WATER DYNAMICS IN MANAGED PINE PLANTATION FORESTS

INTEGRATING SAP FLOW AND EDDY COVARIANCE TECHNIQUES TO UNDERSTAND THE EFFECTS OF FOREST MANAGEMENT ON WATER FLUXES IN A TEMPERATE RED PINE PLANTATION FOREST

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ABSTRACT

Forests provide important ecosystem services and play a dominant role in the global carbon and hydrologic cycles. These ecosystems are becoming more vulnerable to climate change-related threats such as extreme temperature and precipitation events, drought and wildfires. In addition, forest ecosystems have also undergone land use changes and a significant reduction in cover area, specifically in North America. There has been renewed realization to restore and rehabilitate forest ecosystems because they are a major carbon sink and play a key role in sequestering atmospheric carbon dioxide. In response, plantation forests are being widely established to sequester carbon, increase biodiversity, secure water resources and generate economic revenue when harvested. Forest managers employ different management practices such as thinning or retention harvesting to enhance growth, plant structural and species diversity within forest plantations, with the ultimate goal of emulating the characteristics and benefits of natural forests. However, the influence of these forest management practices on the growth, productivity and specifically water cycling in plantation forests is not well studied and reported in the literature.

This experimental study investigated the effect of four different variable retention harvesting (VRH) treatments on evapotranspiration and water balance in an 83-year-old red pine (Pinus *resinosa*) plantation forest in the Great Lakes region in Canada. These VRH treatments included 55% aggregated crown retention (55A), 55% dispersed crown retention (55D), 33% aggregated crown retention (33A), 33% dispersed crown retention

(33D) and unharvested control (CN) plot. Tree-level experimental work was conducted in the control plot and showed that most of the water transport (65%) occurred in the outermost sapwood, while only 26% and 9% of water was transported in the middle and innermost depths of sapwood, respectively. These results help to avoid overestimation of transpiration, which may cause large uncertainties in water budgets in pine forests. Study results further showed that the 55D treatment had the highest tree-level transpiration followed by 33D, 55A, 33A and CN plots. During periods of low precipitation, vapor pressure deficit (VPD) was the main driver or control on transpiration in VRH treatments. However, transpiration was more closely coupled with photosynthetically active radiation (PAR) in the control plot. Moreover, the 55D treatment resulted in on average 58% of total water loss from canopy as transpiration and 42% from the understory and ground surface as evapotranspiration. These findings suggest that dispersed or distributed retention of 55% basal area (55D) provides the optimal environmental conditions for forest growth with reduced competition of trees for water as shown by enhanced transpiration. This study will help researchers, forest managers and decision-makers to improve their understanding of thinning impacts on water and carbon exchanges in forest ecosystems and select and adopt viable forest management practices to enhance their carbon sequestration capabilities, water use efficiency and resilience to climate change.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

This dissertation consists of three individual manuscripts that have been either published or submitted for publishing in peer-reviewed academic journals. Research presented in this dissertation has been conducted at various sites within the Turkey Point Observatory. There is some natural overlap between information presented in each chapter (e.g. site description, methods etc.), however each chapter contains distinct information relevant to the respective study.

Chapter 2

Title: Radial variations in xylem sap flux in a temperate red pine plantation forest

Authorship: Alanna V. Bodo & M. Altaf Arain

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Chapter 3

Title: Effects of variable retention harvesting on canopy transpiration in a red pine plantation forest

Authorship: Alanna V. Bodo & M. Altaf Arain

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Chapter 4

Title: Water dynamics in the understory of a pine plantation forest after variable retention harvesting

Authorship: Alanna V. Bodo & M. Altaf Arain

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In all three manuscripts, Alanna V. Bodo (the PhD Candidate) conducted a literature review, collected and/or contributed to the collection of sap flow, eddy covariance flux and meteorological data at the white-pine (CA-TP39 and CA-TP74) and the red pine (CA-TP31) forest sites. The candidate took the lead role of data analysis and writing of the first drafts of the manuscripts. Insightful discussions were also held with collaborators and committee members throughout the duration of the study program. Specific acknowledgements pertaining to each study are provided at the end of the respective chapters or papers.

CHAPTER 1:

INTRODUCTION

1.1 Climate Change and Water

The earth has experienced natural fluctuations in climate over time, however, in recent decades anthropogenic greenhouse gas emissions have been linked to the unprecedented rate at which global air temperatures are rising (IPCC, 2021). Greenhouse gases such as carbon dioxide (CO_2), trap long-wave radiation and influence the global carbon cycle. Mean global concentrations of CO_2 have increased from 280 parts per million in the year 1750 to 414.3±0.1 parts per million in 2020 (Joos and Spahni 2008, NOAA Global Monitoring Laboratory 2021). Consequently, Earth's global mean air temperature has increased by 0.8°C to 1.2°C and is on track to reach or exceed 1.5°C in the next 30 years (IPCC 2021). The impacts of global warming differ according to geographic location and level of development, but it is widely predicted that changes in climate will lead to sea-level rise, more extreme weather events and altered precipitation regimes.

The earth's climate and the global water cycle are intricately linked systems. Climate change alters the dynamics of the water cycle and impacts on water supply and demand are expected to worsen over the coming years (Ellison et al. 2017, Sheil 2018). In some regions, warmer temperatures are expected to be met with less precipitation and may lead to droughts, wildfires, food shortages and water scarcity. Other regions are expected to experience more variable and extreme precipitation events such as flooding, hurricanes and hail storms (IPCC 2021). These impacts will unarguably have adverse effects on both marine and terrestrial ecosystems and the biodiversity they sustain.

1.2 Forest Ecosystems

Globally, forests cover 30% of the Earth's land surface (Bonan 2008) and provide a wide range of biodiversity, climate and water-related ecosystem services. Forests play a key role in the terrestrial water, energy and carbon cycles. Globally, forests sequester 20% of total anthropogenic carbon each year (Pan et al. 2011) and 10% of terrestrial carbon is held in temperate forests (Bonan 2008). Despite the high carbon sequestration rates of these forests, deforestation and increasing annual temperatures are turning many of these carbon sinks into carbon sources (Bonan 2008, Hadden and Grelle 2016, Baccini et al. 2017, Gatti et al. 2021).

Approximately 61% of the 117,600 km^3 of annual global precipitation is derived from the land (Schneider et al. 2017) and more than 50% of this atmospheric moisture originates as transpiration from vegetation (Jasechko et al. 2013; Wei et al. 2017; Sheil 2018). It is widely accepted that forests return more water vapour to the atmosphere than any other vegetation type (Katul et al. 2012). Terrestrial evapotranspiration is a major component of the hydrologic cycle and is closely linked with precipitation and surface temperatures. Forests also act as a "biotic pump" – drawing in moist air from areas with low leaf area (Sheil 2018). This condensation-driven theory of wind suggests that air rises in high evaporation areas creating a low pressure zones where moist air from the surrounding area is drawn. Hence, these areas may experience local precipitation (Makarieva et al.

2013, Sheil 2018). In addition to this influx of moisture, forests have high transpiration rates – a process which generates rainfall, reduces sensible heat and increases cloud cover (Pokorny et al. 2010, Sheil 2018, Ellison et al. 2017). While carbon sequestration and storage have been regarded as the primary benefits of forests, many scientists argue that the water-related ecosystem services they provide are equally, if not more important (Ellison et al. 2017).

Global deforestation removes 18.7 million acres of forest each year (FAO, 2016). Some researchers estimate these alterations to terrestrial land cover have caused a 5-6% reduction in atmospheric moisture at a global scale (Sterling et al. 2013). This issue has recently attracted global attention at the COP26 climate summit, where the leaders of 110 countries committed to ending deforestation by the year 2030 (UN Climate Change Conference UK 2021). As a direct measure to address deforestation and the rising levels of atmospheric carbon dioxide, afforestation and reforestation practices have been widely adopted to enhance carbon sequestration and mitigate climate change (Pan et al. 2011, Law et al. 2018, Domke et al. 2020). When compared to natural stands, plantation forests are characterized by a more homogenous age distribution and lower species diversity, which decrease their resilience to climate change-related threats such as drought, wildfire and invasive species (Hemery 2008, Dale et al. 2010). Ecological forest management practices have been developed and applied to plantation stands to increase structural diversity, emulate characteristics of natural stands and therefore, increase their resilience to climate change.

1.3 Forest Management

Various forest management practices are employed worldwide to achieve ecological and economic goals. Silviculture, the practice of manipulating forest stands, is strongly rooted in European forest practices and recognizes four regeneration harvest methods: clearcut, seed-tree, shelterwood and selection (Smith 1986, Franklin et al. 1997). Thinning provides economic revenue from harvested timber, while regulating competition between trees in a stand, providing the remaining trees with greater access to resources required for productivity. In addition to growth of the remaining trees, the opening of the canopy results in changes to the microclimate within and above the forest stand. Parameters like radiation and intercepted rainfall are altered, along with wind flow, air temperature and vapour pressure deficit (Vesala et al. 2005).

More recently, research has shown thinning can reduce mortality and increase resiliency to drought and other threats exasperated by climate change (Powers et al. 2010, Knapp et al. 2021). Drought-related stress and mortality is increasingly being documented in temperate, boreal and tropical ecosystems, forecasting the impacts on forests globally (Adams et al. 2009, Dai 2013, Allen et al. 2015, Law et al. 2015, Clark et al. 2016). These studies often provide the basis for policy and management decisions like thinning prescriptions and what species to plant following disturbance.

Of the four recognized regeneration harvesting methods, the selection method is most appropriately used in uneven-aged stands (Smith 1986). While there are several adaptions to this method, the VRH method has been widely applied in managed Canadian forests for the past 30 years (Beese et al. 2019). VRH aims to maintain structural elements of the pre-harvest stand by retaining live and dead trees of various sizes. This method emphasizes the importance of structural complexity for preserving ecosystem function and supporting biological diversity (Beese et al. 2019). The long-term retention of trees which vary in size and age leads to a more structurally diverse and resilient stand (Franklin et al. 2018). While research supports the use of VRH to decrease tree mortality, future studies should examine the complex linkages between soil, vegetation and atmosphere in these ecosystems.

1.4 Study Site Description

This dissertation consists of research conducted at three forest sites in the Turkey Point Observatory (TPO), located within the St. Williams Conservation Reserve (SWCR) near Lake Erie in Ontario, Canada. The study sites consist of two white pine (*Pinus strobus* L.) plantation forests, planted in 1939 and 1974 (referred to as CA-TP39 and CA-TP74, respectively); and one red pine (*Pinus resinosa*) site, referred to as CA-TP31. The abbreviation CA-TP refers to 'Canada-Turkey Point' and the number corresponds to the year in which the stand was planted. All three forest sites are located within a 3-km radius of one another and are subjected to similar edaphic and climate conditions. In 2014, CA-TP31 was subjected to thinning following a variable retention harvesting (VRH) treatment. The four different VRH treatments included 55% aggregated crown retention (55A), 55% dispersed crown retention (55D), 33% aggregated crown retention (33A), 33% dispersed crown retention (33D) and unharvested control (CN) plot. The Turkey Point Observatory is part of the Global Water Futures (GWF) program and FLUXNET. Further site details including instrumentation are reported in the individual chapters.

1.5 Methods Overview

This research utilized thermal dissipation sap flow sensors and eddy covariance instrumentation to quantify components of forest evapotranspiration. Lab-constructed sap flow sensors followed the Granier (1987) method, where two probes containing thermocouples were inserted into the xylem tissue of a tree. The upper probe was positioned vertically from the other, heated at a constant rate and the difference in temperature between both probes was measured. These values are then scaled up to sap flow, sap flux density and transpiration. Sap flow measurements have been used to quantify and examine physiological and environmental controls on transpiration in individual trees and forest stands for the past four decades (Wullschleger et al. 1998, Wilson et al. 2001b, Oishi et al. 2008, Poyatos et al. 2016). Given the heterogeneity of forest stands, the sap flow technique provides important insight into the dynamic interactions that occur at the soil-plant-atmosphere boundary of these ecosystems.

The eddy covariance (EC) method is widely used to quantify the exchange of carbon, water and energy between the land surface and the atmosphere at larger spatial scales

(Baldocchi et al. 1988, Baldocchi 2020). Several studies have used EC to measure these fluxes in the boundary layer above forest canopies which are typically characterized by sufficient turbulence. Eddy covariance is the most widely used method to measure mass and energy fluxes above forest canopies and is the foundation for global, standardized networks such as FLUXNET (Baldocchi 2001). The method is based on the theory that rotating parcels of air (eddies) transport quantities of water vapour, carbon dioxide and other trace gases. Several studies have also successfully used EC below/within a forest canopy to capture the contributions of soil and understory vegetation to the ecosystem carbon and water balance (Baldocchi and Meyers 1991, Baldocchi 1997, Saugier et al. 1997, Wilson and Meyers 2001a, Paul-Limoges et al. 2017). This study collected carbon, energy and water flux measurements using EC instrumentation situated above the forest canopy at the two white pine sites (CA-TP39 and CA-TP74) and below/within the canopy at the red pine site (CA-TP31). In addition to EC and sap flow measurements, soil and meteorological measurements were also collected at each site including air temperature, relative humidity, photosynthetically active radiation, net radiation, precipitation, soil temperature and soil moisture. Additional details about instrumentation are provided in each of the respective individual chapters.

1.6 Study Objectives

This study examined physical and biological components of forest evapotranspiration and the impact of variable retention harvesting on these processes. The primary objectives of this study were:

1) Quantify hydraulic flow through the xylem sap wood of red pine trees to reduce uncertainties when scaling sensor measurements to the tree-level

2) Investigate the environmental drivers of evapotranspiration and compare these controls between variable retention harvesting (VRH) treatments

3) Examine the effect of VRH treatments on tree-level transpiration of the dominant canopy species in a red pine plantation

4) Partition evapotranspiration into dominant components: canopy transpiration and understory soil and vegetation and compare the contribution of these components between VRH treatments

This research may be of interest to those involved in decision-making related to forest management strategies, and to forest researchers studying the adaptation of these ecosystems to future climate. Additionally, the results of this work may provide a better understanding of the various processes contributing to canopy-scale ET and help in the improvement of land-surface models

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CHAPTER 2:

RADIAL VARIATIONS IN XYLEM SAP FLUX IN A TEMPERATE RED PINE PLANTATION FOREST

Abstract

Scaling sap flux measurements to whole-tree water use or stand-level transpiration is often done using measurements conducted at a single point in the sapwood of the tree and has the potential to cause significant errors. Previous studies have shown that much of this uncertainty is related to (i) measurement of sapwood area and (ii) variations in sap flow at different depths within the tree sapwood. This study measured sap flux density at three depth intervals in the sapwood of 88-year-old red pine (*pinus resinosa*) trees to more accurately estimate water-use at the tree- and stand-level in a plantation forest near Lake Erie in Southern Ontario, Canada. Results showed that most of the water transport (65%) occurred in the outermost sapwood, while only 26% and 9% of water was transported in the middle and innermost depths of sapwood, respectively. These results suggest that failing to consider radial variations in sap flux density within trees can lead to an overestimation of transpiration by as much as 81%, which may cause large uncertainties in water budgets at the ecosystem and catchment scale. This study will help to improve our understanding of water use dynamics and reduce uncertainties in sap flow measurements in the temperate pine forest ecosystems in the Great Lakes region and help in protecting these forests in the face of climate change.

2.1 Background

Forests provide essential water-related ecosystem services through the regulation of the hydrologic cycle. Quantitative assessments of these ecosystem services have traditionally focused on direct water availability, failing to recognize the role of forests in moisture recycling from a supply, or 'green water' perspective (Falkenmark and Rockstrom 2004, Ellison et al. 2017, Casagrande et al. 2021). At a global scale, 61% of atmospheric moisture is derived from terrestrial environments (Schneider et al. 2017), more than half of which comes from plant-transpiration (Jasechko et al. 2013, Wei et al. 2017). A thorough understanding of these processes may help to better characterize the complex linkages between forest ecosystems and climate change. Furthermore, the accurate quantification of these green water processes is becoming increasingly important for the development of terrestrial ecosystem and hydrologic models (Guswa et al. 2014) as well as climate models (Marotzke et al. 2017).

Forest ecosystems play a dominant role in the transfer of ground water to the atmosphere through transpiration (Bonan 2008). Precise measurement of transpiration in forest ecosystems is essential to improve our understanding of their water-use and hence regional water resources. It will help to determine how forests may respond to future climatic changes, where future climate scenarios suggest increased air temperatures, more frequent and severe droughts and longer growing seasons (Zhang et al. 2019), which may have a major impact on the transpiration and water-use in forest ecosystems.

Over the past 40 years scientists have developed several methods for estimating transpiration such as the water balance method, soil water budget, isotopes and sap flow (Kool et al. 2014). The latter describes a technique of estimating the water flux through the conductive tissue of a plant (Vandegehuchte and Steppe 2013). There are several different methods to measure sap flow including the heat-pulse (Swanson and Whitfield 1981, Cohen et al. 1981, Green and Clothier 1988) and thermal-dissipation (Granier 1987) techniques. Both methods measure the difference in temperature between a heated and non-heated probe and create a dimensionless flow index (K). This flow index is then used to calculate sap flux density (J_s; g H_2O m^{-2} sapwood s^{-1}), the flow rate per conductive area (Vandegehuchte and Steppe 2013). To estimate whole-tree water use from J_s, the mass flow of sap in the conductive xylem sapwood (F) is calculated as the product of J_s and the sapwood area (A_s) of the stem cross-section ($F = J_s A_s$).

When scaling point-measurements to the whole-tree or stand level, many studies have identified within-tree variations in sap flow as one of the largest sources of error (Hatton et. al 1995, Oren et al. 1998, Clearwater et al. 1999, Wullschleger and King 2000, Zhang et al. 2015). To accurately understand whole-tree water use in the forest stand, scientists rely not only on the accuracy of these point-measurements but also on the methods used to scale-up the results to the tree- and stand-level (Clearwater et al. 1999). This includes an accurate estimation of sapwood depth and an understanding that J_s varies radially throughout the sapwood. Failure to take into consideration these radial differences has been shown to lead to errors as large as 300% when reporting whole-tree transpiration in the literature (Nadezhdina et al. 2002, Ford et al. 2004b).

In addition to variability throughout a cross-section of a tree, the sap flow method is subject to errors associated with uncertainties in the sapwood area. This is often due to the destructive nature of methods such as coring to determine sapwood depth. These errors can lead to insufficient contact area of the sampling probes in the sapwood and inaccuracies when scaling up point-measurements to the tree-level (Vandegehuchte and Steppe 2013, Lu et al. 2004). Few studies using sap flow methods to estimate tree- and stand-level transpiration characterize a radial profile within the sapwood (Ford et al. 2004b). Berdanier et al. (2016) examined studies published between 2013 and 2016 in which authors scaled-up sap flow measurements and found 58% of studies assumed uniform flow throughout the sapwood, resulting in a large margin of error.

This study addresses many of the aforementioned uncertainties in sap flow measurements with the aim of decreasing error in the scaling-up process and further highlighting the importance of characterizing a radial profile of water conductance within the sapwood. The specific objectives of this study are (i) to measure the spatial (radial) variability in sap flow within the xylem sapwood of the red pine trees; (ii) to determine if a species-specific relationship exists between tree diameter and sapwood area; and (iii) to quantify errors associated with up-scaling of single point sap flow measurements to the whole tree level. We hypothesize that sap flux will be greatest closer to the cambium and decrease substantially toward the heartwood, where it is considered to be zero. The study results will help to develop a better understanding of the hydraulic conductivity of sapwood and help in up-scaling sap flow to the tree- and ecosystem levels.

Furthermore, this study is one of the first to study spatial variation in sap flow in red pine (*Pinus resinosa)* - an important plantation species in the region of southern Ontario. It is estimated that 70% of plantation forests in southern Ontario are comprised of red pine, a species which delivers valuable economic revenue from harvested timber (Kim 2020). These red pine plantations produce lumber which is extensively used for pulp wood and utility poles, and are also considered a principal solution for the restoration of wastelands into forests (LRC 2005).

2.2 Methods

2.2.1 Experimental site description

This study was conducted in a temperate red pine (*Pinus resinosa*) plantation forest located in the St. Williams Conservation Reserve (SWCR) (42°42’N, 80°21’W), 3.0 km north of Lake Erie, in southern Ontario, Canada. This 14-ha plantation stand is part of the Turkey Point Observatory or Turkey Point Flux Station (TPFS) and is referred to as TP31, where 31 represents 1931 when the stand was planted. Soils in this region are sandy and well-drained, with a low to moderate water holding capacity (McLaren et al. 2008; Beamesderfer et al. 2020). The TPFS consists of three different-aged coniferous plantations referred to in the literature as TP39, TP72 and TP02, one mixed deciduous site, TPD, one red pine plantation stand, TP31(this study site) and an agricultural site

(TPAg), where eddy covariance flux measurements have been made. These sites are also associated with the Global Water Futures Program and FLUXNET. Further details of TPFS are given in Restrepo and Arain (2005), Peichl et al. (2010) and Beamesderfer et al. (2020).

TP31 was established by planting red pine seedlings in furrowed rows, 2 m apart. In early 2014 the plantation was subject to a variable retention harvesting (VRH) regime to convert or restore this conifer plantation to a native mixed forest. VRH treatment included the division of the stand into 1-hectare plots, and the application of different harvesting patterns to the plots. This study was conducted in three trees in the non-harvested (control) plots of this plantation. These trees are part of much larger VRH study where sap flow is being measured in 80 trees in 15 one-hectare plots comprising five management regimes or treatments. Because TP31 is a monoculture plantation stand with very small difference in tree DBH and structure, measuring radial difference in sap flow in three trees was adequate for this study.

2.2.2 Meteorological information

The climate in southern Ontario is temperate with warm, humid summers and very cold winters. The region receives on average 1036 mm of precipitation per year, of which approximately 13 % falls as snow (Environment and Climate Change Canada, Norms at Delhi, ON).

Local micrometeorological conditions were measured from two flux towers located at the white pine (*Pinus strobus*) plantation sites (TP39, TP74) within a 3-km radius of TP31. These towers are instrumented with eddy-covariance systems and weather stations, where continuous year-round measurements of sensible heat, latent heat, CO_2 and air temperature, humidity, photosynthetically active radiation (PAR), soil temperature and soil moisture are conducted, respectively.

2.2.3 Sap flow measurements

Sap flow sensors were installed in three sample trees selected from a control (unharvested) plot at TP31 (Table 2.1). The sensors were self-manufactured, Granier-style thermal-dissipation sensors following Matheny et al. (2014) and Pappas et al. (2018). Each sensor consisted of two hollow needles, 20 mm in length, each containing a fine-wire, type T thermocouple at the midpoint (10 mm) of each needle. One of the needles was wrapped with insulated, constantan wire, which provided constant heating when connected to the self-made circuit board and supplied 12V power. The needles were coated with thermal grease and inserted into a hollow, metal tube on the north side of the tree at breast height (1.3 m above the ground). The heated probe was installed 10 cm vertically above the non-heated probe.

In each tree, one sensor was installed in the outer-most 0-20 mm of sapwood (from the edge of the cambium to 20 mm depth); a second sensor was installed from 20-40 mm depth and the third sensor was installed at a depth of 40-60 mm in to the trunk. Each sensor was vertically staggered and located 15 cm from each other on the north side of the tree. A dimensionless flow index (K), was calculated from the difference in temperature (T) measured between the two probes following Granier (1987) and can be expressed as:

$$K = \frac{\Delta \mathrm{Tmax} - \Delta T}{\Delta T} \quad (1)$$

K values were calculated by determining zero-flow conditions using the open-source software Baseliner (Oishi et al. 2016). Measurements were collected continuously from 14 August to 20 August 2019 and averaged into half-hour intervals.

Sap flux density (mL $m^{-2}_{sapwood}$ s^{-1}) was calculated following Granier (1987) and using the original coefficients, as a species-specific calibration was not conducted. J_s was then scaled up to whole-tree water use (L d^{-1}) by multiplying by the cross-sectional sapwood area (A_s).

To estimate error, whole-tree water use was calculated both accounting for radial variation (Q_r) and assuming uniform J_s (Q_u). When calculating Q_u, only the sap flux density measurements made in the outermost depth interval (0-20 mm) were used to scale-up to the whole-tree level.

2.2.4 Determining sapwood depth

Sapwood depth, heartwood depth and total xylem depth (from the pith to the xylem edge) were measured using a 5.15 mm increment borer and identified visually based on colouration changes between sapwood and heartwood. A total of 34 cores were taken in 17 trees. Each tree was cored twice to obtain average depth per tree. Cores were collected from trees not instrumented with sap flow sensors to prevent disruption to the hydraulic conductivity of the sapwood.

2.2.5 Integration of non-uniform sap flux density

J_s (mL $m^{-2}_{sapwood}$ s^{-1}) was averaged at each depth interval between the three sample trees and a daily average was computed over the seven-day study period. We then calculated the area under each daily J_s curve to get daily water flux (cm of water) at each of the three depth intervals. Once the average daily water flux was calculated at each depth within the sapwood, a fourth-order polynomial trend line was fit to the data. The following assumptions were made: i) no hydraulic flow within the heartwood and ii) flow at the edge of the cambium (not measured) is 70% of the measured velocity in the outermost depth interval. Assumption ii was based on similar findings from several Pinus species reported in Nadezhdina et al., (2002); and Ford et al. (2004b). Finally, the polynomial was integrated between 7 cm and 14 cm to represent the average daily volume transpired (cm^3).

2.2.6 Study Limitations

Limitations of our study include a small sample size (n=3) and temporally short duration of measurements. As mentioned earlier, this small subset of sensors reported in this article is part of a larger ongoing experimental study comparing transpiration between various forest management techniques. Due to uncertainties associated with the potential disruption of hydraulic flow in trees with multiple sensors, the sample size of this radial study was kept limited so as not to compromise the integrity of the larger study. The short duration of measurements was caused by disruption to the power supply for all sensors, lasting more than one month.

2.3 Results

2.3.1 Meteorological conditions

The study period experienced average daily temperatures when compared to 30-year mean climate record for this region (Figure 2.1a). Precipitation occurred on August 17, 18 and 20 (Figure 2.1a) with a total value of 25 mm during the study period. J_s followed a similar diurnal pattern as air temperature and vapour pressure deficit, (VPD; Figure 2.1b) suggesting transpiration at this site is driven primarily by temperature and VPD.

2.3.2 Relationship between sapwood area and diameter

Previous studies have developed species-specific allometric equations relating sapwood area to tree diameter (Bovard 2005; Matheny et al. 2014; Skubel et al. 2017,) but no such relationship is known for red pine or *Pinus resinosa*. This study developed an allometric equation (equation 2) relating sapwood area (A_s) to tree diameter at breast height (DBH).

$$A_s = aDBH^b \quad (2)$$

The species–specific parameters (a,b) of the allometric equation, are displayed in Figure 2.2 and report an R^2 value of 0.92.

2.3.3 Radial profiles of sap flux density

As expected, sap flux density was greatest in the outermost 0-20 mm of sapwood and decreased toward the pith. Figure 2.3 illustrates the average of all sensors at each depth for the duration of the study period. All sensors exhibited the same diurnal pattern suggesting both a level of accuracy and similar timing of flow, regardless of depth. J_s peaked between 12:00 and 14:00 each day of the study period. The difference in J_s between each of the depth intervals was consistent, except for August 14 in which J_s in the middle (20-40 mm) depth was not significantly different to the innermost (40-60 mm) depth. This could be due to a brief power issue, as it was seen among all sensors.

The average daytime (between 8:00 and 20:00) J_s was 14.8, 7.1 and 3.7 mL m^{-2} s^{-1} for the outer, middle and inner portions of the sapwood, respectively. The maximum J_s in the outer depth was 31.4 mL m^{-2} s^{-1} on 20 August (13:00), while the innermost depth reached a maximum of 7.4 mL m^{-2} s^{-1} on the same day/time.

Figure 2.4 shows an average daily profile of water flux throughout the conductive tissue of the sapwood, showing the measurements at 9, 11 and 13 cm from the pith and assumptions made for both the sapwood-heartwood border and the edge of the cambium. The relationship is best described by a fourth order polynomial and indicates the highest flow at approximately 1 cm from the edge of the cambium.

2.3.4 Errors associated with assuming uniform sap flux density

On average, sap flux at the 20 to 40 mm, and 40 to 60 mm depths accounted for approximately 56 and 32% of that at the 0-20 mm depth, respectively. These results indicate that most of the water transport occurred in the outermost sapwood.

By failing to account for radial variation in J_s, the results show that whole-tree water use is overestimated by as much as 81% (Table 2.2). When possible, it is therefore favorable to measure J_s at various points in the conductive sapwood to report whole-tree transpiration.

2.4 Discussion

The measurement of sap flow is a widely adopted technique to quantify transpiration and water use in vegetation ecosystems including forests. Sap flux density substantially varies within the sapwood of trees and among different forest species. Therefore, to better quantify ecosystem water fluxes, variations in hydraulic conductivity at the tree-level must be considered in forest ecosystems. Our study is one of the first to explore radial sap flux variability in the red pine (*Pinus resinosa*) forests. We found that most of the sap flux occurred in the outermost sapwood, within 3 cm from the cambium, validating our proposed hypothesis. In the literature, Delzon et al. (2004) had explored a similar hypothesis in other species of pine and found that by neglecting the radial variation within the sapwood, transpiration was overestimated by up to 47%. Other studies have suggested that this overestimation can be as large as 300% (Nadezhdina et al. 2002, Ford et al. 2004b). Although for many species sap flux density is highest near the cambium, Cermak et al. (1992) found a Gaussian distribution of sap flux density with depth in Norway spruce (*Picea abies*). Radial variation is, therefore, dependent on wood- and species-type (Berdanier et al. 2016) and is widely agreed that this variability needs to be addressed when scaling sap flow measurements to the tree- and stand-level.

2.4.1 Variability in radial depth profiles

Radial depth profiles have been shown to vary diurnally (Ford et al., 2004b; Poyatos et al. 2007), and with changes in soil water content (Ford et al. 2004a). The study period in which our research was conducted did not show significant changes in soil water content (θ; Figure 2.1d) to investigate the latter. In fact, studies have shown that depth profiles remained relatively constant during periods of stable soil moisture conditions (Lu et al. 2000). Variability between trees and within a single tree has also been studied to determine the need to establish a depth profile for individual trees (Lu et al. 2000; Delzon et al. 2004; Kumagi et al. 2005). In our study, we do not examine differences in depth profile within an individual tree due to the highly symmetrical distribution of sapwood cross-sectionally in this plantation forest.

2.4.2 Relationship between basal diameter and sapwood area

Our study developed an allometric relationship between tree diameter (DBH) and sapwood area for our red pine stand as shown by equation 2. Other studies have similarly established allometric equations for several other species (Matheny et al. 2014; Bovard et al 2005) but our study is one of the first for red pine forests. This relationship, which is highly species-specific, can be used in future studies when determining the positioning of sap flow sensors and scaling point-measurements to the tree-and stand-levels.

2.4.3 Quantification of errors when scaling to tree level

Studies in the literature have shown differences in radial depth profile depending on wood-type (Phillips et al. 1996). For instance, Cermak et al. (1992) found the radial profile in Norway spruce (*Picea abies,* non-porous) to be symmetrical, with sap velocity peaking at the midpoint of the sapwood depth. In contrast, they found an asymmetrical distribution of sap flow in oak (*Quercus robur,* ring-porous) (Cermak et al. 1992). However, Phillips et al. (1996) found sap flux density to decrease from the cambium to the pith in loblolly pine (*Pinus taeda*, non-porous)*,* which more similarly reflects the results from our study.

In Scots pine (*Pinus Sylvestris*) Nadezhdina et al. (2002) showed that the majority of sap flow occurred at a depth of 85 to 95% of the xylem radius. When positioning a single sensor at this depth, sap flow was greatly overestimated by as much as 300%

(Nadezhdina et al. 2002). Other studies on Slash pine (*P. ellioti),* shortleaf pine (*Pinus echinata*), longleaf pine (*P. palustris*) and Loblolly pine (*P. taeda*) (Ford et al. 2004a, 2004b) have given a similar distribution of sap flow. Our study has shown that the majority of water flow in red pine trees occurs in the outer depth of sapwood, closest to the cambium. This pattern of sap flow is consistent with observations made on Scots pine, Slash pine and Loblolly pine as discussed above.

Previous studies in the literature have also examined the variability in conductive tissue of the eastern white pine (*P. strobus*), which is a native conifer species naturally grown or planted in the Great Lakes region. They found that the non-symmetrical nature of sapwood area increased the margin of error associated with estimating the distribution of sap flow in white pine (McIntire 2018). As compared to red pine, white pine trees had 50-70% less sapwood area (Matheny et al. 2014, McIntire 2018), which highlighted the importance of estimating the spatial variation of sapwood and hence sap flow in individual tree species.

To achieve more accurate results when scaling up sap flux density measurements, it is ideal to have multiple measurements at various depths within the sapwood of each individual tree. However, due to time, financial and wounding constraints, in most sap flow measurement studies such an approach is not adopted. Zang et al. (1996) and Delzon et al. (2004) investigated radial variation in sap flow and developed a correction factor adjusting a single measurement to better reflect the actual sap flux on a given day.

However, research has shown there may be high temporal variations in radial depth profiles, indicating that radial depth profiles may change according to tree size (Ford et al. 2004), soil water availability (Lu et al. 2000; Ford et al. 2004a; Nadezhdina et al. 2007) or evaporative demand (Ford et al. 2004b). Therefore, multiple measurements within the sapwood is a preferred methodology for more accurate sap flow results as suggested by the results of our study.

In Canada, fast-growing red pine forests are an important source of softwood for the lumber industry and are widely planted. Red pine logs are straight, and are extensively used in the construction industry and for electricity poles (Nature Conservancy Canada). The red pine plantation forests in the Great lakes region and Eastern North America are susceptible to increasing temperatures and more frequent drought and heat events due to climate change (Bottero et al. 2017, Wang et al. 2014, Li et al. 2018). Therefore, the results of our study will help in the understanding of water use strategies of red pine forests. They will be useful to researchers, forest managers and ecological policy makers.

2.5 Conclusions

Our study results show that transpiration from dominant red pine trees contributed significantly to the overall water balance of the forest. Overall, 65% of water transport occurred in the outer 20 mm of the sapwood, while 26% and 9% of water transport occurred in the 20-40 mm and 40-60 mm depth intervals, respectively. Furthermore, our study reveals that by failing to account for radial variability in sap flow, whole-tree water use may be over-reported by as much as 81%. These results suggest the best-practices for scaling sap flow measurements to the tree- and stand-level involve measuring hydraulic flow at various depths within the conductive tissue. Overestimating stand-level transpiration can have significant implications for hydrological processes and water budgets in red pine stands in the Great Lakes region and Eastern North America. Our study will help to identify physiological traits including water storage which may predict the response of the forest to extreme events such as drought. It will also help to improve the simulation of transpiration and its upscaling from tree- to ecosystem-level and regionally.

List of Abbreviations

A_s	sapwood area [cm^2]
DBH	Diameter at Breast Height [cm]
F	sap flow [mL s^{-1}]
Js	sap flux density [mL $m^{-2}{}_{sapwood}$ s^{-1}]
Ha	hectare
K	a dimensionless flow index describing the relationship between average flow and zero flow (nighttime) conditions
PAR	Photosynthetically Active Radiation [μmol m^{-2} s^{-1}]
Q_r	whole-tree water-use calculated by accounting for radial variation in sap flux density [L day^{-1}]
Q_u	whole-tree water-use calculated by assuming uniform flow throughout the sapwood [L day^{-1}]
SWCR	St. Williams Conservation Reserve
T	Temperature [°C]
TPFS	Turkey Point Flux Station
TP31	Turkey Point pine plantation forest planted in 1931
TP39	Turkey Point pine plantation forest planted in 1939
TP74	Turkey Point pine plantation forest planted in 1974

TP02	Turkey Point pine plantation forest planted in 2002
TPD	Turkey Point mixed deciduous forest stand
VPD	Vapour Pressure Deficit [kPa]
VRH	Variable Retention Harvesting

Declarations

Ethics Approval and Consent to Participate
Not applicable.
Consent for Publication
Not applicable.
Availability of Data and Material
The datasets used during this study are available from the authors upon request.
Competing Interests
The authors declare that they have no competing interests.
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Authors' Contributions
AVB collected, cleaned and processed sap flow and meteorological data and was a major contributor in writing the manuscript. AVB and MAA designed the experiment with grants received by MAA. All authors read and approved the final manuscript.

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Table 2.1. Biometric characteristics of sampled trees.

Sample No.	Diameter at breast height (cm)	Height (m)	Crown area (m^2)	Sapwood depth (cm)	Heartwood depth (cm)	Sapwood area (cm^2)
1	31.7	25.5	145	7.5	7.9	549
2	28.7	21.8	112	6.9	7.0	453
3	32.2	26.4	168	7.7	7.9	568
Mean	**30.9**	**24.6**	**142**	**7.3**	**7.6**	**523**

Table 2.2. Estimates of error in calculating daily whole-tree water use when assuming uniform sap flux density

Sample No.	Q_r (L)	Q_u (L)	Error ($\frac{Qu-Qr}{Qr}$) (%)	Mean Error (%)
1	13.09	20.63	57.6	61.4
2	3.02	5.47	81.1	
3	8.79	12.78	45.4	

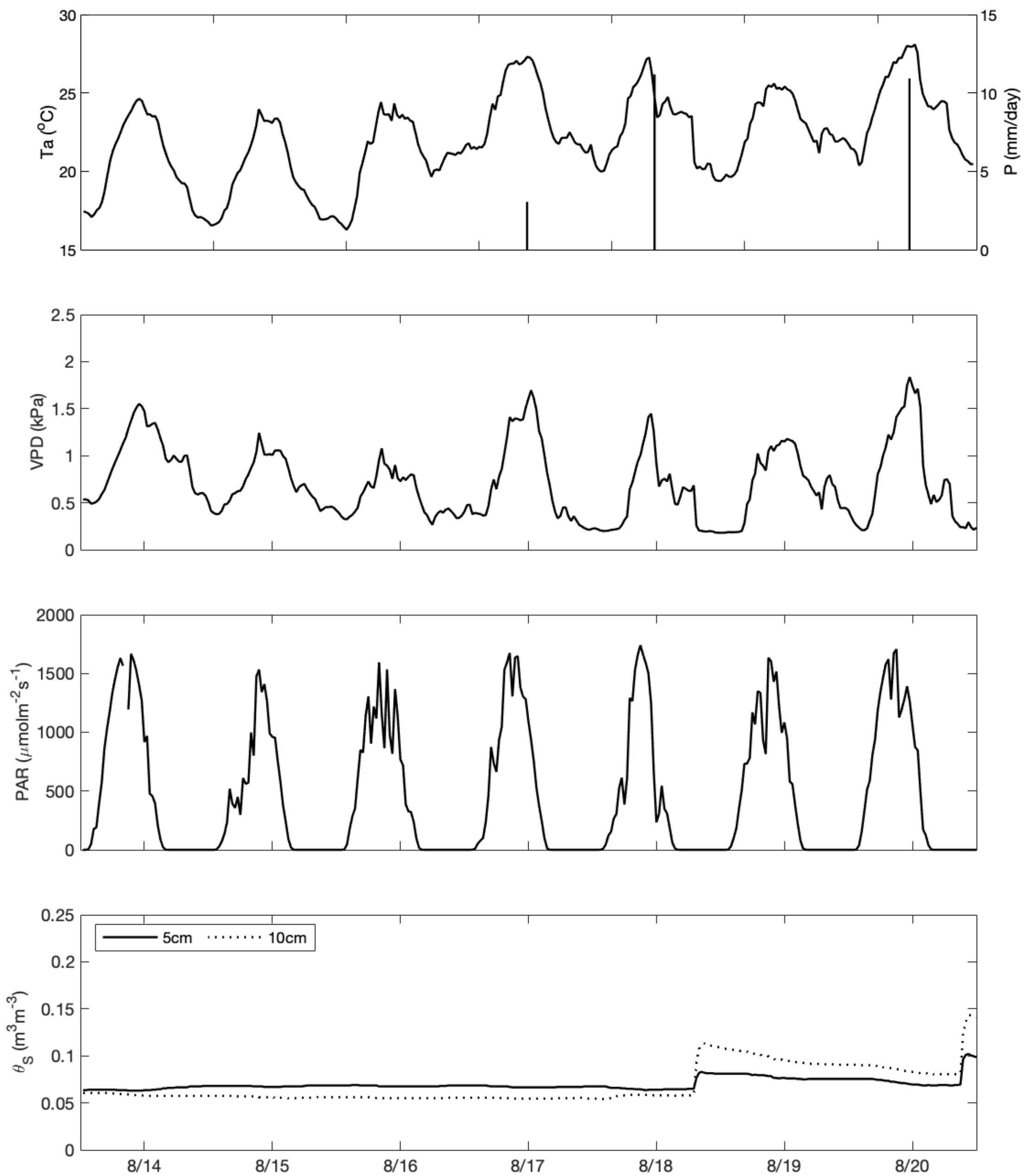

Figure 2.1. Meteorological measurements of (a) air temperature (Ta) and precipitation (P), (b) vapour pressure deficit (VPD), (c) Photosynthetically Active Radiation (PAR) and (d) soil water content (θ) from August 14 to 20, 2019.

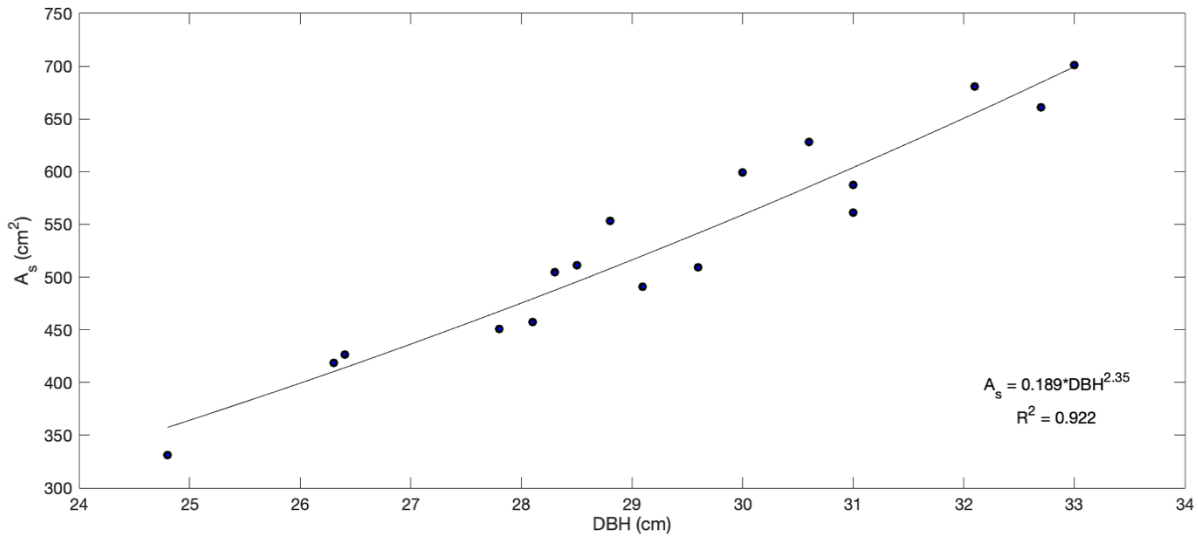

Figure 2.2. A species-specific allometric equation relating sapwood area (A_s) to tree diameter measured at breast or 1.3 m height (DBH).

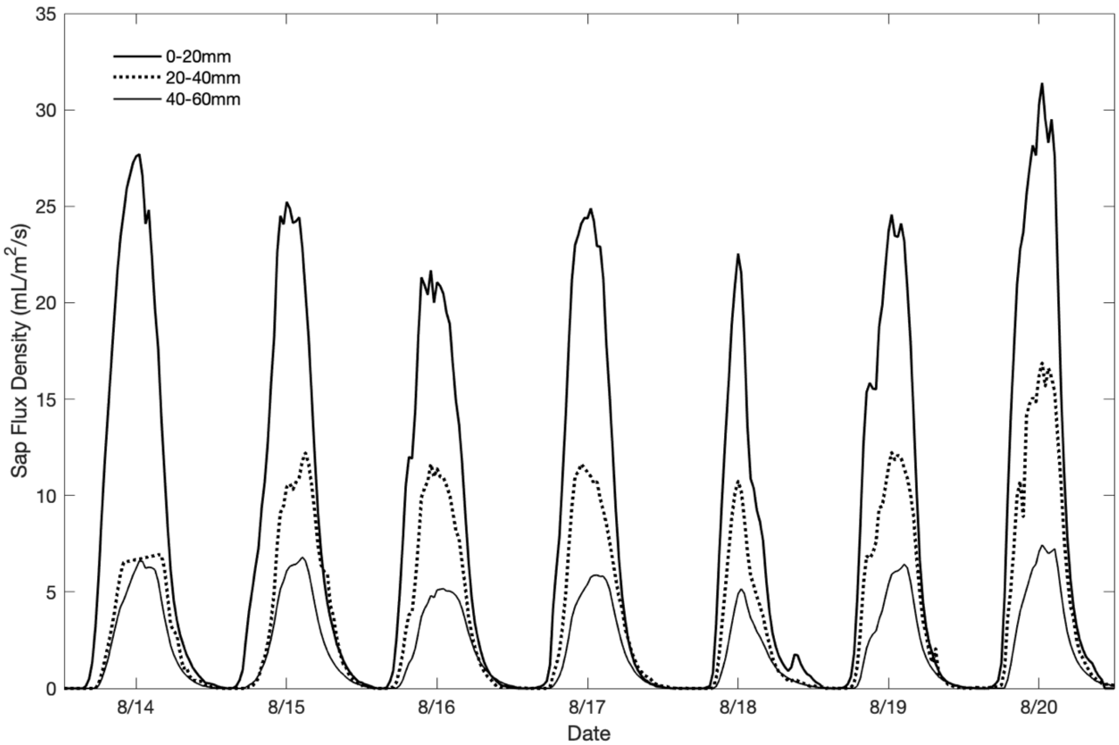

Figure 2.3. Average diurnal patterns of sap flux densities (J_s) at different depth intervals within the sapwood from August 14 to 20, 2019.

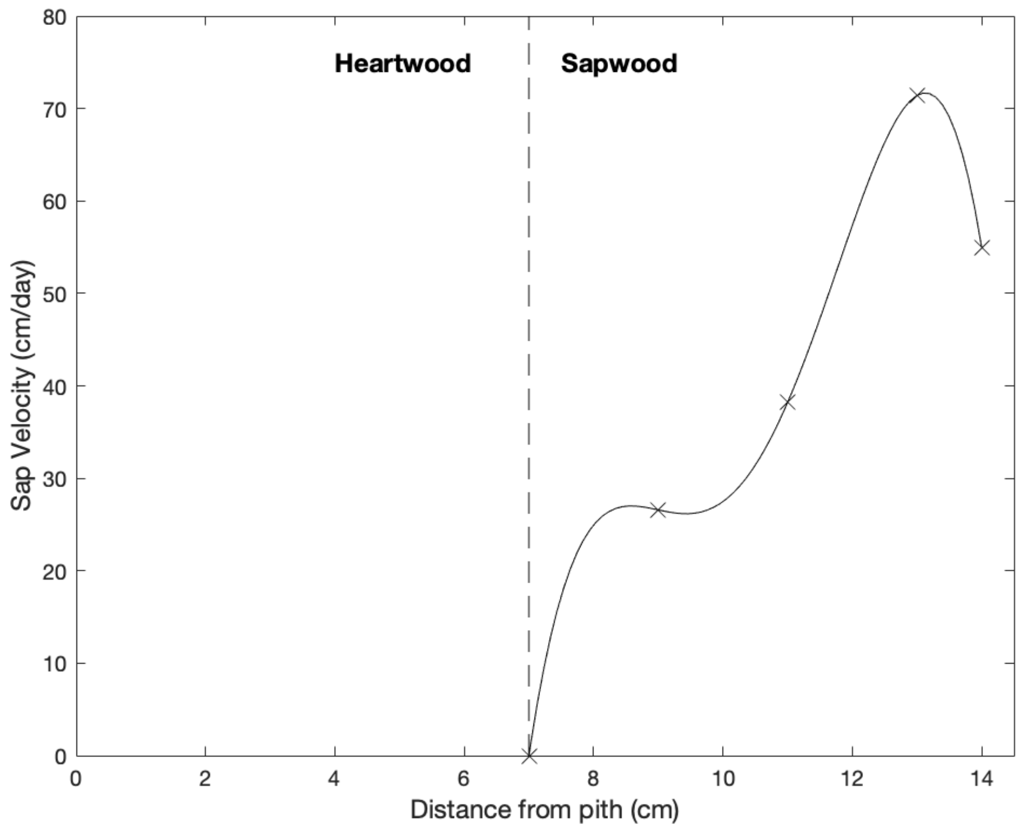

Figure 2.4. Daily mean sap velocity at varying depth from the pith. On average, the heartwood extends approximately 7cm from the pith. At 7cm, the sapwood begins and extends to 14cm where it reaches the edge of the cambium.

CHAPTER 3:

EFFECTS OF VARIABLE RETENTION HARVESTING ON CANOPY TRANSPIRATION IN A RED PINE PLANTATION FOREST

Abstract

Variable Retention Harvesting (VRH) is a forest management practice applied to enhance forest growth, improve biodiversity, preserve ecosystem function and provide economic revenue from harvested timber. There are many different forms and compositions in which VRH is applied in forest ecosystems. In this study, the impacts of four different VRH treatments on transpiration was evaluated in an 83-year-old red pine (Pinus *resinosa*) plantation forest in the Great Lakes region in Canada. These VRH treatments included 55% aggregated crown retention (55A), 55% dispersed crown retention (55D), 33% aggregated crown retention (33A), 33% dispersed crown retention (33D) and unharvested control (CN) plot. These VRH treatments were implemented in 1-ha plots in the winter of 2014, while sap flow measurements were conducted from 2018 to 2020. Study results showed that tree-level transpiration was highest among trees in the 55D treatment, followed by 33D, 55A, 33A and CN plots. We found that photosynthetically active radiation (PAR) and vapor pressure deficit (VPD) were major controls or drivers of transpiration in all VRH treatments. Our study suggests that dispersed or distributed retention of 55% basal area (55D) is a suitable forest management technique to enhance forest growth while efficiently utilizing water resources and sustaining transpiration. This

study will help researchers, forest managers and decision-makers to improve their understanding of water cycling in forest ecosystem and adopt favorable forest management regimes to enhance forest growth, health and resiliency to climate change.

3.1 Background

Afforestation and reforestation are widely adopted practices to enhance carbon sequestration and mitigate climate change (Pan et al. 2011, Law et al. 2018, Domke et al. 2020). However, forest managers and planners are challenged with appropriately managing these forests. They employ various silvicultural treatments to sustain or enhance forest growth and emulate the ecological functions that are typical of natural forests. In this endeavor, they must balance timber production, carbon sequestration and biodiversity aspects while preserving ecosystem health (Martinez Pastur et al. 2020). Converting abandoned agricultural and marginal lands to plantation forests can also impact hydrological cycles by increasing infiltration and evapotranspiration, that may cause higher local rainfall and changes in regional water cycle (Van Dijk and Keenan 2007, Ellison et al. 2017). Under representative concentrations pathways (RCP) 2.6, 4.5 and 8.5, the Great Lakes region in North America is expected to experience an increase in annual air temperature between 2.3 and 7.9 °C (McDermid et al. 2015). Furthermore, global climate models (GCMs) suggest an increase in heat-waves and extreme precipitation events (Zhang et al. 2019), but a decrease in summer precipitation (McDermid et al. 2015) in this region. Therefore, enhancing forest cover and adopting better forest management practices in this region may mitigate these effects by increasing infiltration, reducing surface runoff and hence ‘flash’ flooding events and enhancing and stabilizing precipitation, which in turn may prevent sustained periods of drought (Van Dijk and Keenan 2007, Ellison et al. 2017).

Variable Retention Harvesting (VRH) practices are employed worldwide to address silvicultural objectives and protect and enhance forest ecosystem services (Gustafsson et al. 2012, Beese et al. 2019). VRH often aims to increase resilience by applying partial cutting treatments, leaving single or small groups of trees (Bladon et al. 2006, Gustafsson et al. 2012). In Canada, retention forestry first emerged in British Columbia in the early 1990's and was implemented in more eastern provinces, including Ontario, by the late 1990's (Gustafsson et al. 2012). Today, more than 50% of forestland in Ontario is managed using the retention forestry approach (Gustafsson et al. 2012). In the past, the focus of VRH research has been to assess the impact of these harvesting regimes on wood growth and biodiversity. Some studies, however, have examined the effects on micrometeorological variables and key components of the hydrologic cycle, and have shown that residual trees may benefit from reduced resource competition (Wang et al. 1995, Liu et al. 2003, Skubel et al. 2017). Bladon et al. (2006) reported an increase in wind speed, net radiation, soil water content and vapour pressure deficit following VRH, which contributed to higher rates of transpiration in some species. In addition to hydrological components, tree growth (Bebber et al. 2004, Powers et al. 2010, Dwyer et al. 2010) and carbon sequestration (Zugic et al. 2021) have also been shown to increase in residual trees following VRH.

In the Great Lakes region in Southern Ontario, Canada five different harvesting treatments were applied in a 21-ha 83-year-old red pine plantation stand by the Ontario Ministry of Natural Resources and Forestry (OMNRF) in the winter of 2014 with the ultimate goal of restoring this monoculture pine stand to native mixed forest. These VRH treatments included 55% aggregated crown retention (55A), 55% dispersed crown retention (55D), 33% aggregated crown retention (33A), and 33% dispersed crown retention (33D) and unharvested, control plots (CN). The dispersed method removed trees in an even formation, whereas the aggregated crown retention involves leaving the remaining un-harvested trees in small or large groups (Figure 3.1). The 55% and 33% corresponds to the percentage of basal area retained after harvesting. This experimentally-managed forest is the first research application of VRH in Ontario, and the first experiment anywhere to restore a red pine plantation to native forest type using VRH.

We hypothesize that sap flux density will be highest among the most heavily thinned (33% retention) treatments, due to the openness of the canopy and a reduced competition for water resources. At the tree-level, we hypothesize that the distributed treatments (33D and 55D) will have the highest daily transpiration due to their larger conductive sapwood area and increased growth after thinning. The results of this study will help to develop a better understanding of the effects of silvicultural practices on the overall water balance of plantation forests.

Furthermore, this study is one of the first to examine the effects of VRH on transpiration in red pine (*Pinus resinosa*) ecosystems. An estimated 70% of plantation forests in the Southern Ontario or Great Lakes region are red pine stands, which are an important source of revenue from harvested timber (Kim 2020). Red pine lumber is used for pulp wood and electricity and other utility poles. Therefore, the establishment of these plantation forests not only helps to fulfill timber demand, but also provides a natural solution for the mitigation of climate change, while conserving forest ecosystems and watershed hydrologic functions (LRC 2005).

This study aims to determine the effect of VRH treatments on water resources by examining differences in sap flow and transpiration among remaining dominant canopy trees in each treatment and the control plot. Investigating these differences would help researchers to explore the effects of these thinning treatments on the growth and hydraulic functionality in managed forests and their resilience to climate change. The specific objectives of this study are (i) compare sap flux density and tree-level transpiration between five different VRH treatments and (ii) determine the major environmental drivers of transpiration to better understand the response of managed forests to environmental changes.

3.2 Methods

3.2.1 Experimental site description

This study was conducted in a temperate red pine (*Pinus resinosa*) plantation stand in the St. Williams Conservation Reserve (SWCR) (42°42’N, 80°21’W), located 3 km north of Lake Erie, in Southern Ontario, Canada. This 21-ha red pine plantation stand is part of the Turkey Point Observatory (TPO) and is referred to as CA-TP31, as the stand was planted in 1931. Topography at this site is predominantly flat with an elevation of 184 m. TPO sites are also associated with the Global Water Futures Program and FLUXNET. Further details of the Turkey Point Observatory are provided in Restrepo and Arain (2005), Peichl et al. (2010), Beamesderfer et al. (2020) and Arain et al. (2021).

CA-TP31 was established by planting seedlings 2 m apart, in furrowed rows (~2500 trees/ha). This monoculture plantation was subject to thinning in about 1960-1961 that reduced stand density to about 1875 trees/ha (McKenzie et al. 2021). In the winter of 2014, a VRH regime was employed by the Ontario Ministry of Natural Resources and Forestry (OMNRF) to evaluate the effectiveness of five different VRH treatments (33A, 33D, 55A, 55D and Control) on forest growth and ultimately restore this plantation stand to a native forest ecosystem. Each VRH treatment included a 1-hectare plot with three replicates where different harvesting densities and patterns were applied as shown in Figure 3.1. The percentage of basal area retained in each VRH treatment plot is given in Table 3.1.

Local micrometeorological conditions were measured from two flux towers located at the white pine (*Pinus strobus*) plantation sites (CA-TP39, CA-TP74) within a 2-km radius of CA-TP31. These towers are instrumented with closed-path eddy-covariance systems and weather stations, where continuous half-hourly fluxes and meteorological measurements (carbon dioxide, sensible and latent heat fluxes, four components of radiation, photosynthetically active radiation (PAR), air temperature, humidity, windspeed and direction, soil temperature, and soil moisture) have been conducted, since 2003 (Arain et al. 2021). Soil in this region is sandy and well-drained (McLaren et al. 2008; Beamesderfer et al. 2020). The climate in Southern Ontario is temperate with warm, humid summers and very cold winters. Mean annual temperature is 8.0 ^{o}C and the area receives on average 1036 mm of precipitation each year, approximately 13% of which falls as snow (Environment Canada, 1980-2010 Norms at Delhi, ON).

3.2.2 Sap flow measurements

Sap flow sensors were installed in five plots, representing each of the four treatment types and the un-thinned control plot. Eight trees within each plot were instrumented with one sap flow sensor in the outermost 20 mm of sapwood. Sample trees were randomly selected based on overall health (e.g. full crown, undamaged bark) and on proximity to the data logger and power supply (less than 30 m away). The sensors were self-manufactured, Granier-style thermal-dissipation (TD) sensors following Matheny et al. (2014) and Pappas et al. (2018). Each sensor consisted of two hollow needles, 20 mm in length, each containing a fine-wire, type T thermocouple at the midpoint (10 mm) of each needle. One of the needles was wrapped with insulated, constantan wire, which provided constant heating when connected to the self-made circuit board and supplied 12V power. The needles were coated with thermal grease and inserted into a hollow, metal tube on the north side of the tree at breast height (1.3 m above the ground). The heated probe was installed 10 cm vertically above the non-heated probe.

In each sample tree, one sensor was installed in the outer-most 0-20 mm of sapwood, except for 5 trees which were equipped with radial sensors for the measurement of non-uniform flow (Bodo and Arain 2021). Raw measurements (mV) were collected with 30-minute resolution on a CR10X datalogger (Campbell Scientific, Logan, UT, USA) continuously from 1 July 2018 to 31 October 2020 and averaged into half-hour intervals. A dimensionless flow index (K), was calculated from the difference in temperature (T) measured between the two probes following Granier (1987) and can be expressed as:

$$K = \frac{\Delta \mathrm{T}max - \Delta T}{\Delta T} \qquad (1)$$

Where T represents temperature in degrees Celsius. K values were calculated by determining zero-flow conditions using the double regression method in R package TREX (Tree sap flow Extractor; R Core Team 2017) developed by Peters et al. (2021). All sampled trees were located within 30 m radius from the datalogger box and power supply due to voltage drop considerations. Therefore, in some instances, we were limited in the selection of trees for sap flow sensors in VRH plots, which could lead to uncertainties regarding edge-effects and overall representativeness of the plot.

3.2.3 Wounding/signal dampening correction

It is widely known that the insertion of sap flow sensors into tree stems and subsequent heating of sap flow sensor probes may cause 'wounding' of stem tissue. Over time tree resin is also deposited over the probes due to healing from the drilled holes where sensors are installed. Because of these effects and when sensors have been installed for multiple years, many studies have reported a dampening in the raw sensor signal (Steppe et al. 2010, Wullschleger et al. 2011, Wiedemann et al. 2016) which may lead to significant underestimations. We corrected for underestimations in Js resulting from signal dampening between sensor installation (2018) and the 2019 growing season by installing two new sensors into the CN plot. Using a linear regression model, we determined a 69% reduction in Js values in original sensors, when compared to newly installed sensors (average R^2=0.94). Both the 2019 and 2020 data were corrected to reflect this relationship between time of installation and signal dampening. A correction factor was not determined empirically for 2020 due to field restrictions during the COVID-19 pandemic, so the correction factor was assumed to be the same for both 2019 and 2020.

3.2.4 Scaling sap flow measurements

Sap flux density (J_s; $gH_2O\ m^{-2}\ s^{-1}$) was calculated following Granier (1987). Whole-tree water use (TWU) was calculated following:

$$\mathrm{TWU} = J_s \times A_s \times \rho_w \qquad (2)$$

Where J_s is sap flux density ($gH_2O\ m^{-2}\ s^{-1}$), A_s is the sapwood area of the tree (m^2) and ρ_w is the density of water (1000 kg m^{-3}). TWU was also corrected for radial differences in sap flux density according to Bodo and Arain (2021), which assumes Js is highest in the outermost 20 mm of sapwood and decreases toward the sapwood-heartwood boundary.

3.2.5 Gap filling and statistical analysis

Due to an unpredicted power failure which affected the power supply and data logger, data gaps occurred in the control (CN) and 55D plots from 30 August to 22 October 2020. Other minor (a few hours or a few days) gaps also occurred throughout the study period due to sensor failure and power interruptions. Minor gaps in J_s were filled using a linear relationship with environmental variables PAR and VPD. The average correlation coefficient was 0.68 and the minimum coefficient was 0.56 ($p < 0.01$). Gap-filled data was not used to examine meteorological drivers of sap flux density in our analysis.

A linear regression model was used to test the significance of environmental conditions (VPD, Ta, PAR) on sap flux density. The fit of the model and the significance of the regression coefficients were assessed using the F-statistic. To test for significant differences in sap flux density among the VRH treatments, an analysis of variance test (one-way ANOVA) was conducted. All statistical analyses were conducted using MATLAB (The MathWorks Inc.).

3.3 Results

3.3.1 Meteorological conditions

The site received a total of 1644, 1126 and 1056 mm of precipitation in 2018, 2019 and 2020, respectively (Figure $3.2_{j\text{-}l}$). With regards to growing season precipitation only (1

April to 31 October), 2018 was significantly more wet (985 mm) compared to 2019 (677 mm) and 2020 (619 mm). Air temperature throughout the study period was seasonally consistent between years, with the exception of April 2018, where the average monthly temperature was 3.6 °C, compared with April 2019 (6.7 °C) and April 2020 (5.3 °C)(Figure 3.2$_{g-i}$). Additionally, May 2018 (17.1 °C) was strikingly warmer than May 2019 (13.0 °C) and May 2020 (12.7 °C). This may have led to an earlier onset of photosynthesis and transpiration in the forest, however, sap flow measurements did not begin until July 2018. Finally, we see more prolonged periods of low soil moisture (<0.1 m^3m^{-3}) in 2020 compared to other years (Figure 3.2$_{j-l}$). This is likely due to a combination of factors including higher average temperatures and a lower precipitation in June (19.7 °C) and July (24.0 °C) months on 2020 with a combined total precipitation of 131 mm.

3.3.2 Effects of VRH on sap flux density

We divided the growing seasons into three periods, where 1 April to 30 May is referred to as the early growing season, 1 June to 31 August as the mid growing season and 1 September to 31 October as the late growing season. Our results (Figure 3.3) revealed small differences in J_s among VRH plots in the late growing season of 2018 and 2019, with the 33D and 55A plots exhibiting the highest J_s. However, in the mid growing season (May to July) in 2019, we observed major differences between treatments, with the 55A and 55D plots dominating in terms of J_s. That year, we saw similar values among all treatment types in the early growing season as well, but differences among the treatments arose in mid-to-late June where we saw that the general trend in daily average

J_s was 55A > 55D > 33D > CN > 33A. A similar trend was observed in 2020 where daily average J_s was highest in the 55A, particularly in the early and mid-growing season. With some exceptions, however, in the mid 2020 growing season, we observed higher J_s among trees in the CN plot compared to the 33A, 33D and 55D. Statistically, sap flux density was significantly different between the VRH treatments for all three years: 2018 ($p < 0.01$), 2019 ($p < 0.001$), 2020 ($p < 0.001$).

3.3.3 Differences in tree-level transpiration

J_s reflects water flow per unit of sapwood area, which functions well as a method of comparison between treatment types. However, in order to more accurately compare the water fluxes at the whole tree-level, we quantified tree water-use (TWU) in each VRH treatment for all years of the study (Figure 3.4). The results showed trends similar to that of sapflux density between years, with the 55D and 33D treatments exhibiting the highest water-use in 2018, while 55D, 33D and 55A were the highest in 2019 and for most of 2020. Overall, we observed average TWU followed: 55D > 33D > 55A > 33A > CN.

3.3.4 Controls on sap flux density and transpiration

Our results showed that both VPD and PAR were the main drivers of J_s among all VRH treatments (Figure 3.6). We compared diurnal J_s curves for a warm, sunny day (5 September 2018; Figure 3.5$_{a\text{-}e}$) and a cool, cloudy day (12 October 2018; Figure 3.5$_{f\text{-}j}$). The daily average Ta for these days was 26.7°C and 8.2°C, respectively; and the daily average incoming PAR was 558 and 153 μmol m^{-2} s^{-1}, respectively.

We found that J_s and, by proxy, transpiration was mainly driven by VPD, with some exceptions (Figure 3.6). In 2020, during periods of low precipitation, J_s in the 33A and 33D plots were strongly driven by VPD (R^2 values reported in Table 3.2). By contrast, in 2018, trees in the control and 33A plots were more closely coupled with PAR.

3.4 Discussion

It is widely discussed in the literature that a healthy and productive forest provides numerous benefits like lumber, carbon sequestration and long-term storage (Pan et al. 2011, Le Quere et al. 2018), enhanced biodiversity (Gibson et al. 2011) and better regulation of the hydrologic cycle (Ellison et al. 2017, Bonan 2008, Sheil 2018). Red pine forests are a preferred plantation species in the Great Lakes region in Canada and the USA (Kim 2020). Several studies have been conducted in red pine forests in the Great Lakes region to examine their growth, yield and wood productivity in response to thinning treatments or climatic stresses (Bradford and Palik 2009, Magruder et al. 2013). However, none of these studies have examined effects on transpiration. To our knowledge, this study is the first effort to explore the impact of VRH on transpiration in the Great Lakes region. Some scientists have argued that the hydrologic benefits of forests should be considered among the primary contributions of forest ecosystems to mitigating climate change, highlighting the development for adaptation and management policies (Ellison et al. 2017).

3.4.1 Effects of VRH on sap flux density

Our study showed that thinning reduces water-resource competition among remaining trees for soil water, leading to higher tree-level transpiration in the remaining trees (Figure 3.4). Several understory species have emerged since thinning, and the amount of understory vegetation is positively correlated with the thinning intensity. While we did not measure sap flow in any of the understory species, we acknowledge these plants compete with the dominant red pine for soil water. The significant amount of understory vegetation in the 33A plot may be the cause of lower J_s values in this treatment. Our results from 33A refute the hypothesis that J_s would be highest among trees in the more heavily thinned treatments (e.g. 33A and 33D). It shows the complexities of these linkages and the need for more long-term observations and research. By contrast, we observed higher TWU in 55D and 33D plots (Figure 3.4), which suggests that a dispersed thinning pattern is favorable to that of an aggregated pattern when concerned with promoting transpiration. Because TWU was quantified by applying *Js* to the total sapwood area, which is why these general patterns more closely follow the trend in average tree sapwood area among the treatments (Table 3.1). TWU is an important metric for describing water quantities at the tree-level, because although trees in the 55A plot may exhibit the highest J_s, when scaled to the tree-level, we observe the 55D and 33D to have the highest TWU or tree-level transpiration.

In another study at our site, using tree ring measurements, Zugic et al. (2021) has found that dispersed VRH treatments at both levels of retention (55D and 33D) were more effective in promoting post-harvest tree-level growth and carbon sequestration than aggregate treatments. However, their study also suggested that at the stand-level after accounting for retained tree biomass, the growth and carbon sequestration was highest for greater levels of retention, regardless of the pattern of treatment. These results support our findings that moderate levels of thinning in a dispersed pattern may promote higher tree-level water-use and hence higher growth, which may help to offset the impacts of drought events linked to climate change.

Additionally, several other studies have used sap flow sensors to investigate the effect of thinning on sap flux density. For example, Skubel et al. (2017) used sap flow sensors to examine tree- and stand-level transpiration at CA-TP74 site (part of the TPO) following a 13% reduction in basal area (87% retention) from thinning. Their study found an increase in tree-level transpiration among the remaining trees following the moderate thinning event. In a long-term study on Chinese pine (*Pinus tabuliformis*), Chen et al. (2020) reported greater DBH, greater sapwood area and higher transpiration among heavily thinned stands (80% and 65% reduction) when compared to a moderately thinned stand (55% reduction) 30 years after the thinning. By contrast, Park et al. (2018) observed transpiration in Korean pine (*Pinus koraiensis)* following heavy and moderate thinning and reported an increase in transpiration following thinning in both stands, however, the effects of the light thinning decreased over time. The expansive literature on sap flow studies suggests a positive relationship between thinning and tree-level transpiration, but there seems to be no conclusive recommendation for the optimal thinning intensity and pattern and the controls on these processes may be dependent on the tree species- and climate of the region.

3.4.2 Controls on sap flux density and transpiration

Impacts of forest management treatments on transpiration and water cycle is quite complex where various factors may exert opposing controls. In our study, we found that during periods of low precipitation, VPD was the main driver or control on J_s in our VRH treatments (e.g. 33A and 33D). However, J_s was more closely coupled with PAR in the unharvested or control plot (CN). Studies in the literature have shown that thinning increases penetration of radiation in the canopy, while remaining trees in a treatment regime have been shown to be exposed to higher fluctuations in wind speed, air temperature and evaporative demand (Man and Lieffers 1999, Proe et al. 2001, Bladon et al. 2007). Some studies have also shown that thinning may decrease absorption of PAR by the canopy due to the removal of low-albedo coniferous crown cover (Anderson et al. 2010, Cherubini et al. 2018), however, below canopy transmission of PAR may increase causing higher exposure of understory and ground surface to radiation resulting in higher soil temperatures and increased evaporation. Although VPD was not measured at the canopy level in each treatment plot, we expect VPD to be lower in the control, due to the closed canopy of this homogeneous plot. These results suggest the application of VRH in a plantation forest changes the dominant environmental drivers of water flux, where VPD becomes increasingly significant in addition to PAR. Further, we expect the extent of this change to increase with increased levels of thinning which causes a more open canopy and heating of the canopy and ground.

Thinning may also increase soil moisture due to reduced competition and hence higher transpiration in remaining trees (Breda et al 1995, Reid et al. 2006). While soil moisture was not directly measured in each of the VRH plots, it is possible that the closed canopy of the CN plot allowed for greater retention of soil moisture throughout the growing season, particularly in periods with low precipitation. On the other hand, removal of canopy cover decreases interception, potentially allowing for more precipitation to reach the soil surface, which may result in greater soil moisture availability and hence more transpiration. In fact, Kurpius et al. (2003) and Simonin et al. (2007) showed that thinning led to increased throughfall, greater water availability and more energy at the soil surface resulting in greater soil evaporation. Future studies should measure soil moisture in each VRH plot to support exploration of the effects of thinning on water balances in each treatment. In our, previous research in a similar-age white pine (*Pinus strobus*) stands at our CA-TP39 site, we have also highlighted the complex nature of soil-vegetation-atmosphere interactions in thinned stands (Skubel et al., 2017). Skubel et al. measured sap flow and soil moisture before and after thinning at the CA-TP39 site which was 74-year-old at the time of measurement and found that soil moisture increased immediately following thinning. Ma et al. (2010) also found that soil moisture and VPD increased after thinning, in treatments of various thinning intensities (14-66% basal area removed). These findings suggest a positive net effect of thinning on soil moisture status in harvested stands. However, some studies have also suggested that more intense thinning may lead to a net decrease in soil moisture in thinned stands (Simonin et al. 2007) due to increased surface radiation and subsequent higher evaporation from soil. In our study, two VRH treatments (33A and 33D) involved the removal of 67% of basal area. We found low J_s among the 33A treatment. However, we observed higher tree-level transpiration ~~i~~n the 55D and 33D plot, which suggests that the thinning pattern (dispersed vs. aggregated) has a larger effect on transpiration than thinning intensity alone. Additionally, our results support the findings that thinning decreases competition among remaining trees for water resources and increases soil moisture (Ma et al. 2010).

3.5 Conclusion

Appropriate management of coniferous plantations can provide a balance between ecological restoration, economic benefit and regional climate change mitigation. Our study results support the use of VRH as an efficient silvicultural treatment which may promote atmospheric moisture through canopy transpiration. Our results show that tree-level transpiration was highest among trees in the 55D treatment, followed by 33D, 55A, 33A and CN plots, suggesting moderate thinning in a dispersed pattern may be optimal to promote growth and transpiration among remaining trees following VRH. Managed forests will play an increasingly important role in climate change mitigation at regional and global scales. Our study further provides empirical data to support decision-making in the region and highlight the complex nature of soil-vegetation-atmosphere interactions in forest ecosystems.

List of Abbreviations

33A	33% basal retention in aggregated pattern
33D	33% basal retention in dispersed pattern
55A	55% basal retention in aggregated pattern
55D	55% basal retention in dispersed pattern
A_s	sapwood area [m^2]
CA-TP31	Turkey Point red pine plantation forest planted in 1931
CA-TP39	Turkey Point pine plantation forest planted in 1939
CA-TP74	Turkey Point pine plantation forest planted in 1974
CA-TP02	Turkey Point pine plantation forest planted in 2002
CA-TPD	Turkey Point mixed deciduous forest stand
CN	control treatment
DBH	Diameter at Breast Height [m]
Js	sap flux density [mL $m^{-2}{}_{sapwood}$ s^{-1}]
Ha	hectare
K	a dimensionless flow index describing the relationship between average flow and zero flow (nighttime) conditions
OMNRF	Ontario Ministry of Natural Resources and Forestry
PAR	Photosynthetically Active Radiation [µmol m^{-2} s^{-1}]
SWCR	St. Williams Conservation Reserve
T	Temperature [°C]
TD	Thermal Dissipation
TWU	Tree Water Use [kg day^{-1} or L day^{-1}]
VPD	Vapour Pressure Deficit [kPa]
VRH	Variable Retention Harvesting

Declarations

Ethics Approval and Consent to Participate
Not applicable.
Consent for Publication
Not applicable.
Availability of Data and Material
The datasets used during this study are available from the authors upon request.
Competing Interests
The authors declare that they have no competing interests.
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Authors' Contributions
AVB constructed and installed sapflow sensors, collected and quality controlled sapflow and meteorological data and wrote first draft of the manuscript. MAA wrote proposal, designed the sapflow experimental setup, secured funding and provided comments and feedback on manuscripts drafts. All authors read and approved the final manuscript.

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Table 3.1. Variable Retention Harvesting treatments in CA-TP31

Plot abbreviation	% basal area retained after thinning	Pattern of thinning	Stand Density (trees plot^{-1})	Average DBH (m)	Average As (m^2)
33A	33%	Aggregate	178	0.311	0.0609
33D	33%	Dispersed	118	0.296	0.0542
55A	55%	Aggregate	213	0.279	0.0472
55D	55%	Dispersed	235	0.305	0.0582
CN	-	-	432	0.278	0.0468

Table 3.2. Slope of the linear regression models describing the relationship between daily average sap flux density and daily average PAR, Ta and VPD ($p < 0.001$). Correlation coefficients (R^2) are displayed in parentheses.

2018			
	PAR	**Ta**	**VPD**
33A	0.019 (0.77)	0.316 (0.51)	12.61 (0.72)
33D	0.025 (0.72)	0.363 (0.34)	18.56 (0.83)
55A	0.025 (0.74)	0.385 (0.39)	18.83 (0.83)
55D	0.022 (0.75)	0.302 (0.33)	15.57 (0.77)
CN	0.023 (0.77)	0.356 (0.44)	14.82 (0.64)
2019			
	PAR	**Ta**	**VPD**
33A	0.014 (0.73)	0.299 (0.37)	8.28 (0.66)
33D	0.014 (0.60)	0.378 (0.5)	8.98 (0.66)
55A	0.021 (0.71)	0.494 (0.42)	13.65 (0.74)
55D	0.020 (0.73)	0.474 (0.47)	12.01 (0.71)
CN	0.014 (0.65)	0.328 (0.41)	8.77 (0.69)
2020			
	PAR	**Ta**	**VPD**
33A	0.010 (0.34)	0.388 (0.65)	7.85 (0.65)
33D	0.006 (0.25)	0.263 (0.54)	5.40 (0.55)
55A	0.016 (0.61)	0.373 (0.40)	9.21 (0.60)
55D	0.013 (0.62)	0.239 (0.35)	5.90 (0.50)
CN	0.014 (0.53)	0.303 (0.43)	7.43 (0.61)

Figures

Figure 3.1. Aerial photograph of CA-TP31 study area obtained from Google Earth 2016 showing the various 1-ha VRH treatments.

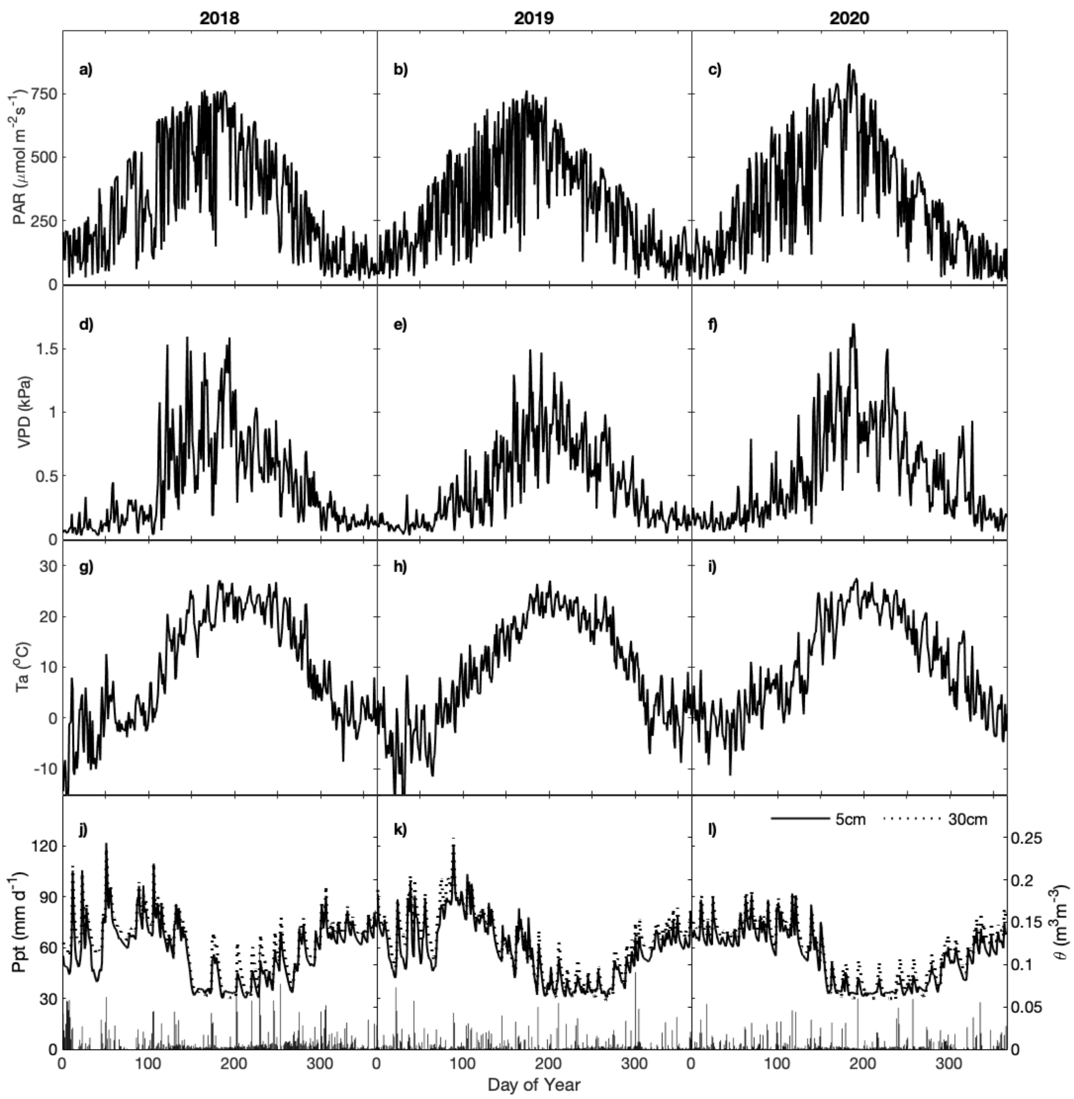

Figure 3.2. Annual daily average measurements of photosynthetically active radiation (PAR; a-c), vapour pressure deficit (VPD; d-f), air temperature (Ta; g-i); daily total precipitation (Ppt; j-l) and daily average soil moisture (θ, j-l) for years 2018, 2019 and 2020 measured at CA-TP39.

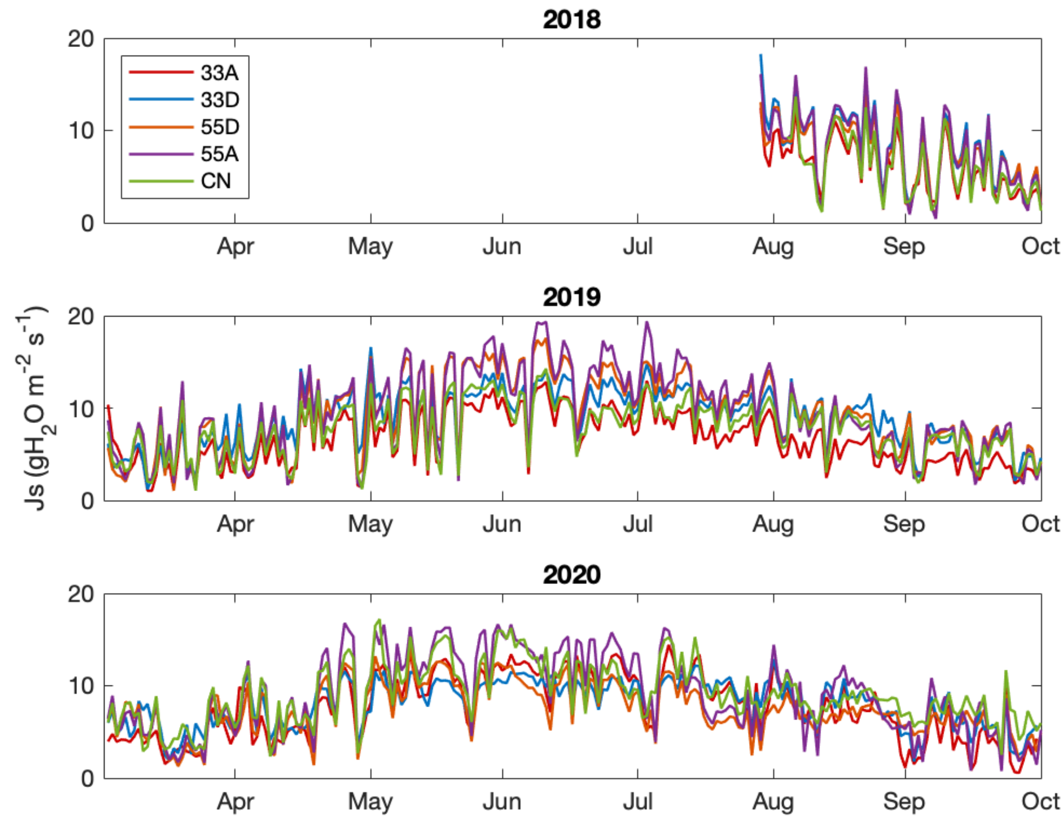

Figure 3.3. Daily average sap flux density for all plot types for the growing season (1 April to 31 October) for all years.

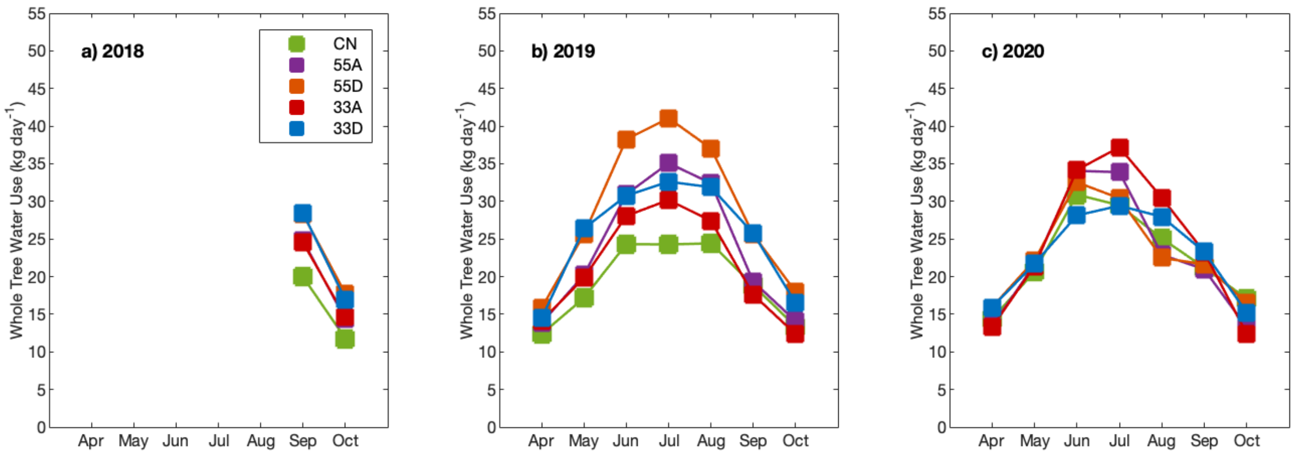

Figure 3.4. Average daily whole-tree water use by month for 2018(a; $p < 0.001$), 2019 (b; $p < 0.001$) and 2020 (c).

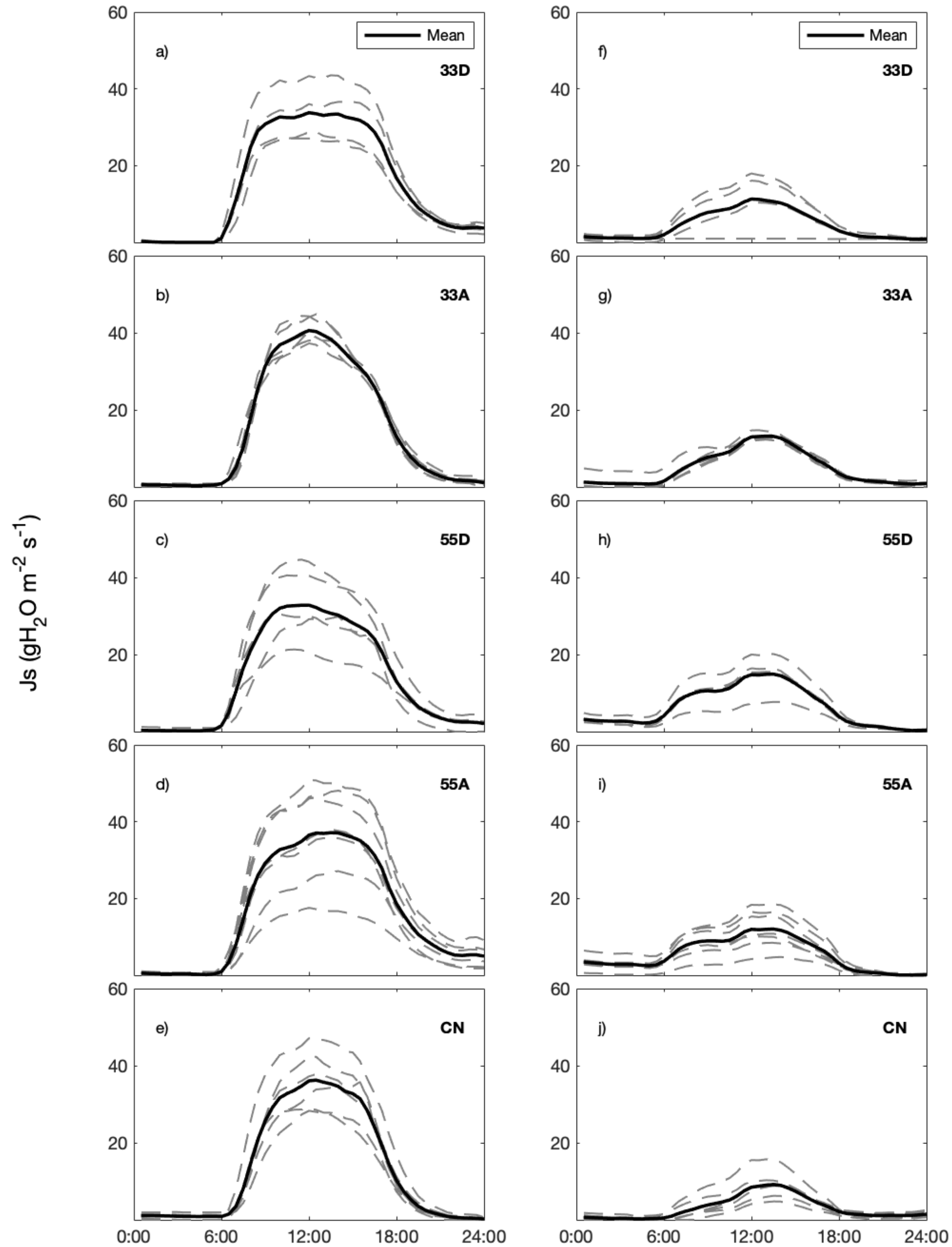

Figure 3.5. Sap flux density for a 24-hour period on a warm, sunny day (5 September 2018; a-e) and on a cool, cloudy day (12 October 2018; f-j). Data from individual sensors (6-8 sensors per plot) is shown in the dashed lines and the mean is shown in solid black.

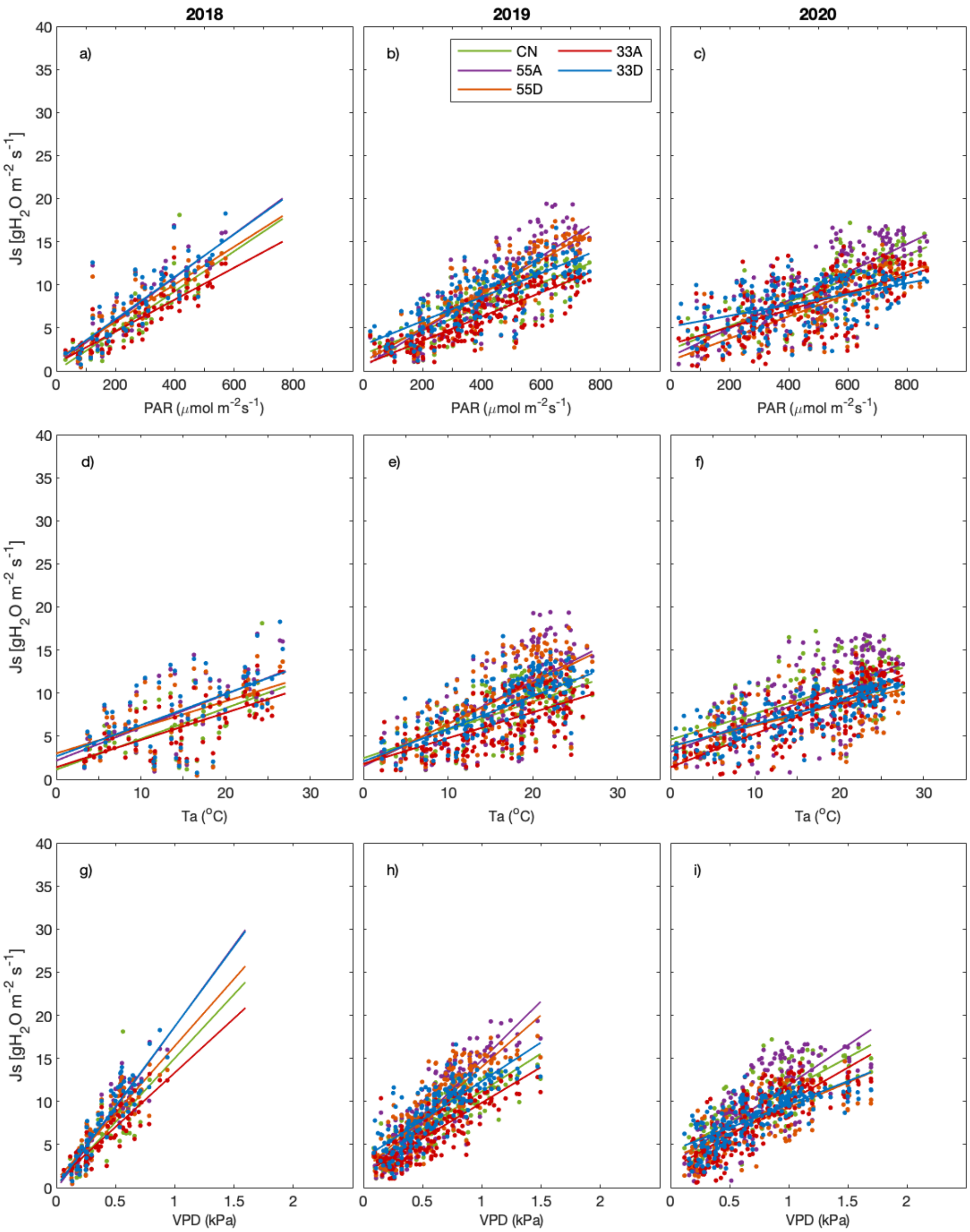

Figure 3.6. Scatter plots showing the correlation between daily average sap flux density (J_s) and photosynthetically active radiation (PAR; a-c), air temperature (Ta; d-f) and vapour pressure deficit (VPD; g-i) for 2018, 2019 and 2020. The slope of each line and corresponding R^2 value are displayed in Table 3.2 ($p < 0.001$).

CHAPTER 4:

WATER DYNAMICS IN THE UNDERSTORY OF A PINE PLANTATION FOREST AFTER VARIABLE RETENTION HARVESTING

Abstract

Variable Retention Harvesting (VRH) is a silvicultural technique applied to enhance forest growth, and restore forest stands to closely resemble their natural composition in the region. This study used sapflow and eddy covariance flux measurements to examine the impacts of four different VRH treatments on water-use efficiency and the dominant components of evapotranspiration including canopy transpiration and water flux from understory vegetation and soil. These VRH treatments were applied to an 83-year-old red pine (Pinus *resinosa*) plantation forest in the Great Lakes region in Canada and included 55% aggregated crown retention (55A), 55% dispersed crown retention (55D), 33% aggregated crown retention (33A), 33% dispersed crown retention (33D) and unharvested control (CN) plot. Study results showed a positive relationship between thinning intensity and the growth of understory vegetation, and hence enhanced understory evapotranspiration. The contribution to evapotranspiration from understory vegetation and soil was more pronounced in the dispersed thinning treatments, as compared to the aggregated treatments. Canopy transpiration contributed to 83 % of total evapotranspiration in the un-thinned control plot and 58, 55, 30, and 23 % for the 55D, 55A, 33A and 33D plots, respectively. Overall thinning or retention harvesting treatments contributed to an increase in stand water use efficiency.

Our study results suggested that VRH treatments that followed a dispersed harvesting pattern such as 55D led to higher evapotranspiration and forest productivity. Furthermore, a balance of contributions from both the canopy and successional understory vegetation and soil, as observed in the 55D treatment, may increase the resiliency of forest to climate change. These findings will help researchers, forest managers and decision-makers to improve their understanding of thinning impacts on water and carbon exchanges in forest ecosystems and adopt appropriate forest management practices to enhance their carbon sequestration capabilities, water use efficiency and resilience to climate change.

4.1 Background

Forest ecosystems play a significant role in global water and carbon cycling through evapotranspiration (ET) and photosynthetic/respiratory processes, respectively. It is estimated that approximately 61% of the 117,600 km^3 of annual global precipitation is derived from terrestrial ecosystems (Schlesinger and Jasechko 2014). Further, more than 50% of this atmospheric moisture originates as transpiration from plants, predominantly forests and crops (Jasechko et al. 2013, Wei et al. 2017, Sheil 2018). In the past century, land-use changes have increased at an alarming rate. Globally deforestation is removing 18.7 million acres of forest every year (FAO, 2016). It is estimated that 18% of current climate warming trends can be attributed to deforestation and land-use change (Ellison et al. 2017, Alkama and Cescatti 2016). One recent study estimated that due to these alterations to terrestrial land cover, there is about 5-6% reduction in atmospheric water at a global scale (Sterling et al. 2013). Despite the recent commitment of global leaders to end deforestation (UN Climate Change Conference UK 2021), it is becoming more important to understand the intricate processes that drive water and carbon cycling at the land-atmosphere boundary. There is a growing need for restoring forest ecosystems through various means such as afforestation and reforestation and developing sustainable forest management methods to enhance forest growth, promote carbon sequestration and sustain and secure regional water resources.

In Canada red pine (*Pinus resinosa*) is a major plantation species and over 70% of plantation forest in Ontario are comprised of red pine (Kim 2020). It is a favourable species due to the straight, robust trunk, resiliency to drought conditions and shade tolerance (Magruder et al. 2013, Sharma and Parton 2018). Red pine stands were widely planted in the early 20th century to convert abandoned agricultural lands to native forest ecosystems. The management of plantation stands has been a challenge and traditional silviculture techniques (e.g. clear-cutting) are often inadequate to enhance stand growth and productivity (Beese et al. 2019). Therefore, forest managers and planners are striving to explore different forest management techniques that can not only increase stand growth but also enhance carbon sequestration, water use efficiency, biodiversity and resilience to climate change.

Variable retention harvesting (VRH) is a selective-thinning silvicultural method designed to increase forest growth, promote productivity and increase carbon sequestration (Franklin et al. 1997, Bladon et al. 2006, Beese et al. 2019). First implemented in the Pacific Northwest region of the USA and Western Canada, VRH strives to mimic natural disturbance and involves the implementation of different thinning intensities and patterns. Remaining trees are typically left in distributed or aggregated groups that vary in size and structure, in order to increase structural complexity, maintain biodiversity and promote growth. Over the past two decades this technique has been widely used in western North America, Australia, Argentina and many of the Nordic European countries (Beese et al. 2019). Several studies have examined tree mortality, growth and carbon dynamics following VRH (Bladon et al. 2006, Bladon et al. 2008, Montgomery et al. 2013, Powers et al. 2011, Xing et al. 2018), but a few have discussed the effect of VRH on evapotranspiration and hydrological processes (Aussenac 2000, Jutras et al. 2006)). In particular, studies examining the changes in the components of total ET (e.g. canopy and understory transpiration and soil evaporation) are lacking. Partitioning of ET into its dominant components is very important to understand the links between plant water use and the impacts of stand structure and environmental conditions (Kool et al. 2014). Additionally, scientists rely on field-based measurements of ET and its components to test and further improve land-surface models and better predict the effects of climate change on terrestrial ecosystems (Lawrence et al. 2007).

While micrometeorological techniques, such as eddy covariance (EC) are widely used to measure ET above forest ecosystems (Baldocchi 2003, 2020), the use of EC systems below a forest canopy is far less common due to numerous challenges such as low wind speed, weak and intermittent turbulence and large surface heterogeneity (Baldocchi et al. 2000, Launiainen et al. 2005). Some studies, however, have successfully measured carbon and water fluxes below the forest canopy and partitioned ET into soil evaporation (E_S) and transpiration (T_C) (Baldocchi and Vogel 1996, Black et al. 1996, Constantin et al. 1999, Mission et al. 2007, Brown et al. 2014). But none of these studies were conducted in forests where different management regimes have been applied to evaluate their effectiveness for stand growth, carbon sequestration and water conservation.

The objectives of this study are to (i) measure ET in four different VRH treatments and a control plot in a red pine plantation forest in the Great Lakes region in Canada (ii) partition ET into canopy and understory components of water fluxes in each plot (iii) determine the water use efficiency of both the canopy and the understory in each treatment and (iv) explore which of these VRH treatments might be best suited to enhance stand growth while conserving water resources. This study is among the first efforts to study and partition ET in to its components in different VRH treatments in pine forests.

4.2 Methods

4.2.1 Site Description

The study site is located within the St. Williams Conservation Reserve (SWCR, 42°42'N, 80°21'W), about 3 km north of Lake Erie in southern Ontario, Canada. The temperate forest stand is a 21-hectare red pine (*Pinus resinosa*) plantation forest established in 1931 and is further referred to as 'CA-TP31'. In 2014, the plantation underwent variable retention harvesting (VRH) to restore the coniferous monoculture to a native Carolinian composition. Soils in the region are well-drained, sandy loam with a low to moderate water holding capacity. CA-TP31 is part of the larger Turkey Point Observatory, which consists of three white pine (*Pinus strobus*) plantation forests of various ages (CA-TP39, CA-TP74 and CA-TP02), one mixed deciduous stand (CA-TPD) and an agricultural site (CA-TPAg). These sites are associated with Global Water Futures and FLUXNET. Further details of the Turkey Point Observatory are provided in Restrepo and Arain (2005), Peichl et al. (2010), Beamesderfer et al. (2020) and Arain et al. (2021).

As part of the VRH scheme, CA-TP31 was segmented into 21 one-hectare blocks and randomly treated with one of 5 harvesting techniques that differed in harvesting density and pattern: 33% basal retention in a dispersed pattern (33D), 55% retention in a dispersed pattern (55D), 33% retention in an aggregated pattern (33A), 55% retention in an aggregated pattern (55A) and an unharvested control (CN). The aggregated pattern of harvesting left remaining trees in small and large groups (Figure 4.1). Further details are given in Bodo and Arain (2021b).

Since the implementation of VRH, successional species have emerged in the understory of the harvested blocks, with varying degrees of growth. Species include black oak (*Quercus velutina*), red maple (*Acer rubrum*), black cherry (*Prunus serotina*), and white pine (*Pinus strobus*). There was almost no understory in control plots where the canopy was almost closed. Figure 4.2 displays imagery captured at the location of the understory EC tower in each VRH treatment and highlights differences in canopy cover.

Soil at the site is sandy and well-drained (McLaren et al. 2008; Beamesderfer et al. 2020). The climate in the region is warm humid continental (based on the Koeppen climate classification) with warm summers, very cold winters. Mean annual temperature in the region is 8.0 °C and mean annual precipitation is 1036 mm, with about 13% falling as snow (Environment and Climate Change Canada, 1980-2010 Norms at Delhi, ON).

4.2.2 Understory Eddy Covariance Flux Measurements

Carbon (CO_2), latent (LE) and sensible heat (H) fluxes were measured over the understory in each VRH treatment during the 2019 growing season using a roving open-path eddy covariance (OPEC) system. The OPEC system was installed in one block of each treatment, for a minimum of 14 days before rotating to the next block (Table 4.1).

Data collected on the day in which the instrument was moved was not included in the analysis. The instruments were installed in the centre of the plot at 5 m above the ground. It consisted of an infrared gas analyzer (Li-7500, LI-COR Inc.) and a 3D sonic anemometer (CSAT3, Campbell Scientific Inc.). Flux measurements were made at 20Hz and averaged every 30-minutes. Meteorological measurements such as photosynthetically active radiation (PAR; LI190SB, LI-COR Inc.), air temperature (T_a) and humidity (*RH*; HC2S3, Campbell Scientific Inc.), soil temperature at depths of 5 and 10 cm below the ground surface (T_s; TS107b, Campbell Scientific Inc.), volumetric water content at depths of 5 and 10 cm below the ground surface (θ; CS616, Campbell Scientific Inc.) were sampled every 5 seconds, averaged every half-hour and stored on a data logger (CR5000, Campbell Scientific Inc.). Net ecosystem exchange (NEE_U) was calculated as the sum of the vertical CO_2 flux and the rate of storage in the air column below the IRGA. NEP_U was then calculated as the opposite of NEE_U (multiplied by -1).

All meteorological and flux data were processed following Brodeur (2014). Meteorological and flux measurements were cleaned using a two-step process described in Beamesderfer et al. (2020). All half-hourly fluxes were subjected to friction velocity (u*) filtering to remove values that may be underestimated during periods of low turbulence. We used the moving-point determination method (Reichstein et al. 2005) to estimate u* threshold values for the understory. The u* threshold value was 0.064 m s^{-1} and the resulting flux data recovery following threshold filtering was 62%. Finally, carbon and water flux measurements collected during rain events (precipitation > 0.5 mm in a half-hourly interval) were considered erroneous and discarded. Gaps in understory

EC measurements that occurred as a result of instrument error or power loss were not filled.

While eddy covariance systems have been used to study below canopy carbon and water fluxes in the past (Black et al. 1996, Baldocchi 1997, Saugier et al. 1997, Wilson and Meyers 2001a, Paul-Limoges et al. 2017), there are challenges regarding understory canopy homogeneity, sufficient turbulence and adequate fetch or footprint required to meet the assumptions of the eddy covariance theory. In figure 4.3a, we report wind speed and wind direction for all VRH treatments when fluxes were measured using the understory EC system in each VRH plot. Additionally, we also conducted a footprint analysis (Kljun et al. 2004, 2015) for each of the VRH treatment plots to ascertain the majority (70%) of fluxes are originating within the VRH plots. (Figure 4.3b).

4.2.3 Above-canopy Eddy Covariance Flux Measurements

Above-canopy fluxes were measured using a reference eddy covariance system (EC_{REF}) installed above the white pine forest stand (CA-TP39), situated about 1 km north of CA-TP31. This flux station was chosen a reference system due to the similar stand age and density as that of CA-TP31. This system is a closed-path EC system consisting of an enclosed infrared gas analyzer (LI-7200, LI-COR Inc.) and a 3D sonic anemometer (CSAT3, Campbell Scientific Inc.) installed at 36 m height above the ground. Continuous half-hourly measurements of momentum, sensible heat, latent heat and CO_2 were measured during the study period, as along with meteorological measurements such as PAR, Ta, RH and soil temperature (2, 5, 10, 20, 50 and 100 cm) and soil moisture (5, 10, 20, 50 and 100 cm) at two locations in the vicinity of the tower. Further details of the CA-TP39 instrumentation are given in Peichl et al. (2010), Beamesderfer et al. (2020) and Arain et al. (2021).

Above-canopy fluxes and meteorological data collected at CA-TP39 were cleaned and gap-filled using in-house software implemented by Brodeur (2014) and following Fluxnet Canada Research Network and AmeriFlux protocols. A friction velocity (u*) threshold of 0.49 m s^{-1} was used to exclude values that are measured under low turbulence conditions. Ecosystem respiration (RE) was modeled as a function of soil temperature and soil moisture in the upper 30 cm of the soil profile (Brodeur, 2014) in order to accurately describe the relationship between RE and soil temperature. Gross ecosystem productivity (GEP) was estimated by adding daytime NEP and RE. Furthermore, gaps in NEP were filled as the difference between modeled GEP and RE (Beamesderfer et al. 2020).

4.2.4 Sap Flow Measurements

Self-manufactured thermal dissipation sap flow sensors were installed in 80 of the dominant red pine trees in CA-TP31. Sensors were Granier-style and constructed as described following Matheny et al. (2014) and Pappas et al. (2018). Eight sap flow sensors were installed in 10 blocks, two of each of the four treatments and two control plots, during the 2018 growing season and measurements are ongoing (Bodo and Arain 2021a,b). Sensors were installed in the outermost 20 mm of conductive sapwood, and measurements were sampled every 30 seconds and averaged every half-hour. Radial variation in hydraulic conductivity within the sapwood was measured in five trees and corrected for following Bodo and Arain (2021a).

Sap flux density (J_s; $gH_2O\ m^{-2}\ s^{-1}$) was calculated following Granier (1987). Tree-level sap flux measurements were scaled to plot-level transpiration for each of the study blocks following equation 1:

$$T_i = J_s\left(\frac{As}{Ag}\right) \qquad (1)$$

Where *T* is transpiration ($mm\ s^{-1}$), *i* denotes the treatment plot, J_s is the average sapflux density of all sensors in plot *I (*$gH_2O\ m^{-2}\ s^{-1}$), and A_s/A_g is the ratio of sapwood area to total wood area in the plot ($m^2\ m^{-2}$).

4.2.5 Water Use Efficiency

Canopy water use efficiency (WUE_C) was estimated as the ratio of net primary productivity (NPP_C) to canopy transpiration (T_C) for each of the five treatment blocks (g C m^{-2}/Kg H_2O). Tree-ring width analysis was used to estimate carbon uptake (NPP_C) in the red pine canopy of each treatment for the growing season. Tree cores were collected at breast-height using a 5-mm increment borer as described in McKenzie et al. (2020) and Zugic et al. (2021).

The water use efficiency of the understory soil and vegetation (WUE_U) was estimated as the ratio of gross ecosystem productivity (GEP_U) to understory evapotranspiration (ET_U). GEP_U was estimated by partitioning NEP_U into its components (GEP_U and RE_U) through the use of R-package REddyProc (Wutzler et al. 2018). NEP_U was partitioned following

Lasslop et al. (2010), which fits a model of daytime NEE and radiation, and Reichstein et al. (2005), which extrapolates respiration measurements made at night to the daytime.

4.3 Results

4.3.1 Meteorological Conditions

Meteorological conditions conformed to typical seasonal averages for the 2019 growing season when compared to the previous five years. Both thinning intensity and pattern influenced below canopy radiation. For example, in the un-thinned control plot, only 8% of PAR reached the ground surface due to the dense canopy. By comparison, in the 33A and 33D plots, on average 26% and 36% of PAR reached the ground, respectively. In the 55A and 55D plots, 18% and 25% of PAR penetrated the canopy to reach the ground surface (Figure 4.4a). These values also suggest that when compared to the aggregated plots, the dispersed pattern of thinning allows for slightly more radiation to penetrate the canopy, which may be an important factor for understory growth and productivity. During the day, *Ta* was cooler below the canopy in each of the treatment plots when compared to the above canopy reference *Ta* on top of EC tower at CA-TP39 as expected. At night, a temperature inversion was observed in each of the treatments where the below canopy *Ta* was higher than above the forest. There was no correlation between VRH treatment and difference in air temperature between the above and below canopy sensors. *Ts* measurements taken at 5 cm and 10 cm depths closely followed *Ta*. The driest measurement period was that of the 55D plot (25 July to 13 August) where only 21 mm of precipitation fell over the 12-day period. By contrast, between 14 August and 30

September we observed 118 mm of rainfall, while the EC_U was measuring fluxes in the control plot.

4.3.2 Partitioning of Evapotranspiration

There is a positive relationship between the level of thinning and presence of understory vegetation, with the more heavily thinned blocks (33A and 33D) experiencing the most understory growth. By contrast, control plots had least understory with the dominant understory vegetation species mostly comprising the non-vascular bryophytes. These differences in understory vegetation among VRH treatments had significant impact on understory ET. We observed the largest understory ET fluxes in the most heavily thinned VRH treatments (33A and 33D) and the lowest in the un-thinned control (Figure 4.5c). On average, the understory ET in the control plot represented 17% of total ET (ET_U + T_C). In the moderately thinned 55A and 55D treatments, ET_U contributed to 45% and 42% of total ET, respectively; and in the 33A and 33D, it contributed up to 70% and 77% of total ET, respectively (Figure 4.5a,c). Further, daytime ET values measured in the understory were linearly correlated with the reference above-canopy ET measurements (ET_{REF}) taken at CA-TP39 (Figure 4.6. The control plot had the smallest slope (0.17), signifying the least contribution from the understory to ET_{REF}. The most heavily thinned plots, 33A and 33D, had the largest slopes (0.45 and 0.59 respectively), confirming that the understory soil and vegetation contributed more to ET_{REF} when compared to the moderately thinned 55A and 55D, and the un-thinned control plots. Additionally, the dispersed VRH treatments (33D and 55D) exhibited greater contribution of ET from the understory when compared to the aggregated plots of the same thinning intensity (Figure 4.6).

We observed the opposite trend in plot-level transpiration, with an average of 83% of total ET (T_c + ET_U) in the un-thinned control plot comprised of T_C. On some days during the study period, the T_C/ ET_U ratio was as high as 1 in the CN plot (Figure 4.7). In the 33D plot, however, we saw T_C/ET values as low as 0.12, with an average ratio of 0.23. Plot-level transpiration closely reflected trends in the stand's tree-density among the VRH treatments.

4.3.3 Water Use Efficiency

Canopy-level water use efficiency, WUE_C (NPP_C/T_C) followed the growth trends of treatment plots with CN < 33A < 55D < 55A < 33D in the 2019 growing season (Table 4.2). The plots with largest net primary productivity (NPP) were 55D (515 g C m^{-2}) and 33D (481 g C m^{-2}). While plot-level productivity was among the highest in 33D, this treatment exhibited the least amount of transpiration (104 mm) during the growing season, therefore the WUE_C was 4.63 g C m^{-2} per kg H_2O – the highest of all treatments. Conversely, in the un-thinned control, plot-level transpiration was highest (297 mm), partly due to the large stand density (432 trees ha^{-1}). Growing season NPP in the CN plot was moderately low when compared to the other treatments (258 g C m^{-2}) but transpired more water, which led to a very low WUE_C of 0.87 g C m^{-2} per kg H_2O.

In the understory, WUE_U (GEP_U/ET_U) followed the general trend with 55A < 55D < CN < 33D < 33A with slight differences among these values (Table 4.2). Due to measurements having been collected at different time periods during the growing season and for varying durations, we cannot compare understory gross ecosystem productivity (GEP_U) between treatments. However, the ratio of GEP_U/ET_U and therefore, WUE_U is upheld regardless of timing and duration. Interestingly, we observed the highest WUE_U in the most heavily thinned treatments, 33A and 33D where the WUE_U was 1.32 and 1.27 g C m^{-2} per kg H_2O, respectively; but the lowest WUE_U among the 55A and 55D (1.03 g C m^{-2} per kg H_2O in both treatments).

4.4 Discussion

4.4.1 Effects of VRH treatments on Meteorological Conditions

Our study showed VRH treatments that follow a dispersed thinning method (33D and 55D) allow for more PAR to reach the understory. This is important for climate change mitigation as it may promote higher growth and productivity in understory vegetation, leading to an increase in carbon sequestration. In fact, Mission et al. (2007) found that the GEP of the understory may reach up to 39% of total canopy GEP and is highly influenced by PAR that penetrates the canopy. While understory vegetation is influenced by PAR, their study found leaf area index (LAI) was more closely linked to overall productivity of the understory and the water balance (Mission et al. 2007). Additionally, Mission et al. (2007) found daytime Ta was generally higher in the understory than above the canopy, in less-dense forests. Our study found the opposite was true, where daytime Ta was cooler beneath the canopy, due to shading provided by the remaining trees in all treatments. To better understand the effects of VRH on micrometeorological conditions, several measurements throughout the plot should be taken to account for spatial variation beneath the canopy. Additionally, the presence and abundance of understory vegetation may influence advective flow and therefore, *Ta* in the understory (Lee 2000, Mahrt et al. 2000, Staebler and Fitzjarrald et al. 2005). While our study was limited in soil moisture and temperature measurements at two depths only, other studies have reported dissimilar results regarding the effect of thinning on forest ecosystems. For example, Gebhardt et al. (2014) and Xu et al. (2020) both observed an increase in soil moisture after thinning in Norway spruce (*Picea abies*) and Larch (*Larix principis-upprechtii*), respectively. By contrast, Trentini et al. (2017) found soil water content decreased following a 50% reduction in basal area in a loblolly pine (*Pinus taeda)* plantation. Due to complex linkages between thinning and the attenuation of both PAR and precipitation, spatially representative measurements of soil temperature and moisture should be collected in future studies.

4.4.2 Partitioning Evapotranspiration

Our study found a significant positive relationship between VRH intensity and ET_U driven by understory vegetation. Like findings by Xu et al. (2020), we observed an increase in the contribution of ET_U to total ET as a result of increased thinning intensity. Moreover, we observed greater understory contributions from the dispersed treatments (33D and 55D), suggesting this may be the preferred treatment pattern. These results follow similar trends in growth among remaining trees determined by Zugic et al. (2021) using tree-ring analysis in the same site (CA-TP31). Their study found higher growth in the dispersed treatments when compared to the aggregated plots of the same retention.

We also found a strong negative relationship between thinning intensity and the ratio of transpiration to total ET (T/ET). There have been several studies that have quantified the contribution of canopy transpiration to total ET at stand, national and global scales (Jasechko et al. 2013, Schlesinger and Jasechko 2014 , Wei et al. 2017, Zhang et al. 2021). While there are significant uncertainties with spatially large-scale values, Skubel et al. (2017) determined transpiration contributed to 89% of total ET in an adjacent white pine plantation (CA-TP39) prior to thinning. After a reduction in basal area by 13%, the contribution of T_C to total ET dropped to an average of 58% in the two years immediately following the thinning event (Skubel et al. 2017). Our study results support these findings, where in an un-thinned, closed canopy (CN), transpiration accounted for an average of 83% of total ET, but in a highly open canopy (33D), transpiration accounted for an average of 23%.

While there are relatively few studies that compare water balance components between thinning treatments, the importance of quantifying these contributions in forest ecosystems is widely accepted. Our study is the first known study to quantify and partition evapotranspiration in red pine following VRH treatments. ET_U is particularly important during periods of drought, when canopy transpiration is low due to stomatal closure (Simonin et al. 2007). Therefore, quantifying the contribution of the understory to ecosystem ET is key to predicting the effects of climate change on these forests, for determining the optimal management strategies and growth and survival of understory species contributing to richness of biodiversity.

4.4.3 Water Use Efficiency

We observed a positive relationship between thinning and the presence of understory vegetation. Several studies have shown that understory vegetation competes with the dominant canopy species for soil water and nutrients (Oren et al. 1987, Kume et al. 2003). However, the effects of understory vegetation on WUE_C may be site- and species-specific. For example, Liles et al. (2019) used isotopic ratios to determine the growth of understory vegetation led to a decrease in WUE of the Ponderosa pine (*Pinus ponderosa*) canopy, in dry climates. By contrast, Kume et al. (2003) and Livingston et al. (1999) found that the presence of understory vegetation led to an increase in WUE in Japanese red pine (*Pinus densiflora*) and white spruce (*Picea glauca*), respectively. More recent studies have also found thinning in Norway spruce leads to an increase in productivity related WUE (Gebhardt et al. 2014). These results support our findings that despite a greater presence of understory vegetation, canopy thinning leads to more productivity, less plot-level transpiration and therefore a higher WUE_C.

When compared to WUE_C, WUE_U was lower in all treatments except for the un-thinned control. Similar findings are reported by Gebhardt et al. (2014) and Binkley et al. (2002) who found understory vegetation was less efficient in resource utilization, and thus had lower WUE than the dominant canopy trees. As previously discussed, there is very little vegetation present in the understory of the un-thinned control plot, due to closed canopy and low level of PAR. Because of resource competition due to a higher number of trees, the control plot had a lower WUE_C than the thinned plots. While we do observe lower WUE_C and WUE_U in the un-thinned control when compared to the four thinned plots, there is no clear pattern to describe the effect of thinning on WUE. Similarly, Park et al. (2018) did not observe a change in WUE as a result of thinning due to the synchronized effects of thinning on both transpiration and productivity. Additionally, WUE is influenced more by productivity (GEP, NEP) than water use (ET, T_C) in the North American Great Lakes region (Yang et al. 2016). Additionally, Yang et al. (2016) determined that WUE in the Great Lakes region decreased as a result of drought. Therefore, a better understanding of WUE in both the canopy and the understory is important in predicting the effects of climate change on the resilience of these ecosystems. Furthermore, knowledge of partitioning of ET and water exchanges in dominant canopy species and subdominant understory vegetation in red pine plantations is important for future forest management decisions.

4.5 Conclusion

Due to the significant contribution of forest ecosystems to carbon sequestration and water resources, forest managers are facing increasing pressure to implement silviculture techniques that balance economic gain and ecosystem services, including carbon sequestration and availability of clean water resources. This study quantified the influence of forest management (variable retention harvesting) treatments on the partitioning of total evapotranspiration. We found a positive relationship between thinning intensity, understory vegetation, and therefore understory evapotranspiration. The contribution from understory vegetation was more pronounced in the dispersed thinning treatments, when compared to the aggregated. Additionally, we observed canopy transpiration contributed to 83% of total ET in the un-thinned control. Finally, we found that water use efficiency increased as a result of thinning in the remaining trees. These findings suggest variable retention harvesting in a dispersed pattern with 55% basal retention (more than half of the trees) may provide the optimal balance between forest productivity and evapotranspiration or water use. Furthermore, a balance of contributions from both the canopy and successional understory vegetation may increase forest resiliency to future threats associated with climate change such as droughts.

List of Abbreviations

33A	33% basal retention in aggregated pattern
33D	33% basal retention in dispersed pattern
55A	55% basal retention in aggregated pattern
55D	55% basal retention in dispersed pattern
A_s	sapwood area [m^2]
A_g	ground area [m^2]

C	carbon
CA-TP31	Turkey Point red pine plantation forest planted in 1931
CA-TP39	Turkey Point pine plantation forest planted in 1939
CA-TP74	Turkey Point pine plantation forest planted in 1974
CA-TP02	Turkey Point pine plantation forest planted in 2002
CA-TPD	Turkey Point mixed deciduous forest stand
CA-TPAg	Turkey Point agricultural site
CN	control treatment
CO_2	carbon dioxide
DBH	Diameter at Breast Height [m]
EC	eddy covariance
EC_{REF}	reference above-canopy eddy covariance system
EC_U	below-canopy eddy covariance system
E_S	soil evaporation [mm]
ET	evapotranspiration [mm]
ET_U	understory evapotranspiration [mm]
g	grams
GEP_U	gross ecosystem productivity
GPP	gross primary productivity
H	sensible heat
Ha	hectare
IRGA	infrared gas analyzer
Js	sap flux density [mL $m^{-2}{}_{sapwood}$ s^{-1}]
K	a dimensionless flow index describing the relationship between average flow and zero flow (nighttime) conditions
Kg	kilograms
LE	latent heat
NEE_U	net ecosystem exchange of the understory
NEP_U	net ecosystem productivity of the understory
NPP_C	net primary productivity of the canopy
OMNRF	Ontario Ministry of Natural Resources and Forestry
OPEC	Open Path Eddy Covariance system
PAR	Photosynthetically Active Radiation [µmol m^{-2} s^{-1}]
RE_U	understory respiration
RH	relative humidity (%)
SWCR	St. Williams Conservation Reserve
T	transpiration [mm s^{-1}]
Ta	Air temperature [°C]
T_C	canopy transpiration [mm]
TD	Thermal Dissipation
Ts	soil temperature [°C]
TWU	Tree Water Use [kg day^{-1} or L day^{-1}]
u*	friction velocity [m s^{-2}]
VPD	Vapour Pressure Deficit [kPa]

VRH	Variable Retention Harvesting
WUE	Water Use Efficiency
WUE_C	Canopy Water Use Efficiency
WUE_U	Understory Water Use Efficiency

Declarations

Ethics Approval and Consent to Participate
Not applicable.

Consent for Publication
Not applicable.

Availability of Data and Material
The datasets used during this study are available from the authors upon request.

Competing Interests
The authors declare that they have no competing interests.

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Authors' Contributions
AVB collected, cleaned and processed sapflow, meteorological data and eddy covariance flux data. AVB was a major contributor in writing the manuscript. AVB and MAA designed the experiment with grants received by MAA. All authors read and approved the final manuscript.

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Tables

Table 4.1: Details of roving eddy covariance flux measurements in the understory of each Variable Retention Harvesting (VRH) treatment and control plots.

Treatment Type	**% Basal Area Retained**	**Pattern of Retention**	**Dates in which the understory Eddy Covariance was in the treatment plot (2019)**	**Duration (# of days)**
55A	55%	Aggregated	2-May to 27-May	24
33D	33%	Dispersed	27-May to 2-July	35
33A	33%	Aggregated	2-July to 24-July	21
55D	55%	Dispersed	24-July to 14-August	19
CN	100%	--	14-August to 30-September	47

Table 4.2: Water use efficiency in understory (WUE_U) and water use efficiency in canopy (WUE_C) in each of the VRH treatment plots. Corresponding gross ecosystem productivity (GEP_U), net primary productivity (NPP_C), canopy transpiration (T_C) and understory evapotranspiration (ET_U) values are also given in parentheses.

Treatment Type	**WUE_U (GEP_U/ET_U) (g C m^{-2} Kg H_2O^{-1})**	**WUE_C (NPP_C/T_C) (g C m^{-2} Kg H_2O^{-1})**
55A	1.03 (16.1/15.6)	2.59 (454/175)
33D	1.27 (100.4/79.4)	4.63 (481/104)
33A	1.32 (62.6/47.5)	1.70 (224/132)
55D	1.03 (26.2/25.5)	2.20 (515/234)
CN	1.18 (18.7/15.8)	0.87 (258/297)

Figures

Figure 4.1: Aerial photograph of the VRH plots at CA-TP31 from Google Earth (2016). The red triangles denote the location of the roving understory EC system.

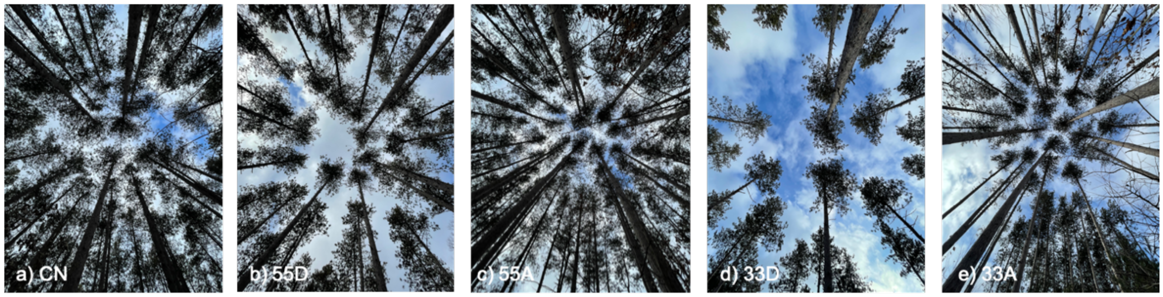

Figure 4.2 Photos from the understory of each VRH treatment plot. Photos were taken at the location of the understory eddy covariance (EC_U) tower while looking up toward the canopy and sky.

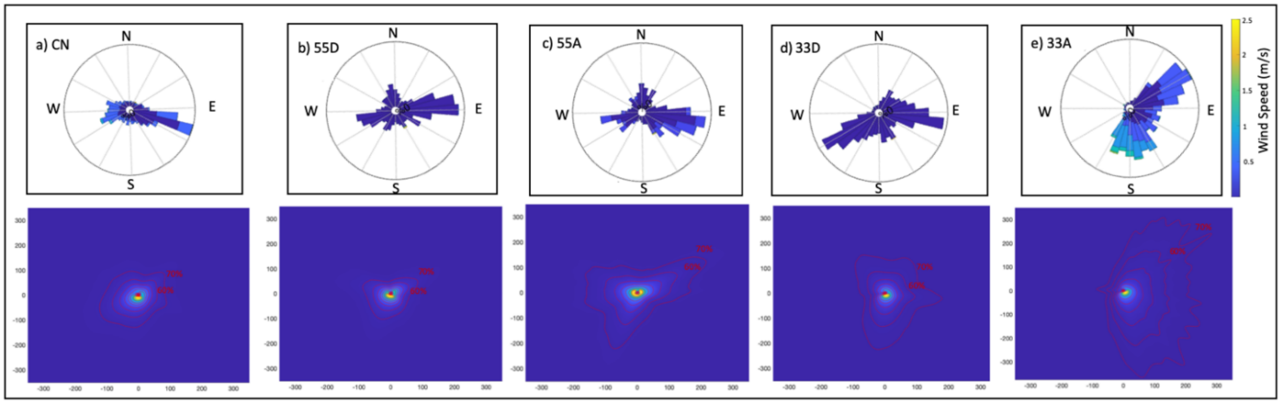

Figure 4.3. Wind rose diagram showing wind speed and direction in the understory of each of the VRH plots (upper panel) and diagrams showing the footprint of the corresponding eddy covariance flux footprints following Kljun et al. 2015 (bottom panel).

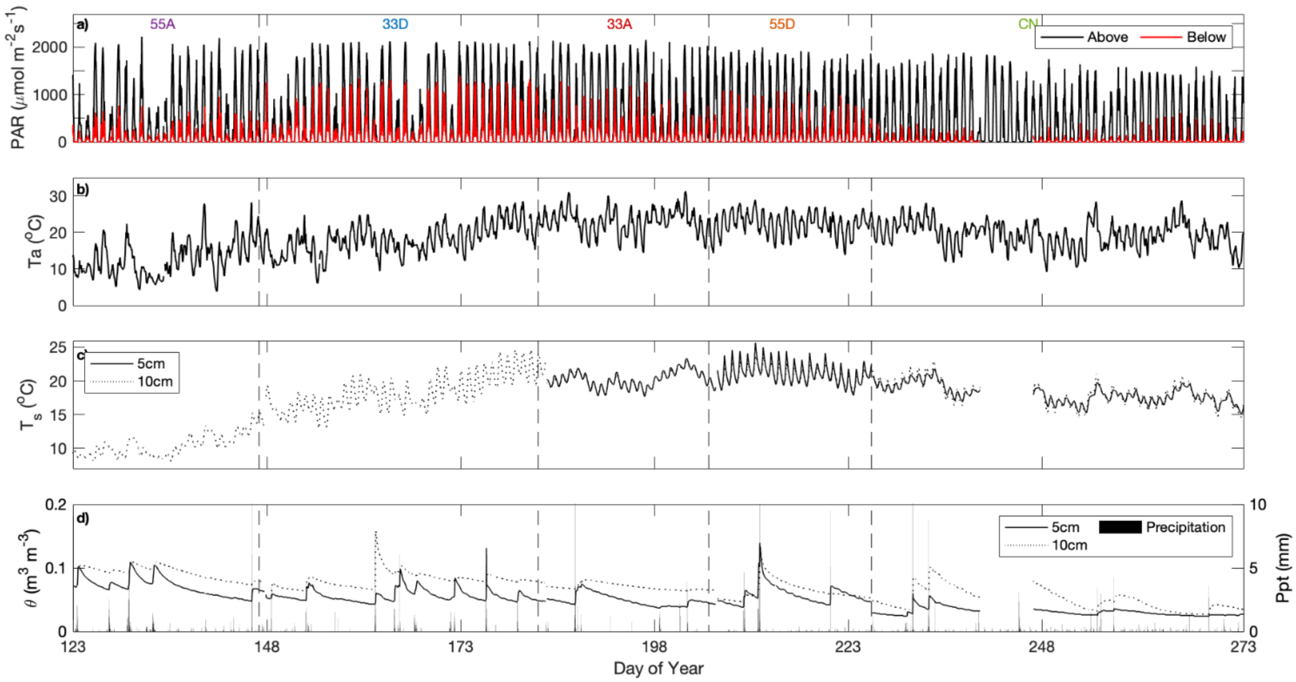

Figure 4.4. Half-hourly values of a) photosynthetically active radiation (PAR) from above the forest canopy (black) and below (red), b) air temperature (Ta), c) soil temperature (Ts) measured 5 cm (solid line) and 10 cm (dotted line) below the surface, d) volumetric water content (*θ)* measured 5 cm (solid line) and 10 cm (dotted line) below the surface and precipitation. The vertical dashed lines indicate the day at which the meteorological instruments were moved to the next plot and the locations are labelled in panel a).

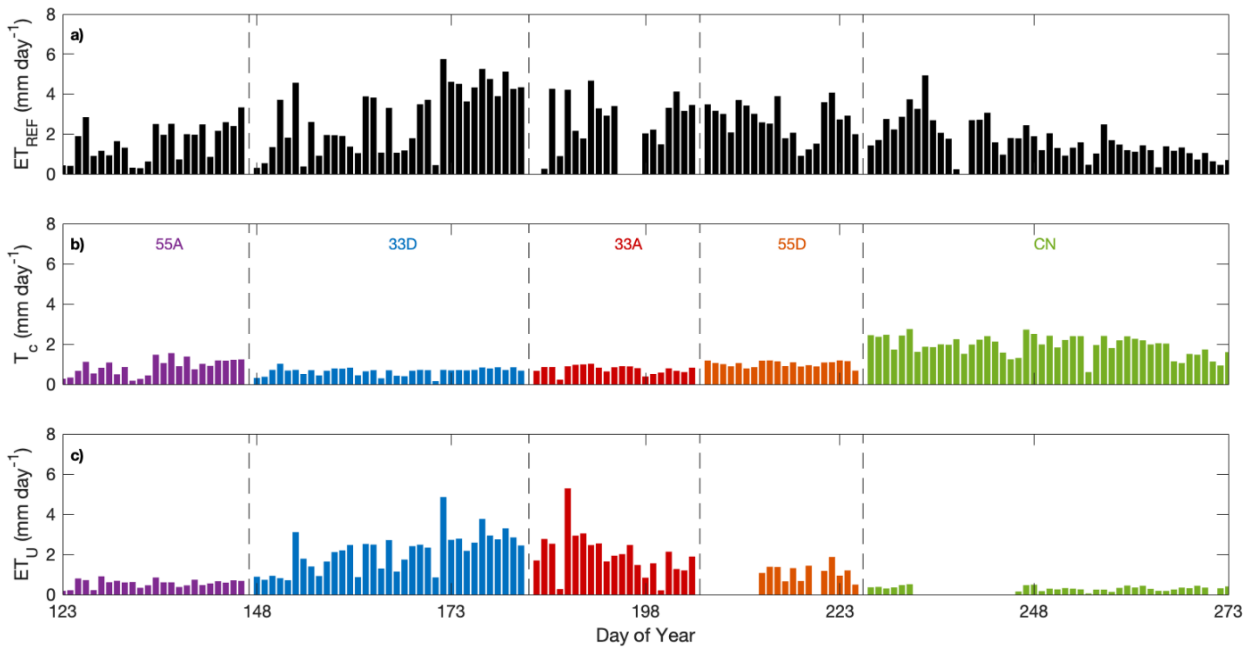

Figure 4.5. Total daily evapotranspiration (ET) measured from the reference above canopy eddy covariance system at TP39 (a); total daily canopy transpiration measured using sap flow sensors in dominant red pine trees in CA-TP31 (b); and total daily evapotranspiration measured from the roving understory eddy covariance system at CA-TP31 (c). The vertical dashed lines indicate the date at which the understory eddy covariance system was moved to the next plot.

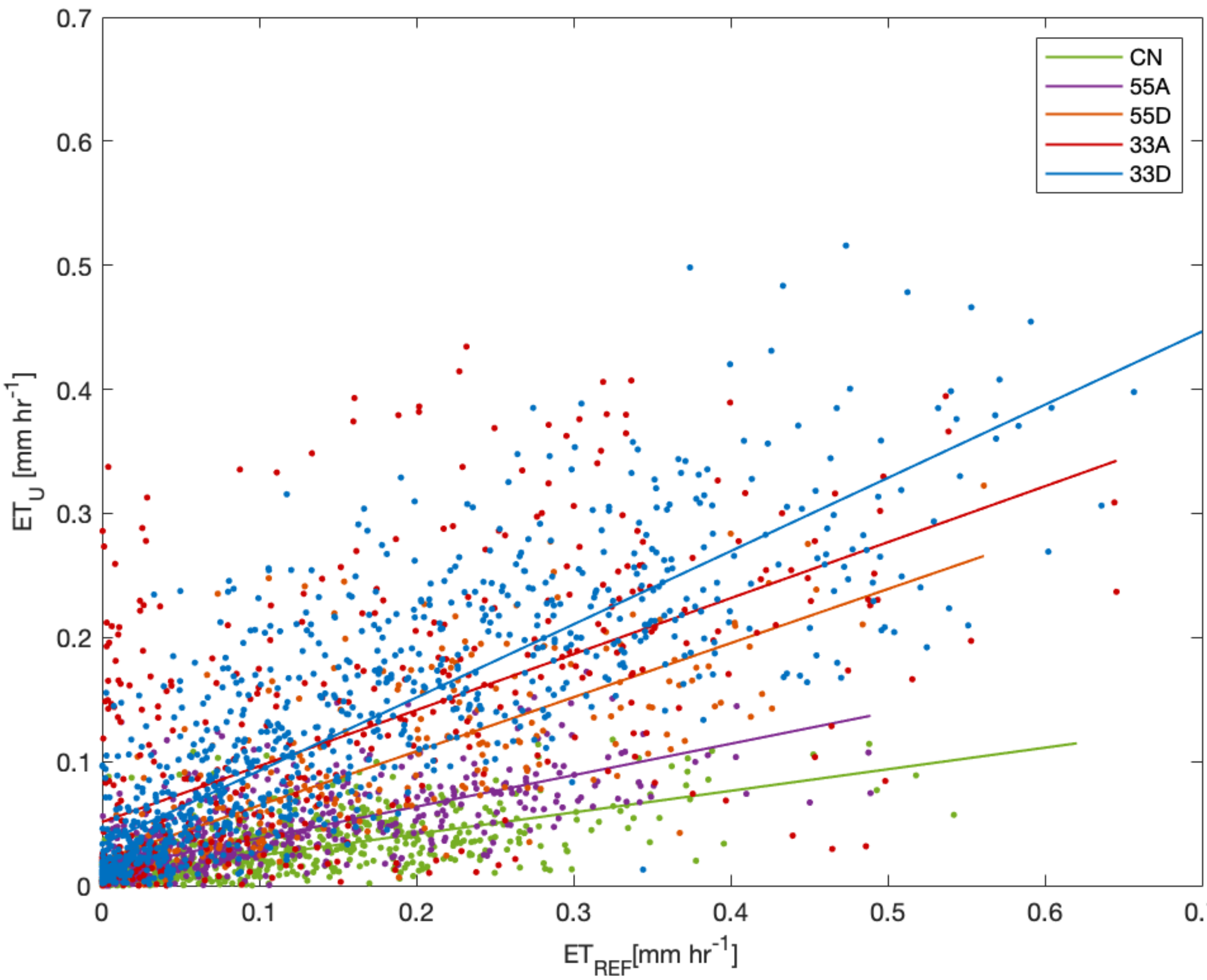

Figure 4.6. Relationship between hourly evapotranspiration (ET) measured above canopy at TP39 site (ET_{REF}) and below the canopy (ET_U) in each of the VRH plots.

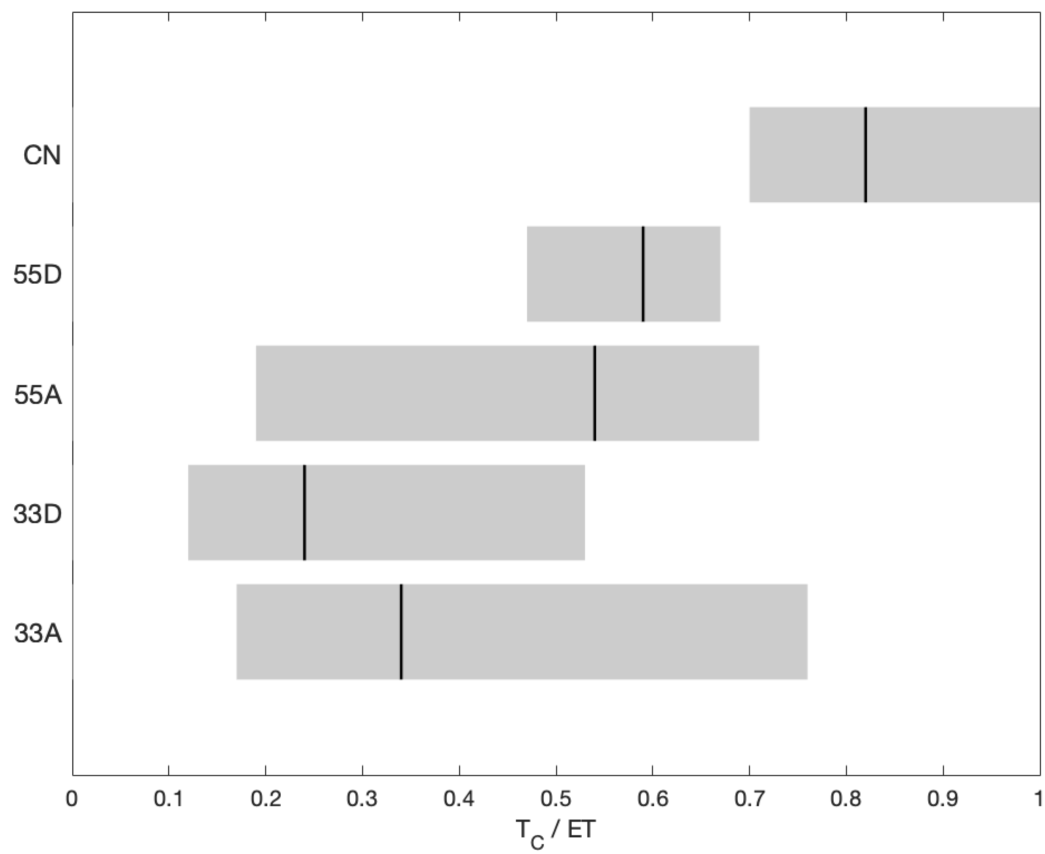

Figure 4.7. The ratio of canopy transpiration, Tc to total evapotranspiration, ET (Tc + ET_U) measured in each of VRH plots. The vertical black line shows the average daily T/ET value during the study period, and the grey bar shows the range of daily values.

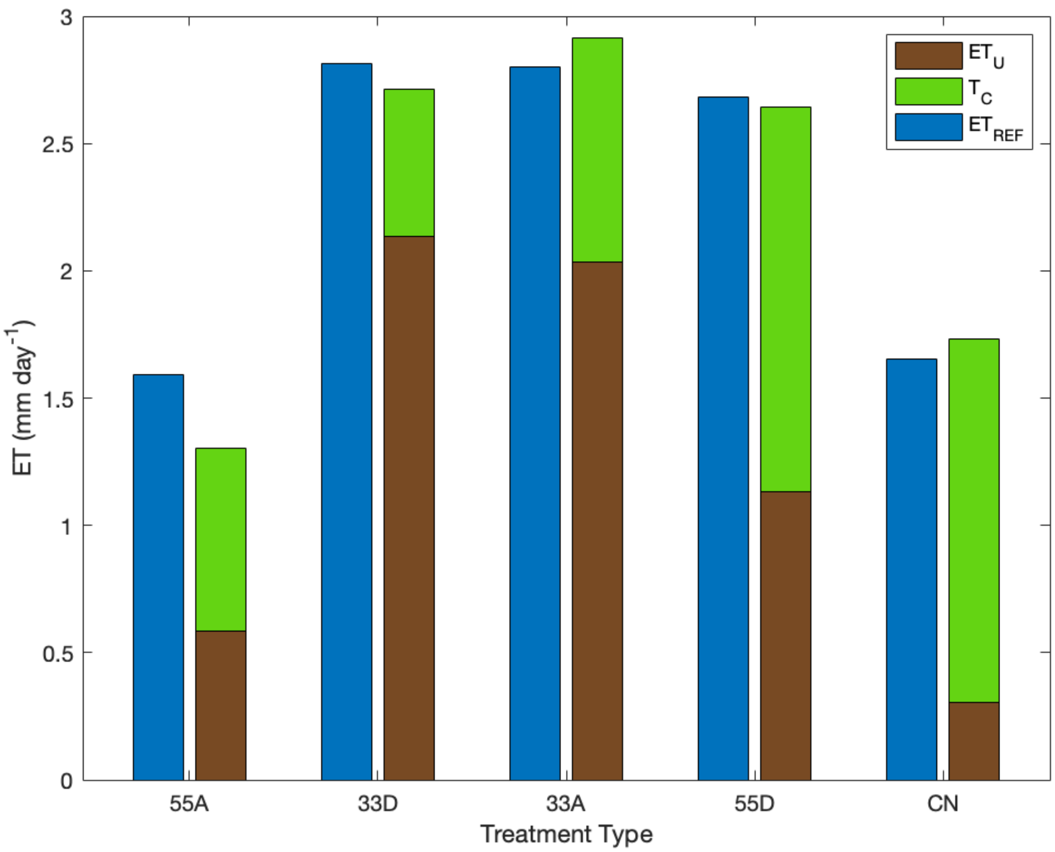

Figure 4.8. Stacked bar plot showing average daily evapotranspiration (ET) measured from the reference eddy covariance at TP39 site (blue); and the average daily contribution to total ET at CA-TP31 from components: canopy transpiration (green) and understory evapotranspiration (brown).

CHAPTER 5:

CONCLUSIONS

5.1 Summary and Conclusions

Ecologically-based forest management may be a primary method to increase the resilience of conifer plantation forests to climate change-related stress. This study investigated the effect of four different variable retention harvesting (VRH) treatments on evapotranspiration and water balance in an 83-year-old red pine (Pinus *resinosa*) plantation forest in the Great Lakes region in Canada. Study results showed that at the individual tree-level, 65% of water transport occurred in the outer 20 mm of the sapwood, while 26% and 9% of water transport occurred in the 20-40 mm and 40-60 mm depth segments of the trunk, respectively (Chapter 2). These results highlight the importance of accounting for radial variations when using sap flow sensors to scale point-measurements to the tree- and stand-level. These results suggest that failing to consider radial variations in sap flux density within trees can lead to an overestimation of transpiration by as much as 81%, which may cause large uncertainties in water budgets at the ecosystem and catchment scale. This implies the best-practices for scaling sap flow measurements to the tree- and stand-level involve measuring hydraulic flow at various depths within the conductive tissue.

While evaluating the effects of VRH treatments on canopy transpiration and understory evapotranspiration, this study showed that tree-level transpiration was the highest among trees in the 55D treatment, followed by 33D, 55A, 33A and CN plots (Chapter 3). Vapor pressure deficit (VPD) was a major control or driver of transpiration in all VRH treatments during periods of low precipitation. However, transpiration was more closely coupled with photosynthetically active radiation (PAR) in the unharvested or control plot. Overall, study results suggests that dispersed or distributed retention harvesting where more than half of the trees are retained (55D plot or 55% basal area) provides favourable environmental conditions for forest growth with reduced competition of trees for water as shown by enhanced transpiration.

In the understory study (Chapter 4), the results revealed a positive relationship between thinning intensity, understory vegetation, and therefore understory evapotranspiration. The contribution from understory vegetation was more pronounced in the dispersed thinning treatments, when compared to the aggregated. Canopy transpiration contributed to 83 % of total evapotranspiration in the un-thinned control plot and 58, 55, 30, and 23 % for the 55D, 55A, 33A and 33D plots, respectively. Overall thinning or retention harvesting treatments contributed to an increase in stand water use efficiency. Our study results suggested that VRH treatments such as 55D that followed a dispersed harvesting pattern resulted in higher evapotranspiration and greater forest productivity. Furthermore, a balance of contributions from both the canopy and successional understory vegetation and soil, as observed in the 55D treatment, may increase the resiliency of forest to climate change

Overall, these findings will help researchers, forest managers and decision-makers to improve their understanding of water cycling in forest ecosystem and adopt the best forest management regimes to enhance forest growth, health and resiliency to climate change. Our study results support the use of VRH as an efficient silvicultural treatment to restore red pine plantations to native forest types, with the added benefit of promoting atmospheric moisture through canopy transpiration. Our results conclude that VRH treatments that following a dispersed pattern may provide the optimal balance between forest productivity, evapotranspiration and successional growth. Furthermore, a balance of contributions from both the canopy and successional understory vegetation may increase the resiliency of these ecosystems to climate change.

5.2 Study Significance and Future Research

Sustainable water resource management is expected to become one of the most paramount environmental challenges of the 21st century (Rodell et al. 2018). Climate change and extreme weather events may disrupt the terrestrial hydrologic cycle at regional and global scales. This study will contribute to a growing set of work which aims to understand and quantify the forest water cycle and its major components.

The findings of this research highlight aspects that should be addressed in future work at CA-TP31 and other variable retention harvesting stands in Eastern North America and elsewhere. In this dissertation, the eddy covariance method was used to capture understory evapotranspiration. Future work should continue in the pursuit to partition understory ET into physical and biological components such as soil evaporation and transpiration from understory vegetation, respectively. There are several existing methods for partitioning ET, including flux variance similarity partitioning of eddy covariance data

(Scanlon and Kustas 2010), field-based methods (Oren et al. 1998, Wilson et al. 2001) and through the use of models (Paul-Limoges et al. 2020). While all methods have both benefits and limitations (Kool et al. 2014), it is clear that understanding the components of total forest evapotranspiration provides a baseline which may be important for interpreting the influence of climate change on the water budget of plantation forests.

This study also examined the meteorological drivers of canopy transpiration and made comparisons between VRH treatments. Future work should expand this research and examine the meteorological controls on understory evapotranspiration, with a particular focus on soil water balance and its controls. A greater understanding of the spatial and temporal dynamics of soil temperature and moisture, and the response of these variables to thinning prescriptions and hence water cycling would be beneficial to better predict the response of these ecosystems to climate change.

Land surface models are an important component of the regional and global climate models used for climate predictions (Bonan 2008). These models use either empirical or semi-empirical approaches to formulate canopy conductance, which causes large uncertainty in simulated evapotranspiration (Bonan 2008). Moreover, the hydrologic and land-surface modelling community need observed water flux data for testing, validation and further improvements in these models. Some of these models such as the Community Land Model (Lawrence et al. 2007) and the Ecosystem Demography model (Medvigy et al. 2009, Longo et al. 2019) are also used to upscale field-based measurements and ecosystem dynamics to large spatial scales. Therefore, data on observed evapotranspiration and its components will be very important in developing and further improving land surface and hydrologic models and help in accurately predicting the effects of climate change and extreme weather events on the global water and carbon cycles. Our study and observed data will contribute in these efforts.

Finally, future research should include a yearly inventory of live trees and their stem growth (DBH) within each VRH treatment. It will help to gain a better understanding of tree growth and mortality as a result of thinning. This information paired with meteorological and flux measurements will be useful for determining stand productivity, carbon sequestration, and water use. Such data and knowledge will help decision-makers when deciding on best practices for the management of red pine plantations in the region.

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