Water Dynamics in the Understory of a Pine Plantation Forest After Variable Retention Harvesting

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Research

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Abstract

Background: Variable Retention Harvesting (VRH) is a silvicultural technique applied to enhance forest growth, and restore forest stands to closely resemble their natural compositions. This study used sapflow and understory eddy covariance flux measurements to examine the impacts of four different VRH treatments on 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.

Results: Study results showed a positive relationship between thinning intensity and the growth of understory vegetation, and hence enhanced evapotranspiration. The contribution to evapotranspiration from understory vegetation and soil was more pronounced in the dispersed thinning treatments, as compared to the aggregated. Overall, canopy transpiration contributed to 83% of total evapotranspiration in the un-thinned control plot and 55, 58, 30, and 23% for the 55A, 55D, 33A and 33D plots, respectively. The thinning or retention harvesting enhanced the water use efficiency in all treatments.

Conclusion: Our results suggest VRH treatments that follow a dispersed harvesting pattern may provide the optimal balance between forest productivity and evapotranspiration or stand water use. Furthermore, a balance of contributions from both the canopy and successional understory vegetation and soil, as observed in the 55% retention harvesting 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.

Background

Forest ecosystems play a significant role in global water and carbon cycling through evapotranspiration (ET) and photosynthesis 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). As the climate is changing and global forest cover is decreasing, 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 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).

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 into its components in different VRH treatments in pine forests.

Methods

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 Global Fluxnet as well. 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 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.

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

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 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.

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 as a reference system due to the similar stand age and density as that of CA-TP31. Further details of the CA-TP39 instrumentation are given in Peichl et al. (2010), Beamesderfer et al. (2020) and Arain et al. (2021). The EC_{REF} continuously measure CO_2, LE and H fluxes as well as meteorological (RH, T_a, T_s, θ, PAR) variables during the study period.

Self-manufactured thermal dissipation sap flow sensors were installed in 40 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 treatment-type, 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:

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

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}).

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 1.3 metres off the ground surface 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 (measured using eddy covariance) into its components (GEP_U and RE_U) through the use of R-package REddyProc (Wutzler et al. 2018).

Results

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 (Figure 2). 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. 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 the 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.

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 3c). 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 3a,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). 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).

We observed the opposite trend in plot-level transpiration, with an average of 83% of total ET (Tc + 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 5). 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.

When comparing the reference above canopy ET (ET_{REF}) with the measured ET (ET_U + T_C), values came within 10% accuracy limit. In the CN and 33A plots, ET was overestimated, by an average of 5%, where in the 55A, 55D and 33D plots, ET was slightly underestimated by an average of 9%. Overall, daily average ET reflected ET_{REF}, with the aforementioned components responsible for varying contributions (Figure 6).

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 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 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).

Discussion

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.

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). While there are significant uncertainties with 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.

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.

Conclusion

This study quantified the influence of different forest management (variable retention harvesting) treatments (33 and 55% retention harvesting in dispersed and aggregate forms) on the partitioning of total evapotranspiration in a red pine plantation forest in the Great Lakes region, in Canada. 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 in all treatments. 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.

As forest ecosystems provide numerous ecosystem services such as wood products, carbon sequestration and clean and sustainable water resources, there is growing realization among forest managers and the scientific community to develop and adopt forest management or silviculture techniques that balance wood production and ecosystem service. Therefore, our study will contribute to further advance these goals.

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

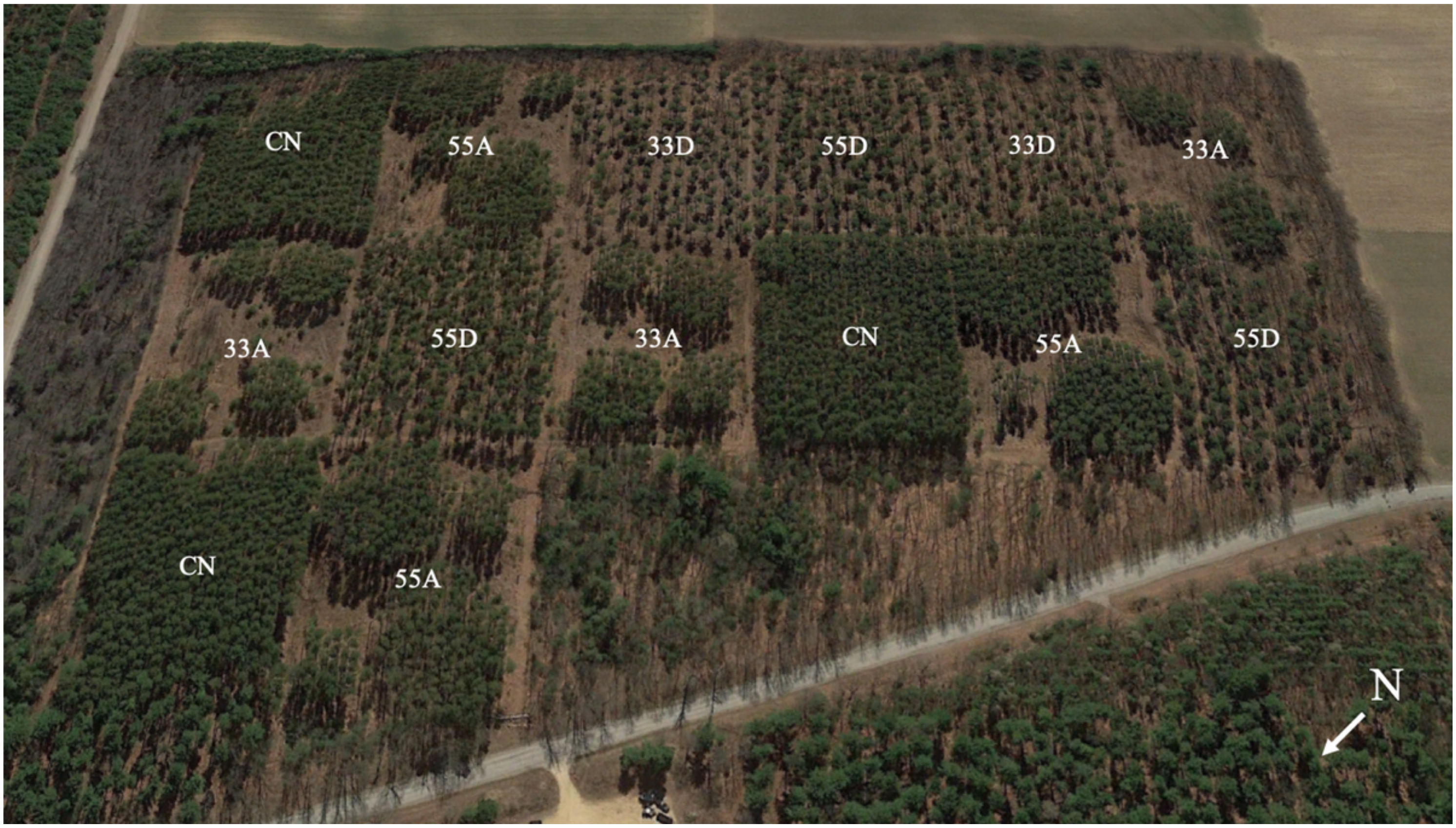

Figure 1

Aerial photograph of the VRH plots at CA-TP31 from Google Maps (2016).

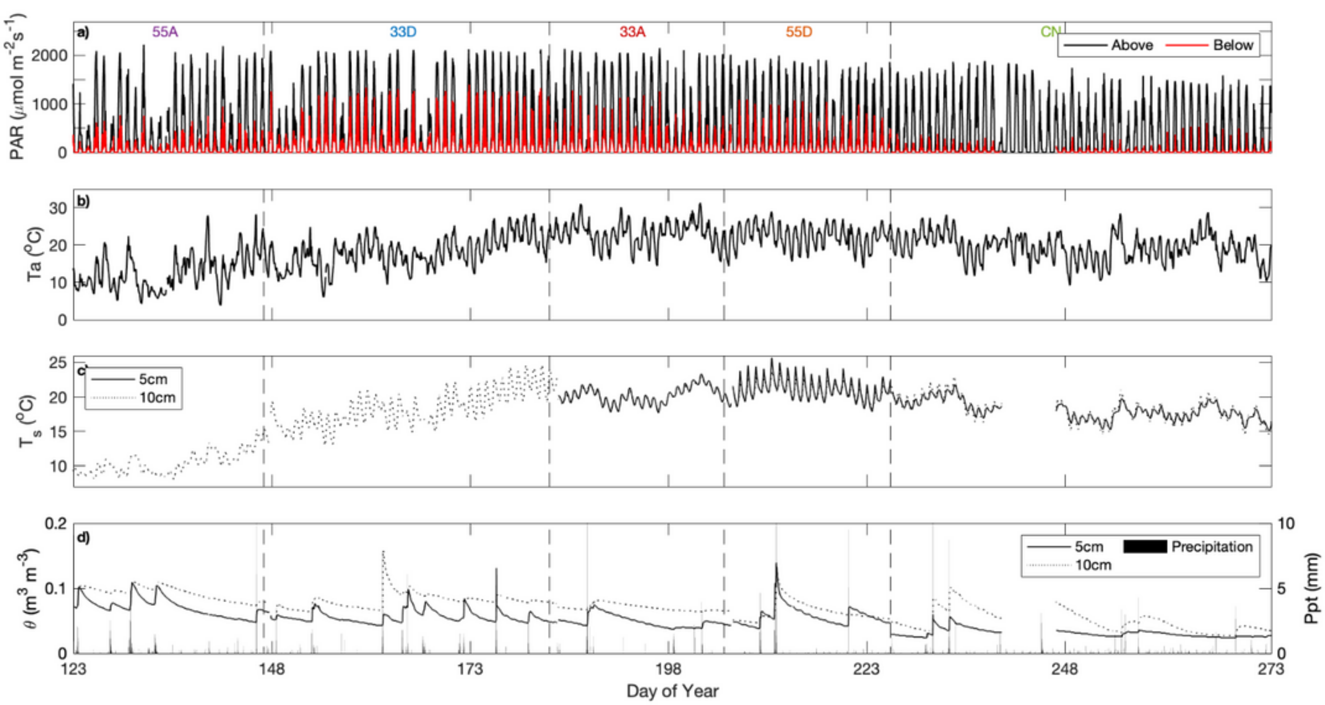

Figure 2

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.

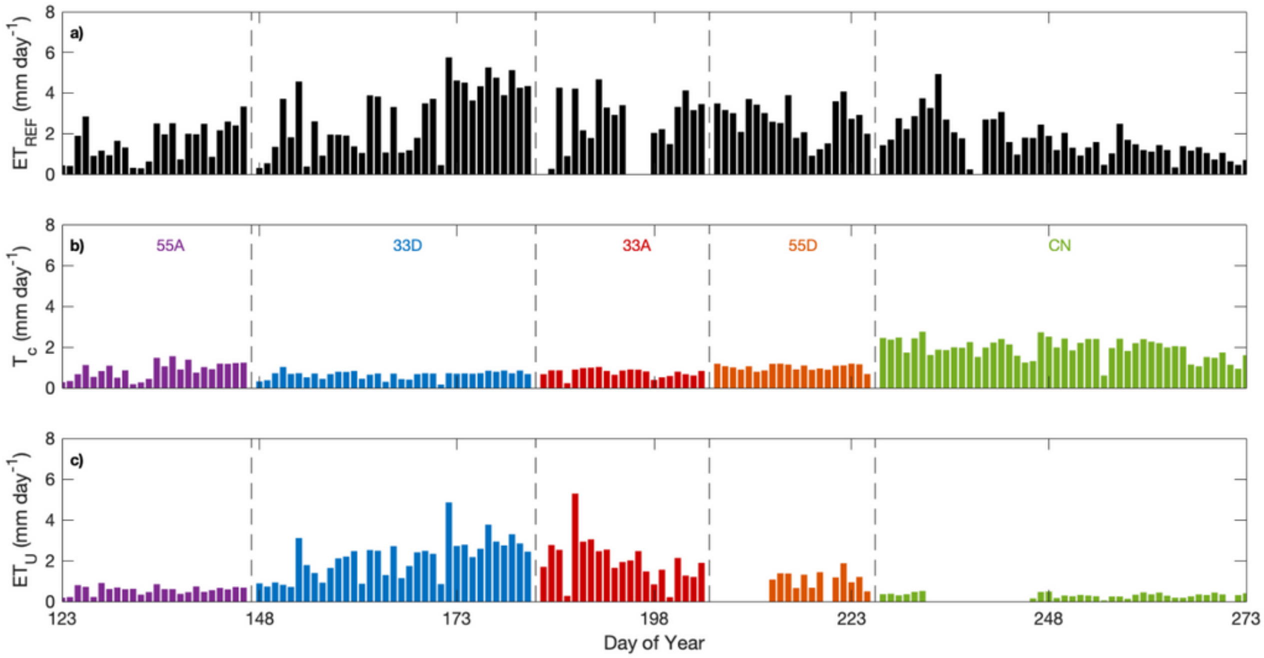

Figure 3

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.

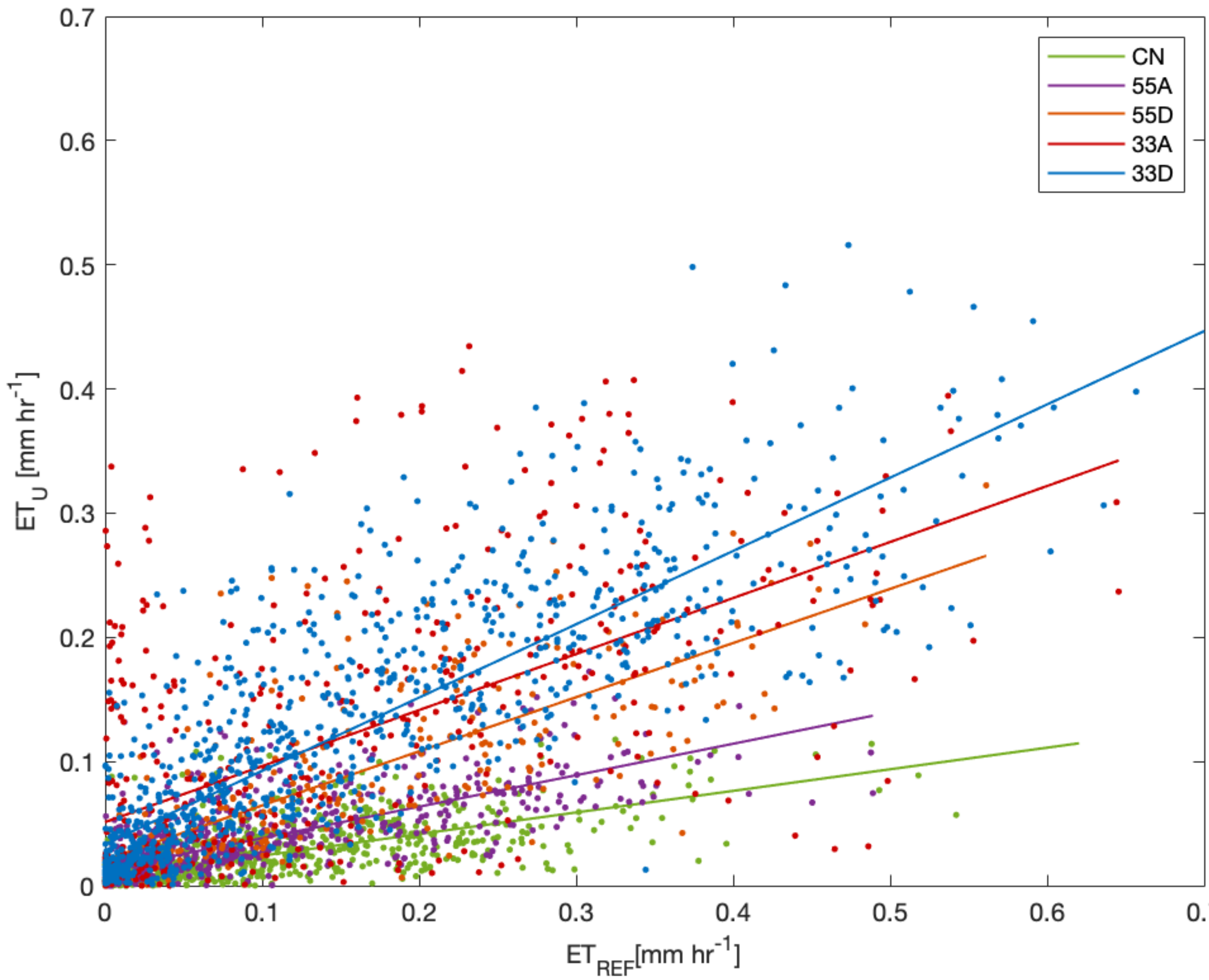

Figure 4

Relationship between hourly evapotranspiration (ET) measured above canopy at TP39 site (ETREF) and below the canopy (ETU) in each of the VRH plots.

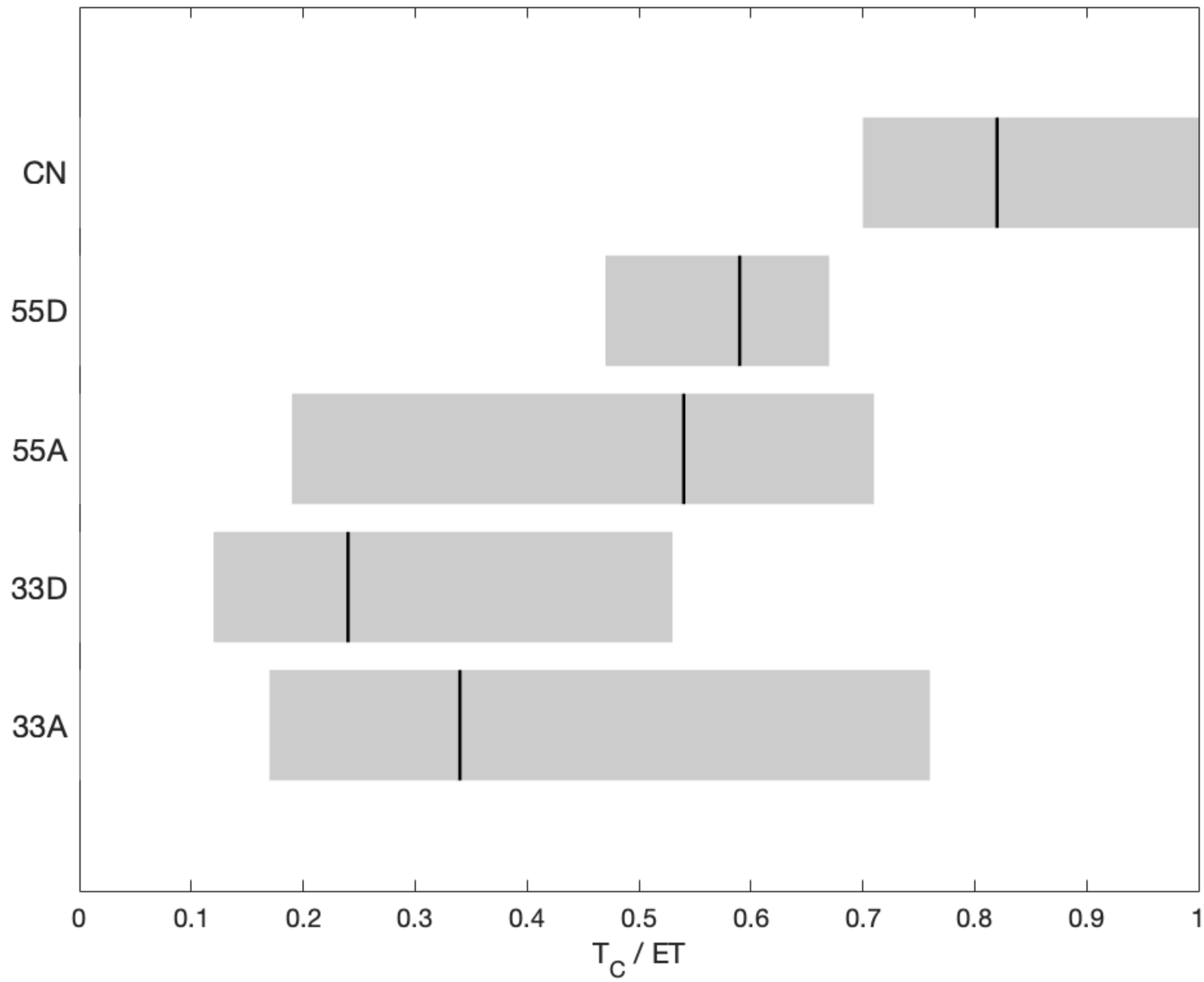

Figure 5

The ratio of canopy transpiration, Tc to total evapotranspiration, ET (Tc + ETU) 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.

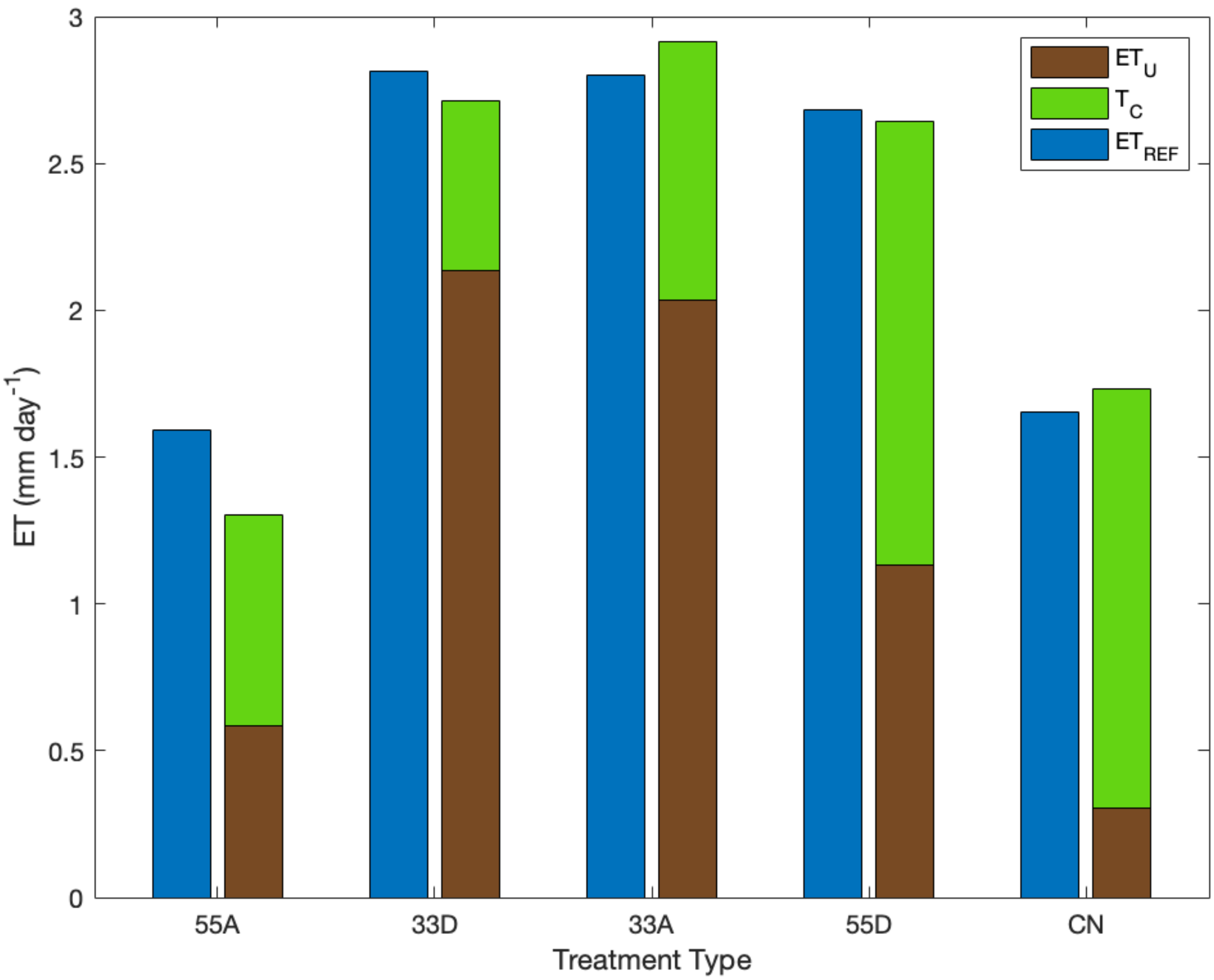

Figure 6

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).