Seasonal variation in water use strategies in thinned lodgepole pine stands

EEGS Seminar Project Proposal: A Masters Thesis Proposal

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1. Introduction

Forests play a critical role in combating climate change effects through increased carbon uptake, nutrient cycling, and stabilizing water processes on a local level through evapotranspiration (ET). Stand level water use can also impact larger watershed or regional water transport (Ellison et al., 2017; van Noordwijk & Ellison, 2019). Forest ET rates are driven by water availability, solar energy, canopy cover, tree rooting area, sapwood area, and stomatal conductance (Irvine et al., 2004). Young trees have lower T because of less canopy, sapwood, and rooting areas, but they have higher stand T rates typically because of high stand density from tree competition, especially in water-abundant systems (Sánchez-Pérez et al., 2008).

Forest management techniques were identified to restore and preserve stand resources. Many restoration techniques originate from focusing on commercial forestry practices and preserving water, increasing carbon storage, and nutrient cycling (Komatsu, 2020). However, the effects of climate change have shifted forest management strategies to focus on preserving forest resilience and ecosystem services (Bosch & Hewlett, 1982; Komatsu, 2020; Wang et al., 2020). One method for increasing stand productivity and minimizing water demand is thinning. Stem removal improves tree radial growth, root development, and canopy cover, which decreases stand T and increases tree T. Studies have shown that thinning can aid ecological health through drought mitigation (Sohn et al., 2016), decreased fire risk (Niemeyer et al., 2020), improved radial tree growth (N. McDowell et al., 2002; Wang et al., 2019), and whole-ecosystem carbon-water exchange (Kerhoulas et al., 2013; N. G. McDowell et al., 2006; Serengil et al., 2007). Effective forest management strategies must account for physical and biotic characteristics and water limitations to effectively preserve, restore, or regenerate prodiuctive and resilient forests.

In water-limited regions, species have adapted to utilizing both surface and groundwater resources to counteract limited water access during the growing season (Dawson & Pate, 1996; Kerhoulas et al., 2013). The southern interior of British Columbia, Canada, has experienced drier summers and fire risk because of climate change, logging, and fire suppression (Silins et al., 2014; Winkler et al., 2021). Thinning was implemented at the Upper Penticton Creek (UPC) experimental watershed to quantify the effectiveness of thinning juvenile lodgepole pine (Pinus *contorta*) on stand hydrologic function. The effects of thinning on stand productivity and general changes in water cycling have been intensively studied (Asbjornsen et al., 2011; Liu et al., 2011; Molina & del Campo, 2012; Reid et al., 2006; Serengil et al., 2007). However, how thinning impacts water sourcing and water uptake strategies is still widely unknown and site-specific.

This study aims to expand on the current understanding of how thinning young stands changes T at both the tree and stand level and water use strategy. By measuring tree sap fluxes, soil moisture, and stable water isotope analysis of stem water compared to precipitation and groundwater, I hope to determine the ratio of lodgepole pine water sources at UPC and how thinning changes surface water or groundwater dependencies, and how lodgepole pine uptake changes over the growing season. I hypothesize that (1) deeper soil water will be the primary water source for lodgepole pines because of limited summer precipitation events, but that (2) unthinned stands will rely more heavily on precipitation events for water uptake-the growing season progresses. Furthermore, (3) I expect that all stands will become increasingly dependent on groundwater over the growing season as surface water and soil moisture decrease, but that the thinned stands will maintain constant groundwater access while the unthinned trees experience restricted water access. Through a detailed partitioning of transpiration sources, we can better understand how lodgepole pines use water, where they access water from, if water uptake changes seasonally, and how thinning affects their water use and uptake strategies.

2. Methods

2.1. Study site

Our study site is at the Upper Penticton Creek (UPC) experimental watershed 26 km northeast of Penticton, British Columbia, Canada (49º39'34" N, 119º24'34" W), which originated in the 1980s as a long-term paired watershed study focused on the impacts of deforestation on hydrological processes. The thinning experiment was established in 2016 when 16-year-old stands were thinned to two different treatment levels, moderately thinned (T1: 4,500 stems ha^{-1}) and heavily thinned (T2: 1,100 stems ha^{-1}) compared to a control (C: 27,000 stems ha^{-1}). Each treatment plots are 20 by 20 m with 5 m of space between plots and repeated across three 25 m by 75 m blocks.

The biogeoclimatic zone of UPC is dry cold Engelmann Spruce Subalpine Fir (Coupe et al., 1991; Lloyd et al., 1990; Wang et al., 2019). Dominant canopy species across the watershed include Douglas Fir (Pseudotsuga *menziesii*), Engelmann Spruce (Picea *engelmannii*), and lodgepole pine. The daily temperature ranges from -11.3 C in December to approximately 19.2 C in July, and the mean annual temperature is 1.9 C (Winkler et al., 2017). Mean annual precipitation from 1986 to 2014 is approximately 770 mm, with 60% of that being snowfall, and late winter snow depth can range between 1 to 1.5 m and can last until mid-June (Wang et al., 2019; Winkler et al., 2021). The elevation is approximately 1675 m. The soil is coarse sandy loam derived from morainal and glaciofluvial sediments and coarse-grained granitic bedrock, with low water holding capacity and well-drained (Hope, 2011). Soil depth ranges from 0.5 to 0.6 m.

Tree growth will be quantified by calculating basal area increment (BAI) from 45 trees with similar diameter at breast height (DBH) per plot. DBH for each of the 45 trees per plot and ten mature trees has been measured biannually since 2016 to monitor changes in radial growth and stand growth rates.

2.2. Meteorological monitoring

Multiple long-term meteorological stations were installed across UPC in 1991 and monitor air temperature, surface and soil temperature, relative humidity, solar radiation, wind speed, rainfall, snow depth, and snow temperature (Winkler et al., 2017, 2021). Soil moisture probes will also be deployed across the thinned plots for the growing season of 2021. Groundwater levels were recorded twice daily from 2007 to 2010, and in 2013 one of the wells (approximately 30 m deep) began recording hourly depth to groundwater levels as a part of the BC Observation Well Network. Depth to groundwater at UPC ranges from 3.1 to 11.6 m below the surface, and approximately 19% of annual precipitation contributes to groundwater recharge, and groundwater contributes about 1.3% of measured streamflow (Hunter et al., 2020; Winkler et al., 2021).

2.3. Sap flux data

Granier-type sap flow sensors are deployed annually over the growing season since the thinning experiment began. Sixteen thermal dissipation probes (Model TDP-30, Dynamax, Inc., Texas, USA) will be inserted at the beginning of this summer at breast height across five trees per treatment plot (C, T1, and T2) in one block (B1) and will be insulated with thermal insulation aluminum foil to prevent error caused by ambient temperature. Heat pulses will be recorded every 30 minutes using a CR1000 (Campbell Scientific Inc., Utah, USA). Each tree will have one probe, and I assume that the sapwood area is symmetrical in each tree. Sapwood area (A_s) was calculated from DBH using the equation from Wang et al. (2019) (Eq 1, R^2=0.98).

Empirical equations (Eq 2-4) calibrated from Granier will be used to calculate tree-level sap fluxes (1985). K is a dimensionless term calculated from the measured difference in the sensor probes' heat pulse (ΔT) and the maximum sensor temperature assuming no nighttime sap fluxes (ΔT_{max}). Sap flow velocity (SFD) (g/cm^3) is calculated from a modified specific heat formula and used with sapwood area to determine tree flow rates (F, g/hr). Daily stand transpiration (E_s) will be calculated by upscaling daily mean SFD and summed stand sapwood area using stand density (As_g) (Eq 5).

2.4. Isotopic composition

2.4.1. Sample Collection

Woody tissue from 3 trees per treatment across the three blocks will be collected during three distinct hydrological phases during the growing season. The first planned sample period is early June, when there is still high soil moisture and more available snow-melt at shallower rooting zones. The second sampling time will be in August during the drier period of the growing season. The final sampling will occur in mid-September when light rain events become more common, potentially alleviating some surface water limitations. I will collect approximately 6 cm sapwood cores at breast height (1.4 m) during each sample collection period and remove the bark and phloem to avoid the Péclet effect (Sánchez-Pérez et al., 2008; Sohn et al., 2014). Cores will immediately be placed in tightly sealed vials and placed in a cooler until after sample collection, where vials will be stored at less than -8ºC (Kerhoulas et al., 2013; Sánchez-Pérez et al., 2008; Sohn et al., 2014). Samples will be collected midday when flow is highest to maximize sample volume and assume no daily isotopic composition variation (Kerhoulas et al., 2013).

Soil will be collected by digging a pit at each treatment and collecting five samples at 20 cm intervals, immediately bagged and stored in a cooler until transported to a freezer at -18ºC until extraction (Kerhoulas et al., 2013). Soil sample results will be used with soil moisture data to determine the water isotope profile in the vadose zone. When possible, groundwater samples from a well at UPC and seasonal precipitation events without evaporative fractionation will also be collected for comparison.

2.4.2. Sample Analysis

Water will be extracted through one-hour cryogenic vacuum distillation to extract at least 2 mL of water from each sample. However, glass wool will be included to pack the soil samples before extraction to avoid particle movement (Kerhoulas et al., 2013; West et al., 2006). After water is extracted from the sample, the water will be refrigerated until analyzed. All water samples will be analyzed for their stable water isotopic composition using the Los Gatos Research (LGR) liquid water isotope analyzer at the University of British Columbia Okanagan (Kelowna, BC, Canada) to measure $\delta^{18}O$, $\delta^{17}O$, and $\delta^{2}H$. The "delta" notation refers to the isotopic composition of the sample relative to a standard (Vienna Standard Mean Ocean Water, V-SMOW) (Gonfiantini, 1978; Kerhoulas et al., 2013; Sánchez-Pérez et al., 2008). $\delta^{18}O$ is found from $R^{18}O_{sample}$ and $R^{18}O_{V\text{-}SMOW}$ and expressed in parts per thousand (Eq 6) (Barbour, 2007; Dawson & Pate, 1996; Kerhoulas et al., 2013; Meinzer et al., 2001; Sánchez-Pérez et al., 2008).

2.5. Data Analysis

All statistical analysis will be conducted in R Studio (version 1.3.1073) using the appropriate tests to determine site distinctions and seasonal variance (RStudio Team, 2020).

3. Expected Results

3.1. Sap flow and transpiration

Results of sap flow monitoring during the two years immediately after thinning showed significantly higher, and transpiration in the control plot and increased tree mean daily sap flow in the two thinning treatments (Wang et al., 2019). Changes in radial growth from 2019 to 2020, and previous years, indicate that the largest annual increase in DBH was in the heavily thinned stand, then the moderately thinned, and that the change in diameter was less in the control plot, but statistical analysis of the data has not been conducted (Figure 1)(Wang et al., 2019). Preliminary results of tree sap flow from 2020 show prominent seasonal variation in transpiration rates between the three treatments (Figure 2). There is more cumulative tree-level transpiration in the two thinned plots than the control plot (Figure 3). Growing season data from 2021 will likely support the patterns seen in previous growing seasons that tree-level transpiration is higher in thinned stands and stand-level transpiration is less than the control. Combining sap flow data with meteorological data will also provide more insight into potential seasonal variation drivers in peak sap flow periods.

3.2. Seasonal water use

Lodgepole pines have deep rooting zones and the ability to source groundwater (Andrews et al., 2012). The literature on water isotopic ratios and seasonal variation in uptake across similar species and climates indicates that lodgepole pine water sourcing depends on soil moisture and water availability (Andrews et al., 2012; Andrews & Science, 2009; Meinzer et al., 2007). I suspect that, like similar coniferous subalpine forests, that the isotopic signatures from tree samples will indicate that lodgepole pines across all treatments are relying on both surface water and groundwater sources. However, because thinning reduces competition, lodgepole pines in thinned stands are likely to have a higher groundwater uptake volume. As the growing season progresses, the control plot will experience a faster decrease in soil moisture, particularly in shallow soils. As stated in my hypothesis, I expect that the groundwater uptake ratio will have the most significant seasonal variance in the control plot because of high stand water demands, but that access will be limited. Towards the end of the growing season, when precipitation events begin to occur more frequently, the response of more densely populated stands will shift uptake ratios towards surface water more quickly. These results will be obtained through rigorous statistical modeling of seasonal water uptake depending on soil moisture and stand transpiration. Distinct seasonal trends will be identified through changes in the isotopic ratio variance across the three sample periods (wet early growing season, mid-dry growing season, and late-wet growing season). The analysis of distinct isotopic ratios between treatments and over time, informed by meteorological data and sap flow-based water demand, will give us the information to potentially say something significant about how lodgepole pine water strategies, how stand density impacts water availability and water uptake, and seasonal distinctions in water sources.

4. Implications

Discovering where lodgepole pines source their water and how they use water throughout the growing season will provide details on water cycle processes at UPC. This study will inform how forest regeneration and thinning young stands can alter water sources and shift local water partitioning. If thinned stands can rely more heavily on groundwater, and snow-melt, rather than summer precipitation events, then transpiration may be more consistent across the growing season, they can mitigate the effects of drought, increase runoff to preserve streamflow, and allow surface water the potential to infiltrate as groundwater recharge (Andrews et al., 2012; Kerhoulas et al., 2013). The high water demands of young, dense, regenerating forests can lead to water budget deficits, leading to high vegetation mortality rates and poor stream health (Asbjornsen et al., 2011; Irvine et al., 2004). Integrating isotopic analyses into a stand-level water budget focusing on transpiration will provide new insights into how water is stored and transported. This study will help inform future thinning management practices to preserve or restore hydrologic function in regenerating forests efficiently.

This study sets out to determine the effects of thinning young lodgepole pines on water strategy and seasonal water uptake. This study's scope is limited in its direct application to other forests because water strategies are highly species-specific and intrinsically connected to both the local water cycle and stand composition. One application of these findings is to better partition transpiration by source with these results and deduce the total ET percentage into surface water evaporation, surface water transpiration, and groundwater transpiration at UPC. Partitioned ET could be used in combination with other studies to infer more significant impacts of thinning on general water processes, which can be used to inform management practices in other water-limited regions. When using thinning as a water management strategy, the stand's water uptake strategies may influence how and where trees source water, and this information is critical for the future of stable water access in the face of climate change. As climate change intensifies, we must use informed management strategies that account for the future unknowns of water flow so that diverse ecosystems can adapt and preserve water function.

5. Funding

Funding for this study and other research at UPC focused on young forest water use is provided by the British Columbia Ministry of Forestry.

6. Equations

$$A_s(mm^2) = 102.871 * DBH(mm) - 3709.3 \quad (1)$$

$$K = \frac{\Delta T_{max} - \Delta T}{\Delta T} \quad (2)$$

$$SFD = 0.0119 * \mathrm{K}^{1.2311} \quad (3)$$

$$F = A_s * SFD * 3600 \quad (4)$$

$$E_s = As_g * SFD \quad (5)$$

$$\delta^{18}O = \frac{R^{18}O_{sample} - R^{18}O_{V-SMOW}}{R^{18}O_{V-SMOW}} \quad (6)$$

7. Figures

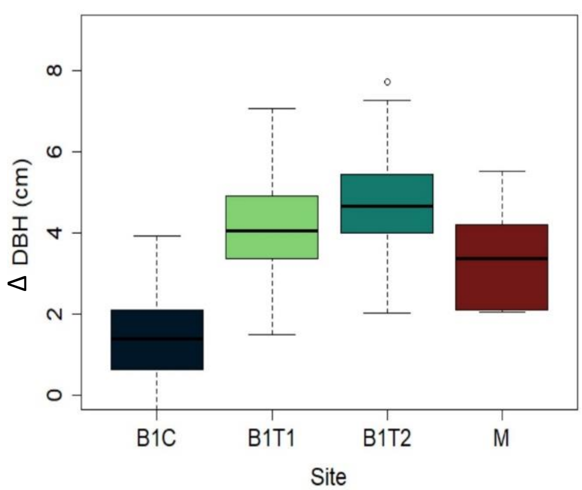

Figure 1. Change in diameter at breast height (Δ DBH) between October 2019 and October of 2020 for the control (B1C), moderately thinned (B1T1), and heavily thinned (B1T2) stands with sap flow sensors and a mature stand adjacent to the thinning plots.

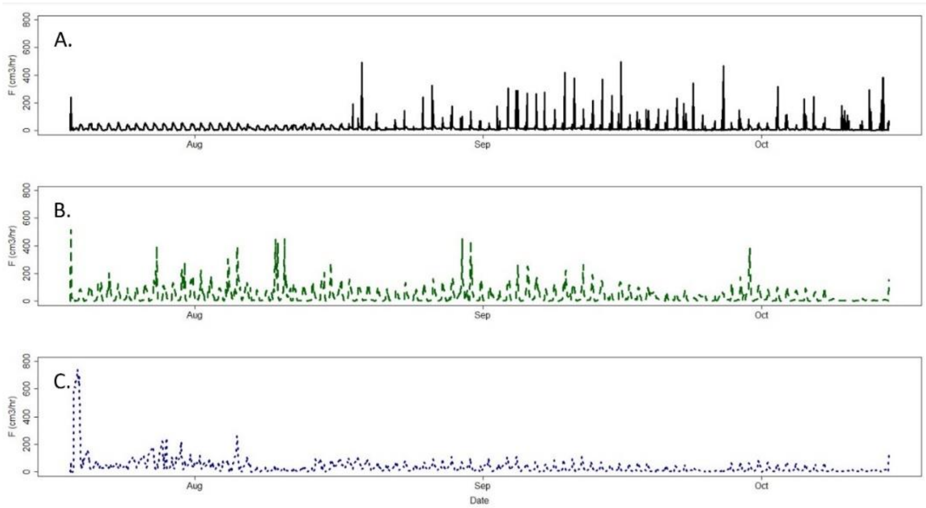

Figure 2. Mean daily tree sap flow from A. the control plot, B. the moderately thinned plot, and C. the heavily thinned plot from July to October of 2020.

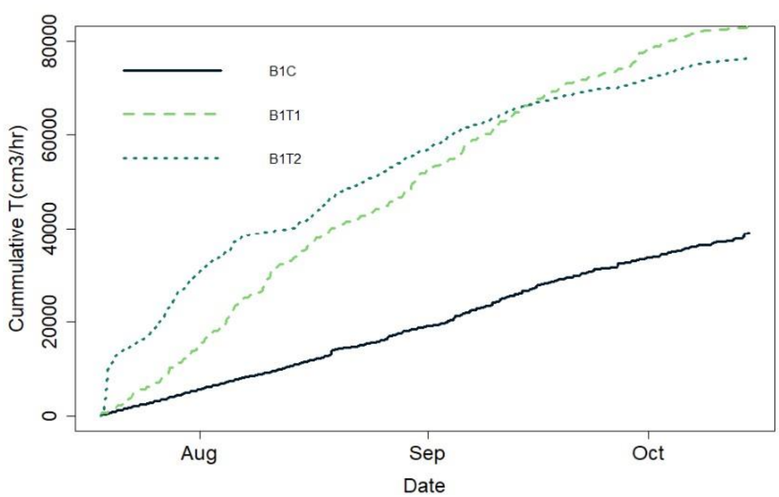

Figure 3. Mean cumulative sap flow for each treatment between July and October of 2020.

8. Budget

Item	Quantity	Unit Price	Total Cost
Two-thread increment borer	1	$200-250	
Glass screw top vials	81	$0.75	$60.75
Sealable Plastic bags	80	$0.40	$35.94
Cryogenic extraction set up	1	Unknown	NA
$\delta^{18}O$ analysis	167	~$15	$2,505
Parafilm	1	$40.00	$40
Total			~$2,891.69

9. References

Andrews, S. F., Flanagan, L. B., Sharp, E. J., & Cai, T. (2012). Variation in water potential, hydraulic characteristics and water source use in montane Douglas-fir and lodgepole pine trees in southwestern Alberta and consequences for seasonal changes in photosynthetic capacity. *Tree Physiology*, *32*(2), 146–160. https://doi.org/10.1093/treephys/tpr136

Andrews, S. F., & Science, U. of L. F. of A. and. (2009). *Tracing changes in uptake of precipitation and groundwater and associated consequences for physiology of Douglas-fir and lodgepole pine trees in montane forests of SW Alberta* [Thesis, Lethbridge, Alta. : University of Lethbridge, Dept. of Biological Sciences, c2009]. https://opus.uleth.ca/handle/10133/2482

Asbjornsen, H., Goldsmith, G. R., Alvarado-Barrientos, M. S., Rebel, K., Van Osch, F. P., Rietkerk, M., Chen, J., Gotsch, S., Tobón, C., Geissert, D. R., Gómez-Tagle, A., Vache, K., & Dawson, T. E. (2011). Ecohydrological advances and applications in plant–water relations research: A review. *Journal of Plant Ecology*, *4*(1–2), 3–22. https://doi.org/10.1093/jpe/rtr005

Barbour, M. M. (2007). Stable oxygen isotope composition of plant tissue: A review. *Functional Plant Biology*, *34*(2), 83–94. https://doi.org/10.1071/FP06228

Bosch, J. M., & Hewlett, J. D. (1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, *55*(1), 3–23. https://doi.org/10.1016/0022-1694(82)90117-2

Coupe, R., Steward, A. C., & Wikeem, B. M. (1991). *Engelmann Spruce—Subalpine Fir Zone*.

Dawson, T. E., & Pate, J. S. (1996). Seasonal water uptake and movement in root systems of Australian phraeatophytic plants of dimorphic root morphology: A stable isotope investigation. *Oecologia*, *107*(1), 13–20. https://doi.org/10.1007/BF00582230

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Van Noordwijk, M., Creed, I. F., & Pokorny, J. (2017). Trees, forests and water: Cool insights for a hot world. *Global Environmental Change*, *43*, 51–61.

Gonfiantini, R. (1978). Standards for stable isotope measurements in natural compounds. *Nature*, *271*(5645), 534–536. https://doi.org/10.1038/271534a0

Granier, A. (1985). Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. *Annales des Sciences Forestières*, *42*(2), 193–200. https://doi.org/10.1051/forest:19850204

Hope, G. D. (2011). Clearcut harvesting effects on soil and creek inorganic nitrogen in high elevation forests of southern interior British Columbia. *Canadian Journal of Soil Science*. https://doi.org/10.4141/CJSS06032

Hunter, S. C., Allen, D. M., & Kohfeld, K. E. (2020). Comparing Approaches for Reconstructing Groundwater Levels in the Mountainous Regions of Interior British Columbia, Canada, Using Tree Ring Widths. *Atmosphere*, *11*(12), 1374. https://doi.org/10.3390/atmos11121374

Irvine, J., Law, B. E., Kurpius, M. R., Anthoni, P. M., Moore, D., & Schwarz, P. A. (2004). Age-related changes in ecosystem structure and function and effects on water and carbon exchange in ponderosa pine. *Tree Physiology*, *24*(7), 753–763. https://doi.org/10.1093/treephys/24.7.753

Kerhoulas, L. P., Koch, G. W., & Kolb, T. E. (2013). Tree size, stand density, and the source of water used across seasons by ponderosa pine in northern Arizona. *Forest Ecology and Management*, *289*, 425–433. http://dx.doi.org.ezproxy.library.ubc.ca/10.1016/j.foreco.2012.10.036

Komatsu, H. (2020). Modeling evapotranspiration changes with managing Japanese cedar and cypress plantations. *Forest Ecology and Management*, *475*, 118395. https://doi.org/10.1016/j.foreco.2020.118395

Liu, X., Silins, U., Lieffers, V. J., & Man, R. (2011). Stem hydraulic properties and growth in lodgepole pine stands following thinning and sway treatment. *Canadian Journal of Forest Research*. https://doi.org/10.1139/x03-061

Lloyd, D., Angove, K., Hope, G., & Thompson, C. (1990). A guide to site identification and interpretation for the Kamloops Forest Region. *Land Management Handbook - Ministry of Forests, British Columbia*, *No. 23*. https://www.cabdirect.org/cabdirect/abstract/19950613243

McDowell, N., Barnard, H., Bond, B., Hinckley, T., Hubbard, R., Ishii, H., Köstner, B., Magnani, F., Marshall, J., Meinzer, F., Phillips, N., Ryan, M., & Whitehead, D. (2002). The relationship between tree height and leaf area: Sapwood area ratio. *Oecologia*, *132*(1), 12–20. https://doi.org/10.1007/s00442-002-0904-x

McDowell, N. G., Adams, H. D., Bailey, J. D., Hess, M., & Kolb, T. E. (2006). Homeostatic Maintenance Of Ponderosa Pine Gas Exchange In Response To Stand Density Changes. *Ecological Applications*, *16*(3), 1164–1182. https://doi.org/10.1890/1051-0761(2006)016[1164:HMOPPG]2.0.CO;2

Meinzer, F. C., Clearwater, M. J., & Goldstein, G. (2001). Water transport in trees: Current perspectives, new insights and some controversies. *Environmental and Experimental Botany*, *45*(3), 239–262. https://doi.org/10.1016/S0098-8472(01)00074-0

Meinzer, F. C., Warren, J. M., & Brooks, J. R. (2007). Species-specific partitioning of soil water resources in an old-growth Douglas-fir–western hemlock forest. *Tree Physiology*, *27*(6), 871–880. https://doi.org/10.1093/treephys/27.6.871

Molina, A. J., & del Campo, A. D. (2012). The effects of experimental thinning on throughfall and stemflow: A contribution towards hydrology-oriented silviculture in Aleppo pine plantations. *Forest Ecology and Management*, *269*, 206–213. https://doi.org/10.1016/j.foreco.2011.12.037

Niemeyer, R. J., Bladon, K. D., & Woodsmith, R. D. (2020). Long-term hydrologic recovery after wildfire and post-fire forest management in the interior Pacific Northwest. *Hydrological Processes*, *34*(5), 1182–1197. https://doi.org/10.1002/hyp.13665

Reid, D. E. B., Silins, U., & Lieffers, V. J. (2006). Sapwood hydraulic recovery following thinning in lodgepole pine. *Annals of Forest Science*, *63*(4), 329–338.

RStudio Team. (2020). *R Studio: Integrated Development Environment for R* (1.3.1073) [Computer software]. RStudio, PBC.

Sánchez-Pérez, J. M., Lucot, E., Bariac, T., & Trémolières, M. (2008). Water uptake by trees in a riparian hardwood forest (Rhine floodplain, France). *Hydrological Processes*, *22*(3), 366–375. https://doi.org/10.1002/hyp.6604

Serengil, Y., Gökbulak, F., Özhan, S., Hızal, A., Şengönül, K., Nihat Balcı, A., & Özyuvacı, N. (2007). Hydrological impacts of a slight thinning treatment in a deciduous forest ecosystem in Turkey. *Journal of Hydrology*, *333*(2), 569–577. https://doi.org/10.1016/j.jhydrol.2006.10.017

Silins, U., Bladon, K. D., Kelly, E. N., Esch, E., Spence, J. R., Stone, M., Emelko, M. B., Boon, S., Wagner, M. J., Williams, C. H. S., & Tichkowsky, I. (2014). Five-year legacy of wildfire and salvage logging impacts on nutrient runoff and aquatic plant, invertebrate, and fish productivity. *Ecohydrology*, *7*(6), 1508–1523. https://doi.org/10.1002/eco.1474

Sohn, J. A., Brooks, J. R., Bauhus, J., Kohler, M., Kolb, T. E., & McDowell, N. G. (2014). Unthinned slow-growing ponderosa pine (Pinus ponderosa) trees contain muted isotopic signals in tree rings as compared to thinned trees. *Trees - Structure and Function*, *28*(4), 1035–1051. https://doi.org/10.1007/s00468-014-1016-z

Sohn, J. A., Saha, S., & Bauhus, J. (2016). Potential of forest thinning to mitigate drought stress: A meta-analysis. *Forest Ecology and Management*, *380*, 261–273. https://doi.org/10.1016/j.foreco.2016.07.046

van Noordwijk, M., & Ellison, D. (2019). Rainfall recycling needs to be considered in defining limits to the world's green water resources. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(17), 8102–8103. https://doi.org/10.1073/pnas.1903554116

Wang, Y., del Campo, A. D., Wei, X., Winkler, R., Liu, W., & Li, Q. (2020). Responses of forest carbon and water coupling to thinning treatments from leaf to stand scales in a young montane pine forest. *Carbon Balance and Management*, *15*(1), 24. https://doi.org/10.1186/s13021-020-00159-y

Wang, Y., Wei, X., del Campo, A. D., Winkler, R., Wu, J., Li, Q., & Liu, W. (2019). Juvenile thinning can effectively mitigate the effects of drought on tree growth and water consumption in a young Pinus contorta stand in the interior of British Columbia, Canada. *Forest Ecology and Management*, *454*, 117667. https://doi.org/10.1016/j.foreco.2019.117667

West, A. G., Patrickson, S. J., & Ehleringer, J. R. (2006). Water extraction times for plant and soil materials used in stable isotope analysis. *Rapid Communications in Mass Spectrometry*, *20*(8), 1317–1321. https://doi.org/10.1002/rcm.2456

Winkler, R., Diana, A., Giles, T., Heise, B., Moore, R. D., Redding, T., Spittlehouse, D., & Wei, X. (2021). *Approaching four decades of Forest Watershed research at Upper Penticton Creek, British Columbia: A Synthesis*.

Winkler, R., Spittlehouse, D., & Boon, S. (2017). Streamflow response to clear-cut logging on British Columbia's Okanagan Plateau. *Ecohydrology*, *10*(2), e1836. https://doi.org/10.1002/eco.1836