**Dendrometer paper: maybe something like…**



**“Contextualizing the Pacific Northwest’s 2021 Heat Dome Via Climatic Relationships and High Resolution Dendrometry”**

*Summary: Mature and old-growth (MOG) forests are at risk of climate change-related stressors and mortality. This is important because they are crucial for carbon storage, biodiversity, and cultural values. My proposed project will study the short-term and long-term growth patterns of two dominant MOG tree species at the HJ Andrews Long Term Ecological Research site before, during, and after heat waves to quantify hypothesized negative effects of heat stress and compare those effects on different tree ages and species.*

**Introduction  
Research Gap   
Methodology  
Results**

**Discussion and Conclusions**

**Literature**

# INTRODUCTION

*Stating the broader problem and how to study it*

Forests all over the world are sequestering less carbon from the atmosphere due to stressors imposed by anthropogenic climate change, namely drought, heat, pathogens, and more (Davis et al., 2023). Climate change encompasses events such as heat waves in which temperatures are extremely high for acute periods. Heat waves and other climate change-related events are often co-occurring, and they are projected to increase in frequency, duration, and severity over time (Duarte et al, 2016; Dai et al. 2013; Salomón et al. 2022).

For trees, heat-related climate stress can result in physical damage, increased vulnerability to pests and pathogens, reduced carbon uptake, reduced fecundity, hydraulic failure in leaves, water loss, and mortality (Rastogi et al 2018; Kunert et al 2022; Still, Sibley et al. 2023; Allen et al. 2010; Breshears et al. 2021). The effects of drought and heat stress have been globally identified and could completely reshape ecosystems and their functioning (Allen et al. 2010; Hammond et al. 2022). Dendrometry is one method to understand these effects. Dendrometers are devices placed on tree trunks that measure changes in stem size, which happens due to cycles of transpiration (resulting in stem shrinkage) and rehydration and/or permanent incremental growth (resulting in stem swelling). Such measurements are helpful because stem biomass typically accounts for 72-75% of a tree’s biomass (Reich et al., 2014). Automated or electronic dendrometers can measure microscopic changes in stem size at high time frequencies and with great microscopic precision. When paired with site-specific temperature and moisture information, one can use dendrometer data to estimate when water stress and biomass accumulation occur in the tree (Downes et al. 1999; Balducci et al. 2019).

*Zooming in on PNW and MOG*

The American Pacific Northwest (**PNW**) is particularly vulnerable to such changes in climate. Even under low emission scenarios, the PNW is projected to experience increased temperatures, heat waves, wildfires, and droughts. These changes are already being observed, for example via the unprecedented and record-breaking Heat Dome of June 2021 (Heeter et al. 2023). Such changes in climate will further reduce the potential for carbon sequestration despite the region’s high concentration of forests, many of which include mature (80-200 years old) and old-growth (200+ years old) trees (Chang et al. 2023; Swanson 2023). Although they occupy different age classes, mature and old-growth (**MOG**) forests are often studied together since mature forests can grow into old-growth (**OG**) conditions and both classes of trees are quite large. Such magnitude allows, large and old trees store more carbon than their younger counterparts. In over 90% of tree species across all continents, the rate of above-ground biomass growth continually increases with tree size. One study went so far as to estimate that in western US, OG forests, one-third of the forest’s annual mass growth comes from *just* the large trees (with a diameter exceeding 100 cm) (Stephenson et al., 2014). What’s more impressive is that these large trees only make up 6% of the total number of trees in these forests. Put another way, a single large tree gains an average of 103 kilograms of aboveground dry mass each year, which is equal to adding one new 10-20 cm-diameter tree to the forest annually. Globally, the greatest potential for carbon storage exists in areas where forests could be restored into MOG conditions (Mo et al. 2023). This potential accounts for 139 gigatons of carbon.

Two common MOG species native to the PNW are Douglas-fir (*Pseudotsuga menziezii*) (**DF**)and western hemlock (*Tsuga heterophylla*) (**WH**). DF is shade intolerant, often standing 30 meters tall and taller. WH is traditionally viewed as shade tolerant, occupying a forest overstory up to 30 meters in height (Johnson and Swanson 2009). Both species retain their leaves year-round, meaning that prolonged hydraulic deficits could lead to further foliar stress and/or damage (Salomón et al. 2022), exemplifying the importance of studying this phenomenon in these species.

*Getting into specific climate variables*

The importance of MOG carbon storage is a valid justification to invest continual research and protection efforts into such forests. However, MOG research is complicated by concurrent intertwined factors related to each tree’s specific growing environment (Italiano et al., 2023). Fortunately, some factors are consistently more influential than others; such is the case for vapor pressure deficit (**VPD**). The degree to which stomata can conduct leaf-level gas exchange in many ways negatively depends on VPD (Grossiord et al. 2020). In other words, high VPD is associated with reduced photosynthesis and therefore reduced net carbon uptake (Jarecke et al., 2023). At its most severe, photosynthesis reductions due to high VPD can lead to carbon starvation and/or hydraulic failure. Since VPD exponentially increases with increasing temperature, VPD can help uncouple heat and drought-related effects on tree growth (Grossiord et al. 2020; Breshears et al. 2013). For example, especially when there is warming during already warm months such as the later spring or summer, VPD is often the dominant regional driver of drought-stress among forests (Williams et al. 2012). Some studies have even found VPD-induced embolism in young and mature trees despite having abundant soil moisture (Novick et al., 2024). Other times, though, high VPD increases rates of soil moisture evaporation, making soil moisture another key variable to help uncouple heat and drought effects (Breshears et al. 2013; Breshears et al. 2021).

# RESEARCH GAP

The aforementioned importance of MOG research in the context of climate change, especially heat waves, has not yet been thoroughly addressed by current literature. Heat tolerance and the mechanisms that dictate it within both young and old trees are poorly understood because they are easily overshadowed by the droughts that often accompany heat waves (Still, Sibley et al., 2023; Yi et al., 2022). Lastly, heat waves and their effects can vary widely by tree species and age (Wang et al., 2023; Allen et al., 2010). Regardless, heat waves undoubtedly make forest disturbances worse and more deadly. Therefore, expanding knowledge of this area is vital for assessing and predicting ecological risk since it is unlikely that forests can be managed to mitigate the effects of heat waves (Breshears et al. 2021). High-resolution dendrometry analyses have become more refined within the last five years(Knüsel et al., 2021; Haeni et al., 2020; Wickham et al., 2019; Zweifel et al., 2016), but the present work pairs high-resolution dendrometry with climate variables for a new methodological approach to analyzing tree growth. More specifically, the current study serves to meet four research needs:

1. quantify the growth and water use of varying ages and species of trees amidst heat waves,
2. explore the limitations and applications of dendrometer analysis tools,
3. visualize trends in tree growth alongside relevant climatic variables, &
4. decipher whether the heat waves themselves are the primary culprit

affecting the trees’ physiological mechanisms.

# METHODOLOGY

*Location*

To achieve the stated research needs, we rely on high-resolution dendrometry and climate measurements provided by A map of a mountain range

Description automatically generatedthe H.J. Andrews Experimental Forest (**HJA**) (**Figure 1**). The HJA is situated on the western side of the Cascade Mountains near Blue River, Oregon (approximate coordinates: 44.1734° N, 122.1968° W). The area is diverse both topographically and biologically, containing well-documented sites of MOG DF and WH forests. Both species can surpass 500 years at the HJA while younger, secondary forest plantations are younger than 75 years (Swanson 2023). The present study focuses on a few key sites at the HJA, one being the Discovery Tree Trail. This site is located in the moist valley of the HJA and has an elevation of approximately 450 meters. The oldest DF trees in this area are between 450-500 years old and 60-70 meters tall.

Figure 1: Map of the HJ Andrews Experimental Forest's location in western Oregon ("Maps").

*Specific goals*

HJA measurements allows us to compare plant performance before, during, and after the Heat Dome. The Heat Dome thereby acts as a case study for plant stress that is likely to have drastic effects. This will be important considering the novelty of the Heat Dome’s severity (Heeter et al. 2023). While analyzing these measurements, we aim to notice if:

* there are significant differences in growth responses between MOG trees and younger trees
* there are significant differences in growth responses between DF and WH
* growth during and shortly following the 2021 Heat Dome slowed or stopped
* changes in growth are closely correlated with heat waves in the absence of drought
* the timing of a heat wave (i.e., at what point in the growing season) has a significant effect on subsequent growth
* key relationships and/or trends emerge between growth and VPD, soil moisture, air temperature, (soil temp?);
  + We will pay special attention to whether changes in growth are closely correlated with heat waves during periods of normal precipitation—i.e., in the absence of drought. While these variables may not be able to uncover other influences such as wildfire or smoke exposure, they are nonetheless impactful metrics to quantity valuable growth patterns.

*Data origins*

Climate analyses are derived from measurements taken at two HJA meteorological stations then uploaded onto the HJA Provisional Data Portal. Firstly, the Primary Meteorological Station (**PRIMET**), with an elevation of 430 meters, has coordinates of  44.21189300

West: -122.25594100

? Site is close to Lookout Creek, at the bottom of the valley; cold-air drainage . PRIMET records of interest for this study go as far back as 2013 (Daly and McKee 2019 (need to put in WC).

* Daly, C. and W.A. McKee. 2019. Meteorological data from benchmark stations at the Andrews Experimental Forest, 1957 to present ver 36. Environmental Data Initiative. https://doi.org/10.6073/pasta/c021a2ebf1f91adf0ba3b5e53189c84f (Accessed 2024-09-18).

Secondly, the Discovery Tree Meteorological Station (**DSCMET**), with an elevation of 436 meters. North: 44.21658692West: -122.24965723. DSCMET records of interest for this study go as far back as 2016 (Still, Kim et al. 2023). These two meteorological stations are 0.72 kilometers apart and are situated near the southwestern boundary of the HJA.

Still, C. 2023. Meteorological data from the Discovery Tree at the Andrews Experimental Forest, 2015 to present. Long-Term Ecological Research. Forest Science Data Bank, Corvallis, OR. [Database]. Available: http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=MV005. https://doi.org/10.6073/pasta/88040f52946c09c74ac0bfc2a3167717. Accessed 2024-09-18.

PRIMET metrics used for this study include:

* Upper canopy air temperature taken at X meters (is fan aspirated important?)
* Soil moisture taken at 10, 20, 50, and 100 cm depths
* Upper canopy VPD taken at X meters
* Precipitation
* Soil temp?

DSCMET metrics used for this study include:

* Upper canopy air temperature taken at 40 meters
* Soil moisture taken at 10, 20, 50, and 100 cm depths
* Upper canopy VPD taken at 40 meters
* Soil temp?

Automated dendrometry records at the HJA come from two different dendrometer types, both providing data in microns or micrometers. Three Ecomatik DC3 band dendrometers are installed on treesnear the Discovery Tree Trail—1 OG DF; 1 OG WH,and? Moreover,we have access to 4 additional Ecomatik dendrometers beyond this site, as well.

309 10 and 11 are mature and PSME?

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I will have access to 3 automated band dendrometers on OG DF trees, 1 dendrometer on an OG WH tree, and 4 other dendrometers on ca. 70-year-old, secondary growth DF trees. These dendrometers have been consistently collecting data every 5 minutes since 2018, meaning that they have captured one of the most recent and severe heat waves, the 2021 Heat Dome (Still, Sibley et al. 2023). Additional manual dendrometers from DF and WH trees at the Discovery Tree and nearby sites of similar elevation will allow me to determine whether seasonal and annual growth impacts from the heat dome observed in this sample are reflected in a larger population of trees. If time allows, I could analyze automated and manual dendrometry data from a nearby higher elevation (4,500 feet) site, PC17. This site was well above the elevation at which foliage scorch was observed in WH and DF in 2021, and temperatures here remained below 42C throughout the heat wave. These site differences also allow me to ask additional questions regarding the effect of absolute temperature and VPD thresholds versus anomalous combined heat and drought stress on growth.

Directly comparing these species will provide interesting examples of how stress responses can vary based on location in the forest structure.

*R Analyses for Climate Variables*

Critical VPD (Breshears et al. 2013) and temperature (Breshears et al. 2021) thresholds for lethal or sublethal plant stress are routinely discussed in the literature. A new metric of stress degree hours (**SDH**) records the number of hours plants are exposed to temperatures above a set threshold and also records the extent to which the temperature exceeded the threshold. This enables more precise and detailed analyses of plant performance beyond such thresholds (Brackett, Still, & Puettmann 2024). We utilize this metric in this study and also apply it to VPD to introduce stress VPD hours (**SVH**). Our thresholds are as follows:

*Temperature threshold:* ***≥25 ºC***

*VPD threshold:* ***≥3 kpa***

Moreover, HJA data are given based on water year (October-October) rather than calendar year. To preserve the cycles and patterns that exist in the water year, we developed an R function to convert day-of-year values as well as year values to a water year scale. The code for these functions can be found in supplement?.

Most dendrometry records come from trees near the Discovery Tree, so our analyses primarily use DSCMET temperature and VPD values but defer to PRIMET values to fill in missing values.

*R Analyses for Dendrometry*

TNP for point dendrometers only

I will analyze dendrometry data using an R package titled TreeNetProc (**TNP**), which summarizes and cleans data while pairing it with air temperature to provide 6 documents of data in the form of phase statistics, data tables, growth charts, and the R document itself (Knüsel et al., 2021; Haeni et al., 2020; Wickham et al., 2019; Zweifel et al., 2016). The use of this four-year-old package will show what is possible with current technologies in dendrometer analyses while also exhibiting areas where it can potentially be refined in the future. Air temperature will come from the HJA primary meteorological station, Primet. An example of such an analysis in TNP is shown below in **Figure 6**. Air temperature comes from a different met station 40 meters up into the canopy to more accurately reflect the canopy microclimate that affects leaf (Still, Kim et al. 2023). “upper-canopy of forests is known to experience a very different microclimate than the

rest of the forest: it is often simultaneously brighter, hotter, windier, and drier.

The upper canopy also contains most of the leaf area, and because it absorbs most of

the solar radiation, it accounts for the great majority of carbon and water exchanges

in most forests. Critically, this is also the zone where most climate variations and

stress likely manifest. Finally, the upper canopy is the region of the forest that is

sampled by satellite imagery. With intensive canopy microclimate monitoring, we can

provide connections to satell

“

Maybre show some as an example then put the rest in a supplementary attachment

**Figure 6A** displays the raw dendrometer data from tree ID 311 along the HJA Discovery Trail, which I will use in my proposed study. The data are displayed in microns and range from October 2022-October 2023. **Figure 6B** displays the same micron data that has since been processed to show three separate time series during the 2023 growing season: raw data ordered chronologically (gray line); the raw data converted to cumulative growth during the given time frame (green line); and the specific tree water deficit (defined as the difference between that day’s maximum stem radius and stem radius at that specific point) (red line) (Zweifel et al., 2016). Lastly**, Figure 6C** zooms in on just the green and red lines of **Figure 6B**. Non-oscillating increases in values represent permanent radial increment or growth.

|  |  |
| --- | --- |
| A graph with numbers and lines  Description automatically generated | **Figure 6A:** Raw dendrometer data from tree ID 311 at the HJ Andrews Discovery Trail. |
| A graph of growth in different colors  Description automatically generated with medium confidence | **Figure 6B:** Processed dendrometer data from tree ID 311 at the HJ Andrews Discovery Trail (gray line = raw data; green line = cumulative annual growth; red line = modeled tree water deficit. |
| A graph of a growing season  Description automatically generated | **Figure 6C:** Zoomed-in view of Figure 6B. |

The HJA met stations and Discovery Tree also provide other climatological variables that can be compared with dendrometer increments such as soil water content, VPD, relative humidity, and more. For example, the VPD from the same met station and time period described in **Figure 6** is shown below in **Figure 7**. Moreover, I anticipate that the relationships between these variables and tree growth are as shown in **Figure 8** below. I predict that when precipitation is stable and/or close to average, high temperatures will promote an increase in VPD, which will slow or cease tree growth of both species of all ages. For WH, I predict that foliar scorch will also lead to reduced growth. However, I predict that older trees will be more resilient to these effects than younger trees will.

# RESULTS

# DISCUSSION & CONCLUSIONS

Our findings could be beneficial to researchers, land managers, and everyday citizens alike by allowing them to better understand and predict tree responses to heat and drought stress by combining short-term and long-term growth data and climatological data all in one synthesis. While not comprehensive, our results provide a high-resolution view of tree growth at the HJA. Consequently, this work serves to provide a framework whereby future studies can similarly look at high-resolution growth responses of trees alike to define growth variation in the future for other species, ecosystems, and times.

Make mention of future work on smoke effetys and soil profile

# SUMMARY OF ABBREVIATED TERMINOLOGY

PNW = Pacific Northwest

MOG = mature and old-growth

OG = old-growth

DF = Douglas-fir

WH = western hemlock

VPD = vapor pressure deficit

HJA = HJ Andrews Research Forest

PRIMET = Primary Meteorological Station

DSCMET = Discovery Tree Meteorological Station

SDH = stress degree hours

SVH = stress VPD hours

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