation regimes demonstrated noticeable differences in water use among the younger tree population. The summer with more rain (2016) had water use totals in the 'water limited period' of the growing season being variable among DBH, with the only source for trees to utilize being rooting zone soil moisture. The <2 cm DBH transpire less than 50 g/h and >5 cm DBH as much as 350 g/h. 2017 shows 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/h, respectively). In 2017, trees appeared to utilize water as it was available to them while also being driven by climatic influences. This was especially apparent in the trees of smaller DBH (Preisler et al., 2016), which comprised 73% of the total forest population at the sites examined. In 2016, the demand for water use appeared to be higher, with younger trees using water as it was available to them. Variations in usage magnitude differed among DBH, 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. Earlier timing of water use by trees has also been highlighted in other studies with conclusions that earlier snowmelt increased growing season length actually detracts from season long water use totals (Boyce & Lucero, 1999; Harpold et al., 2014; Hu, Moore, Burns, & Monson, 2010; Hu, Moore, Riveros-Iregui, et al., 2010; Tague et al., 2009). Despite the results supporting the hypothesis of water use sensitivity for trees born and raised under a changing climate, earlier starts to the growing season and less overall moisture availability for water use and growth could reverse these coping mechanisms (Adams et al., 2009; Carroll et al., 2017; Kueppers et al., 2017).

5 | CONCLUSIONS

This study was designed to understand and quantify subalpine forest ET in two climatically contrasting summers (more vs. less summer precipitation) in the Canadian Rockies. Examining soil and climatic conditions on water use illustrated that young trees relied strongly upon sufficient radiation and abundant water availability during the beginning of the growing season; more specifically during spring snowmelt. Despite lower season-long moisture availability in the drier summer (composed of SWE and P), less overall P and lower soil moisture contents, forest ET was 103.8 mm, 37% higher than the wetter summer. Young tree T was higher in the rainy summer with greater access to moisture for their shallow rooting zone structures, and longer exposure to radiation due to a shorter winter snowmelt period and longer snow-free period. Young trees transpired 17.8 mm, 31% more in the summer with more precipitation than the drier summer. Winter snowpack volume and higher quantities of early-growing season P were the most important sources of available water for subalpine forests throughout

the length of the growing season, helping achieve higher overall ET rates in the dry summer. The hypothesis that the younger population of trees in the subalpine stands examined would display sensitivity to water availability and local climate and hydrologic patterns was borne out by the results, which indicate that the population examined was adjusting its water use patterns based on moisture availability. This raises questions of fir and spruce physiological processes, in addition to an understanding of long-term water use dynamics under scenarios such as subsequent summers of drought stress. Questions of impacts to forest growth or health are raised under drought stress scenarios where there is a negative loss of water to the system, potentially impacting longer term growth of these subalpine forests despite short term increases of water use with high snowpack years.

While this study has added to research of subalpine fir and spruce water use volumes and seasonal timing in the Canadian Rockies, it has also shown that stand age, and consequent density, could begin to impact future forest health under a changing climate. Coupled climate and hydrological models have shown densely treed patches along the treeline are expected to accumulate less snow, although altitudinal gradients are important to consider with lower elevations receiving less snow overall. Less snow accumulation and SWE in dense patches could be a detriment to more mature stands, as this moisture is especially important for season-long T totals with a majority of water use occurring during this time. Season long T and ET trends and volumes in this study support reliance on a strong winter snowpack and confirm the importance of early season moisture. This is true even in years of decreased summer P and increased net radiation levels. Of the population examined in the rainy summer, trees of differing DBH had variable water use patterns, with no strong trends in magnitude or timing. The dry summer showed trees of all size classes utilising water, as it was available, due to lower overall water availability mainly in the form of soil moisture and P. In addition to continuing to understand 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 contrasting summers examined, which was especially apparent in cumulative T comparisons.

Overall, the subalpine forest had very different water use responses to contrasting hydrologic conditions between a wet and dry summer growing season. Insights from tree response in the drier summer provide basis for further, long term studies especially over subsequent dry growing seasons to understand subalpine forest health in a changing global, and local, climate. In addition, a further understanding of tree physiology in both species in timing and utilization of specific water sources during pivotal points of the growing season, such as spring snowmelt, would be beneficial for further understanding subalpine forest water use in the Canadian Rocky Mountains.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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