Research Proposal for Master's Thesis
Oregon State University
College of Forestry
Forest Ecosystems and Society
VERSION 4 (signed off version)

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"Old Trees, New Climate: How Do Douglas Fir and Western Hemlock Respond To Heat Waves?"

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.

BACKGROUND, MODELS, AND BROADER SIGNIFICANCE

General background

Forests all over the world are sequestering less carbon from the atmosphere due to stressors imposed by anthropogenic climate change, namely drought, heat, increased pathogens, and more (Davis et al., 2023). Climate change encompasses events such as acute periods of extremely high temperatures, also known as heat waves (Filewood and Thomas 2013). Heat waves and other climate change-related events like drought are often but not always co-occurring, and they are projected to increase in frequency, duration, and severity as time continues (Duarte et al, 2016; Dai et al. 2013; Salomón et al. 2022). Heat-related climate stress can severely negatively affect trees resulting in physical damage, increased vulnerability to pests and pathogens, reduced carbon uptake, hydraulic failure in leaves, water loss, and mortality (Rastogi et al; Kunert et al; Still et al. 2023; Allen et al. 2010). 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). Even under low emission scenarios, the Pacific Northwest (**hereafter PNW**) is projected to experience increased temperatures, heat waves, wildfires, and droughts, thereby further reducing the potential for carbon sequestration despite this region being replete with forests relative to the rest of the country (Chang et al. 2023).

This is especially worrying for mature and old-growth (**hereafter MOG**) trees because they are unusually impactful as climate change buffers, disproportionately housing both carbon and a myriad of plant, animal, and fungal species (Swanson 2023). Mature forests are between 80-200 years and old-growth (**hereafter OG**) forests are older than 200 years (Cohen et al., 1996). Many researchers study MOG forests together despite their separate age classes (Strittholt, DellaSala, and Jiang, 2006). Studying MOG forests together can allow researchers to estimate the future of OG coverage since mature forests could grow into OG conditions if given adequate protective measures by forest managers or government policies. Moreover, both mature and old-growth trees are large, especially Douglas-fir (*Pseudotsuga menziesii*) (**hereafter DF**).

Due to their size, 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

Commented [Gb1]: New sentence to clarify grouping of mature and old growth

Commented [Gb2]: Split these sentences as Mark suggested to separate the ideas of old trees providing carbon storage AND carbon sequestration

Commented [Gb3]: Added a statistic rather than "almost all"

Commented [CS4]: Do you mean a single large old tree adds on average the equivalent of one 10-20cm tree each year?

Commented [Gb5R4]: Yes, I have since added new details to this sentence.

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. These details of MOG carbon storage are an important motivation to protect such forests, especially when some publications in the past claimed that younger forests are inherently more productive than older ones (Cohen et al., 1996).

In addition to their productivity, OG forests are lauded for their contributions to biodiversity. Some wildlife species spend part or all of their lives in MOG forests, most famously the threatened northern spotted owl (Johnson and Swanson 2009). OG forests can additionally serve as living museums due to their advanced age in a way that cannot be replaced by plantation forests, as OG forests add a cultural and recreational value to these forests. The distribution of MOG forests in the lower 48 US states is shown in **Figure 1A. Figure 1B** adds an ordinal scale to show the range of MOG forests in these areas (DellaSala et al., 2022).

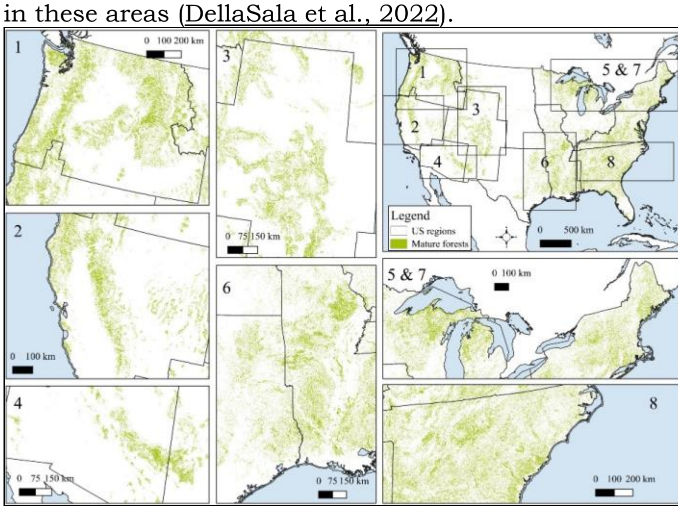

Figure 1A: Spatial distributions of MOG forests in the contiguous US with the PNW depicted in Box 1 (DellaSala et al., 2022)

Commented [SC6]: not sure what you mean by this statement. as the young trees mature and become old growth they will eventually be just as productive as the old trees are now (all things being equal).

Commented [Gb7R6]: I changed this sentence to be more clear

Commented [MS8]: I agree with Chris here, this statement doesn't do any productive work for you. The second growth stands on the HJA mostly approaching that magically 80 year number, in the 55-70 year range. So if you wanted to you could talk about the combined contribution to carbon stores from conserving MOG and from managing older previously logged second growth forests for transition to MOG structure. But with current focus on MOG you are better off just hitting delete on this part of the sentence, I think. Probably more productive would be to mention that this carbon strategy is dependent on the continued health and productivity of MOG forests in the face of climate stressors - if these forest tip over from sinks to sources the carbon challenge becomes that much greater.

Commented [CS9]: specifically OG and not MOG forests?

Commented [Gb10R9]: MOG indeed!

Commented [SC11]: Is it federally endangered, and not just threatened?

Commented [MS12R11]: Still just threatened officially.

Commented [PM13]: See also the MOG spatial distribution mapping that Andy Gray worked on. It suggests a somewhat larger extent of MOG nationally.

Commented [Gb14R13]: I could not find this resource. If you could send it my way I'd be very appreciative!!

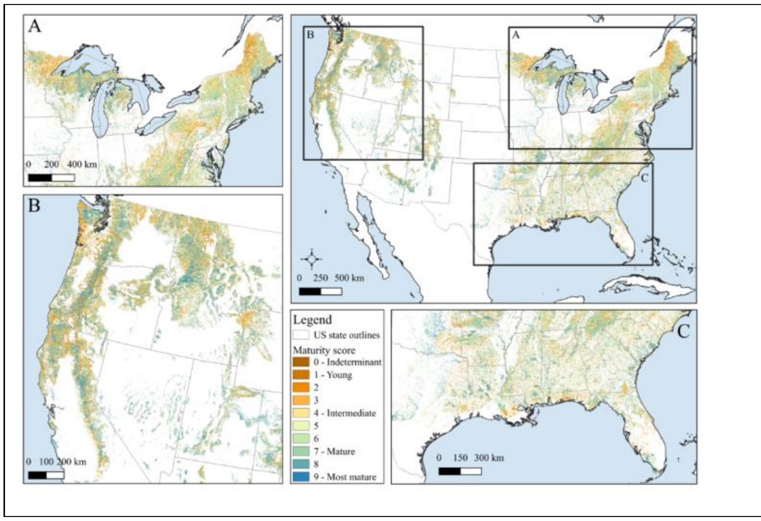

Figure 1B: Range of forest maturity in the contiguous US with the western US shown in Box B (DellaSala et al., 2022)

MOG forests in the contiguous US make up nearly 36% of all forest structural classes, and they are primarily in the western part of the country (DellaSala et al., 2022). This makes sense considering that most American MOG forests were removed with the influx of European colonization for settlement or agriculture, thus provoking federal protection for many remaining MOG forests by the time settlers made it to the Pacific coast (Johnson and Swanson 2009). In the PNW specifically, 72% of original OG conifer forests have been lost since European settlement, leaving the region with 4.67 million hectares of OG conifer forest and 4.76 million hectares of mature conifer forest (Strittholt, DellaSala, and Jiang, 2006).

Commented [CS15]: Just OG or including mature forests as well?

Commented [Gb16R15]: MOG, and I have updated the sentence with more detail with a better citation to support the new figure in 1B

Commented [MS17]: This timing seems a bit off to me. We were hammering MOG forests well into the 1980s.

Commented [Gb18]: New sentence to add a contextualizing statistic

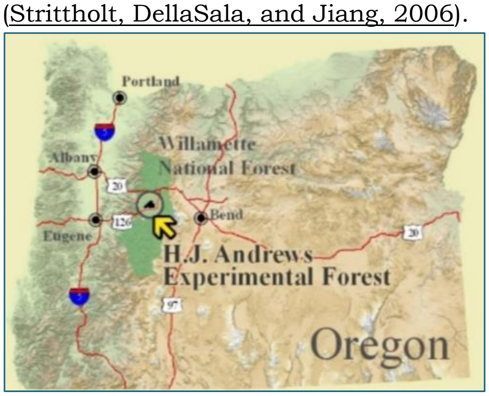

Figure 2: Map of the HJ Andrews Experimental Forest's location in western Oregon ("Maps").

The H.J. Andrews Experimental Forest (**Figure 2**) (**hereafter HJA**) contains several well-documented sites of continuous OG forests. LTER sites are unique for their holistic, interdisciplinary, and collaborative approaches to demystifying both short-term and long-term issues in ecology such as those proposed in this present project (Jones and Driscoll 2022). More information HJA is described below in "Proposed Methodology."

Commented [SC19]: I think I would use different language here. Like "asking and addressing importan science questions"

Because of the mounting stressors climate change imposes on forests, it is important to predict the future of climate-tree relationships so that researchers can plan accordingly. Future climatic variables are modeled in **Figure 3**. Data are from the Climate Toolbox and show how three parameters vary from historical values under RCP 8.5 "business as usual" high emissions (Hegewisch and Rangwala). The three selected parameters are maximum daily temperature, number of days above 86°F, and vapor pressure deficit (original units kPa) times 100. Vapor pressure deficit (**VPD**) is the difference between the vapor pressure of the air at saturation and the actual vapor pressure of the air (Grossiord et al., 2020). Plants will close their stomatal pores to minimize water loss during periods of high VPD like droughts and heat waves. While increases in all three parameters have been observed since the start of the 21st Century, **Figure 3** shows how these increases will continue to break historical records and result in widespread heat and moisture stress and possibly plant mortality. The figure shows a distinctively sharp increase in the deviation from historical VPD values between 2050 and 2080.

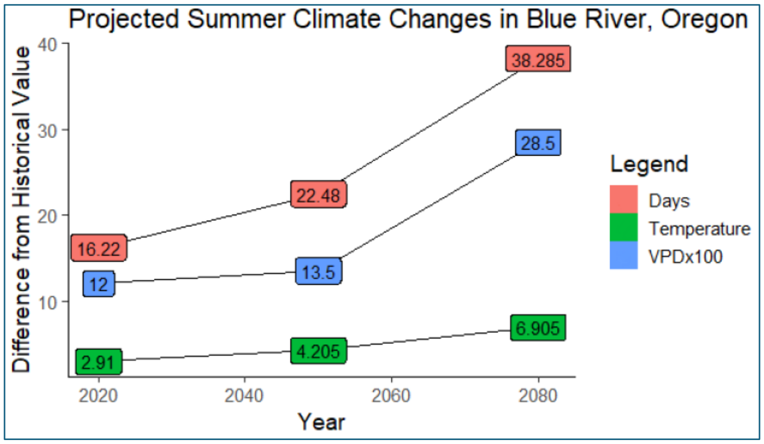

Figure 3: Projected differences in maximum daily temperature, number of days above 86 °F, and 100 times the vapor pressure deficit (original units kPa) compared to historical values in Blue River, Oregon (Hegewisch and Rangwala).

Every plant has a specific water use efficiency (**WUE**), but stomatal conductance and carbon assimilation are directly related to one another regardless of WUE. In other words, high VPD can be associated with reduced photosynthesis and therefore reduced net carbon uptake (Jarecke et al., 2023). 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). However, drought is not the only concerning factor affecting VPD. Some studies have even found VPD-induced embolism in young and mature trees despite having abundant soil moisture (Novick et al., 2024). Temperature strongly and non-linearly affects VPD and soil moisture, which also affect transpiration rates. Warmer air has a greater capacity to hold moisture, thereby increasing the saturation vapor pressure.

Commented [AL20]: What are the units for the y-axis for Fig 3? Percentage? I see the units for the individual variables in the legend, but please clarify the numbers in the tick marks on the y-axis itself.

Commented [Gb21R20]: There aren't really united since each variable is different. I suppose value? I'm not sure how best to fix this and would love some feedback!

Commented [SM22R20]: You could make this a figure with three y axes and spell out the units for each dataset. I can't tell you how to do that in R, but it isn't too rough to do it in programs like sigmaplot. Or just add it to the legend labels. VPDx100 is really the only one that is a bit confusing.

Commented [LA23R20]: If the y-axis is percentage, then adding a percent symbol would suffice (e.g. "Difference from Historical Value (%)"

Commented [SC24]: This seems a little odd. A typical mean daytime VPD would be around 1.5-2 kPa, or 15-20 hPa.

Commented [SC25]: VPD is the difference between the water vapor pressure in the air and its value at saturation given that air temperature

Commented [Gb26R25]: I have since changed this sentence and added some after.

Commented [Gb27]: Added phrase for clarity

Commented [SM28]: This turn of phrase is a bit confusing to me. You are setting this up for the next sentence which is the other negative effect of VPD on trees, so it feels like the order of what is affecting what is off here.

Commented [SC29]: Really temperature is the most important factor affecting VPD - the actual water vapor content of the atmosphere does not vary that much across a season but temperature does and it is non-linearly related to the saturation vapor pressure. So really VPD is a temperature story.

For this reason, looking at VPD may be helpful to uncouple heat and drought-related effects on tree growth.

RESEARCH GAP

As with many ecological topics, it is challenging to disentangle overlapping processes that work together to affect heat stress and ultimately tree growth (Italiano et al., 2023). Nonetheless, there is a severe lack of research on MOG trees in the context of heat waves. Heat tolerance and the mechanisms that dictate it within both young and old trees are poorly understood because they are easily overshadowed by aforementioned co-occurring events such as drought (Still 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). Therefore, there is a need to: **A)** use field methods to quantify the growth and water use of OG trees amidst heat waves on a species level, and **B)** decipher whether the disturbances themselves are affecting those physiological mechanisms. Given the established value of MOG trees and the dangers of heat waves, the findings of a study addressing the interactions between the two would be of great benefit to researchers, land managers, and everyday citizens alike. However, the interactions between trees and climate are often species-specific. Many parts of the PNW, namely western Oregon and Washington, have mesic OG conifer forests dominated by DF and western hemlock (*Tsuga heterophylla*) (**hereafter WH**) (Johnson and Swanson 2009). Focusing on these species therefore is relevant and timely. More information about these species and the proposed site are detailed below in “Proposed Methodology.”

Based on the research precedent established above, it would be useful to merge the aforementioned research needs into one study in a way that has not yet been done.

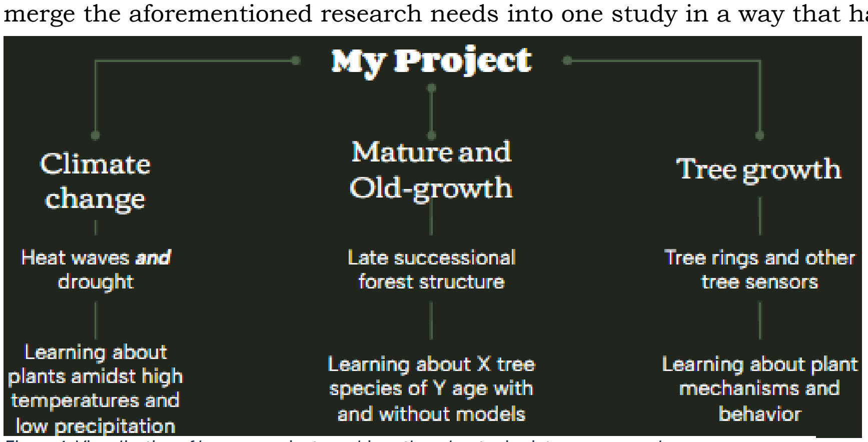

Figure 4: Visualization of how my project combines three key topics into one research area.

Commented [SM30]: Don’t you also need soil moisture to trying and uncouple these? You have that at DT.

Commented [SC31]: A good paper to read and cite is this one:

New Phytologist (2021) 231: 32–39 doi: 10.1111/nph.17348

Commented [SM32]: If feels like in the prior sentence you were setting yourself up to contrast effects for old and young trees, but then the next sentence you go back to OG trees only.

Commented [SC33]: very awkward phrasing

Commented [Gb34R33]: Fixed!

Commented [Gb35]: Added sentence

Commented [Gb36]: Added new and less incorrect ideas

Figure 4 visualizes this approach. While there are studies that focus on climate change, MOG forests with and without models, and dendrology / dendrochronology, we can better understand how these three variables interact with one another to jointly affect how trees grow. It is important to concurrently collect live data to methodologically ensure model accuracy and identify nuances between forest types and species. This is especially true considering the novel methods and data to work with. The climate trends we are currently observing in the PNW—such as the Heat Dome of June 2021—are unprecedented and likely to have drastic effects on small-scale and large-scale plant stress (Heeter et al., 2023).

Moreover, 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). Dendrometers are devices placed on tree trunks that measure changes in stem size. Using dendrometers and tree cores to ask and answer questions related to stem growth is important 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 circumference or radius at high temporal resolution (sub-hourly). Stems can shrink when losing water to transpiration and swell when rehydrating or adding permanent increment or growth. Electronic dendrometers can detect these shrinking and swelling events, often with a resolution down to 1 micrometer or less. When paired with site-specific temperature and moisture information, one can use dendrometer data to estimate when water stress and biomass accumulation is occurring in the tree (Downes et al. 1999; Balducci et al. 2019). At the HJA, both manual and electronic dendrometers have been collecting data for years and therefore will show changes in tree diameter during heat waves such as the 2021 Heat Dome (Still et al. 2023).

Commented [LA37]: dendrology is arguably a tool, not a variable. I suggest saying "how these three topics interact" instead.... or, even better, keep variables but clarify/specify which variables related to climate change you will examine with dendrology tools.

Commented [SC38]: Kind of a funny sentence. What is "live data"?

Commented [SM39R38]: I think if you reframe this whole paragraph with the idea that there is no obligation whatsoever to present your study as a completely novel blend of methods you can make it less awkward and more to the point. I feel like with rare exceptions when researchers go down the path of claiming that their approach is unprecedented it detracts from the overall proposal rather than aiding it. I think if you focus on the problem and how your study can contribute to understanding the problem, regardless of whether the overall approach is completely novel or tried and true, the framing will be more compelling, not less.

Commented [Gb40]: From Mark: Manual dendrometers are not sensors as typically defined. Devices might be a better term that encompasses all dendrometers. Precise isn't usually applied to time unless you are talking about an atomic clock. High temporal resolution is jargony but accurate. All the automated dendrometers can go to a measurement increment well below 30 minutes. At HJA we have a mix of 5, 15 and 30 minute collection, which is based more on power demand and datalogger storage than on capacity of the sensing system.

Commented [Gb41]: From Mark: I wouldn't use phases. Your last two can and do happen concurrently. Also, under shrining/swelling there is another important source - bark expansion/contraction.
In our climate, most of the bark contraction happens in the early to mid summer and most of the wet up and expansion happens in the fall and early winter. Most of the contraction is masked by growth and the fall/winter swelling is primarily a deferred signal of earlier growth.
In the peak dry season internal water loss and recovery likely accounts for most or all of the daily circumference osscillations that are not producing a net positive increment for the day. But there is likely a period in the dry season before a full growht shutdown where the daily growth increment is masked by incomplete rehydration.
The main point is that there is a fair amonut of fuzzines ...

Commented [Gb42R41]: Done! Added new stuff here to clarify.

Commented [Gb43]: From Mark: Maybe, depends on the heat wave definition. Didn't have any automated dendros that caught the 2017 heat wave which is #2 in HJA history. There have been some tamer heat waves in other years. Your tree core study will have a more complete selection of heat waves to choose from, but ...

Commented [Gb44R43]: Reworded!

RESEARCH QUESTIONS AND HYPOTHESES

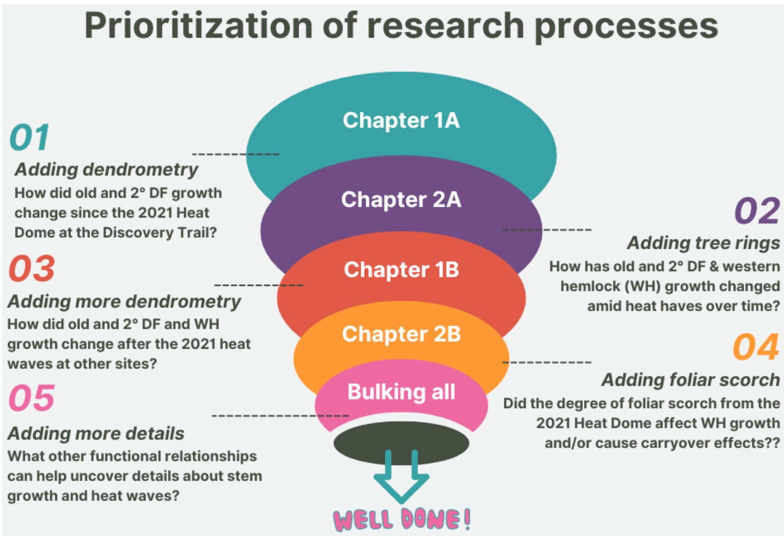

Figure 5: Flowchart demonstration my priorities for research questions in this project.

Figure 5 to the left establishes the priority of questions that will dictate the proposed master's project. Answering these questions will allow us to better understand DF and WH responses to heat and drought stress by combining short-term and long-term growth data and climatological data all in one synthesis. Each proposed component will broadly provide data from which we can predict how trees might grow under future conditions. While not comprehensive, this proposed work is nonetheless a high-resolution view of tree growth at the HJA which allows for methodological refinement of dendrometry and tree ring records. Consequently, if my work is successful, it will provide a framework whereby future work can similarly look at high-resolution growth responses of old and young trees alike to define growth variation in the future for other species, ecosystems, and times.

More specifically, my proposed questions are as follows:

- Chapter 1:
  - **General question: How did the 2021 Heat Dome affect short-term and subsequent year growth of DF and WH at the HJA?**
    - **Specific question 1A:** Are these growth changes similar or different between MOG trees and younger trees?
    - **Specific question 1B:** Do growth changes persist during periods of normal precipitation—i.e., in the absence of drought?

Commented [Gb45]: Added figure and reworked the entire section.

Commented [LA46R45]: Nice figure!

Commented [Gb47]: From Mark: Probably want to be careful with this term. The metrics you are using are related to physiology but they are indirect. From this term, I would assume you are using pressure bombs and some of the other ecophys gizmos Chris has his lab, not tree cores and dendrometer measurements.

Commented [Gb48R47]: I have changed "physiological" to "growth"

Commented [SC49]: This is just around the Discovery Tree, yes?

Commented [SC50]: meaning due to heat waves?

Commented [SM51R50]: In general heat waves occur in the dry season and there may be weeks or months of dry weather after the heat wave before fall rains start up again (in 2021 in was 2+ months). So is your question whether the growth impacts from a (or "the") heat wave persist into the fall rainy season? Or persist into the spring of the following growing season when moisture should not be a limiting factor on early growth? Normal probably isn't quite the right term here, as dry as a bone is pretty normal for August. Miserably wet is normal for December, but there shouldn't be any real growth happening then (can be quite a bit of bark expansion though).

- **Specific question 1C:** Is there a relationship between growth and other climatic variables such as VPD or soil moisture based on Discovery Tree and Primet data?

- Chapter 2:
  - **General question: How have heat waves of varying timing and magnitude influenced same year and subsequent year growth of DF and WH at the HJA across the last few decades?**
    - **Specific question 2A:** Are these growth changes similar or different between MOG trees and younger trees?
    - **Specific question 2B:** Specific question 1B: Do growth changes persist during periods of normal precipitation—i.e., in the absence of drought?
    - **Specific question 2C:** How did the degree of foliar scorch from the Heat Dome affect growth of WH?
      - Is there a relationship between proportion of scorched crown volume and growth rate?
      - Did growth significantly differ among scorched vs. non-scored WH trees?
    - **Specific question 2D:** Does the timing of a heat wave (e.g., early vs. late summer) affect growth response?

PROPOSED METHODOLOGY

The proposed study will take place at the HJA. It is situated on the western side of the Cascade Mountains near Blue River, Oregon (approximate coordinates: 44.1734° N, 122.1968° W). The area encompasses over 15,800 acres (6,400 hectares), which includes the Lookout Creek watershed. HJA is jointly operated by the US Forest Service's Pacific Northwest Research Station, the Willamette National Forest, and Oregon State University (Swanson 2023). It is as diverse in its topography as it is in its biota. Elevations range from 380-1600 meters (1,247-5,249 feet). Native forest species (DF and WH) can surpass 500 years in age while the younger plantations are the result of clearcutting practices of the 1960s (Swanson 2023). In the more mesic areas of the HJA, the fire regime tends to be infrequent with high intensities.

DF trees rely on larger canopy disturbances like mixed severity fire for successful regeneration since they are shade intolerant. This is why they often occupy the peak of a forest overstory, standing 30 meters tall and taller. WH, on the other hand, is traditionally viewed as a shade-tolerant species occupying a forest overstory up to 30 meters in height (Johnson and Swanson 2009). WH and DF are both evergreen conifers. The years-long retention of their leaves means that prolonged hydraulic deficits could lead to further foliar stress and/or damage (Salomón et al. 2022). Directly comparing these species will provide interesting examples of how stress responses can vary based on location in the forest structure.

Commented [Gb52]: From mark: I think you can come up with a less generic hypothesis here. This framing makes it sound like heat wave is an on-off switch. But heat waves are a question of degree, and can occur both when soil moisture is limiting and when it is not. From this framing we might expect the exact same growth response from the 2017 or 2022 heat waves as we got in 2021, which was completely off the charts and produced scorched foliage. Did this climate anomaly represent a totally different form of stressor, or just a more extreme version of the stress we are seeing in the summer heat waves that are within the historic range of variability but at the upper edge?

Commented [Gb53R52]: I took out the hypotheses for now

Commented [SM54]: I think this might require a slightly different general question than question 1, which is focused on the 2021 heat wave. To look at this relationship you need at least a few years of data.

Commented [Gb55]: From mark: You can't really answer the long-term question here (you will only have heat scorch data from 2021 and growth up through a portion of the 2024 season). But you can answer whether there is a carryover effect from the 2021 heat wave on subsequent growth and whether that effect is related to the proportion of scorched crown volume.

Commented [Gb56R55]: Fixed!

Commented [SC57]: I wonder if this can be moved to Chapter 1? Or do we not have enough WH trees banded around the DT to answer this?

Commented [SM58R57]: Correct, not a good enough sample size.

Commented [SC59]: might be hard to say it's all heat since heat wave summers are often dry summers. Will depend a lot on when the heat waves hit. See paper by Salomon et al. The 2018 European heatwave led to stem dehydration but not to consistent growth reductions in forests ...

Commented [Gb60R59]: Got it! I've since changed this hypothesis

Commented [Gb61R59]: From mark: What about carryover effects on growth? What about timing of heat wave and mixed effects of drought and heat. Thresholds of heat/drought?

Commented [Gb62]: From mark: I probably wouldn't go with fire return intervals. The more we learn about the fire regime the less the concept of return intervals seems to make sense. I would talk about it as a mixed severity ...

Commented [SM63]: It is probably more of an overall life history strategy comparison. For WH you could look at individuals in different canopy positions and not have the complicating factor of different species, but when ...

Chapter 1 Methodology

To answer the question reserved for chapter 1, I will use shrinking and swelling data (in microns or micrometers) from automated dendrometers (Ecomatik DC3) already installed on OG and secondary-growth DF and WH trees near the Discovery Tree Trail in the Andrews. This site is located in the moist valley of the Andrews and has an elevation of approximately 1,475 feet. The oldest DF trees in this area are between 450-500 years old and 60-70 meters tall. 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 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.

I will analyze dendrometry data using an R package titled TreeNetProc (**hereafter 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, 2023).

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

Commented [SC64]: You should also use the automated band dendrometer data (Ecomatik) as there are more of those records than there are of TOMST point records

Commented [MS65R64]: For 2021 heat wave the tomst will be useless, as they were not installed at DT yet. Could be used for specific analysies that aren't dependent on capturing the 2021 heat wave

Commented [SC66]: always report in SI units (m, not ft)

Commented [Gb67]: From mark: long way of saying this

Commented [Gb68R67]: fixed

Commented [SC69]: how many younger trees of each species?

Commented [AL70]: It seems difficult to confidently compare species if you only have dendrometer data for one WH tree.

Commented [Gb71R70]: From mark: I know you have pitched this whole thing at MOG, but you have 4 second growth PSME right there, potentially doubling your sample size. There is also a high elevation site with three MOG DF from 2021. And manual dendrometer data from other trees at DT and all over the place. We should talk more about how to make the most of the available data for the 2021 heat wave question.

Commented [Gb72R70]: Added an acknowledgement of this (albeit vaguely so—Mark I would appreciate some insight on this part)

Commented [SC73]: at PC17 or at both sites?

Commented [MS74]: Previous sentence brings in Pc17, which means you can't say 5 minute anymore. That on ...

Commented [SM75]: Here is where you could really ...

Commented [LA76]: This paragraph is a helpful ...

Commented [Gb77]: From mark: For coring yes, not f ...

Commented [SC78]: always report in SI units (m, not ft)

Commented [MS79]: I pulled this number out of my h ...

Commented [SC80]: An example figure here would ...

Commented [Gb81R80]: Done! This sentence has be ...

Commented [Gb82R80]: I also added two other ...

Commented [SM83]: If you want to dive into this aspe ...

Commented [SC84]: In the next sentence you say you ...

Commented [MS85R84]: There might be a good reas ...

Commented [SC86]: It's not the prior maximum radiu ...

Commented [AL87]: I'm a little confused about the ...

Commented [Gb88R87]: Added a statement on how ...

on just the green and red lines of **Figure 6B**. Non-oscillating increases in values represent permanent radial increment or growth.

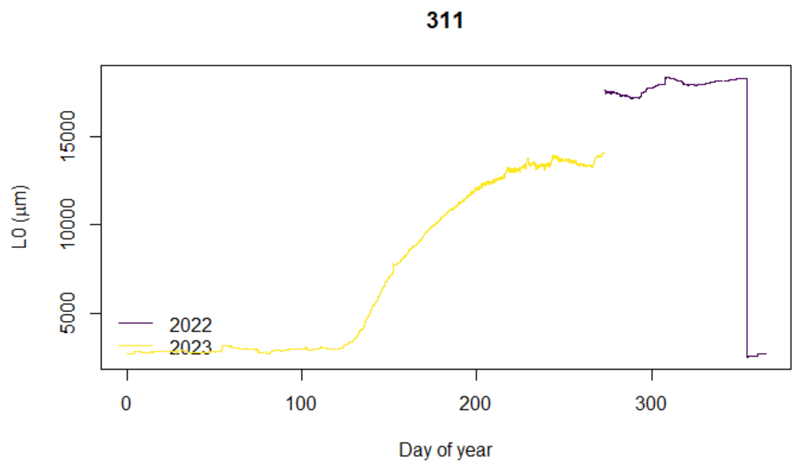

Figure 6A: Raw dendrometer data from tree ID 311 at the HJ Andrews Discovery Trail.

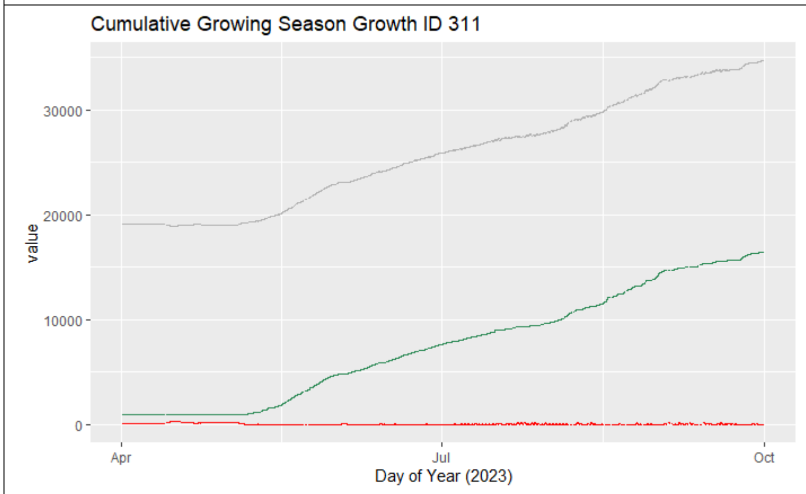

Figure 6B: Processed dendrometer data from tree ID 311 at the HJ Andrews Discovery Trail (gray line = raw data; green line = cumulative annual growth; red line = modeled tree water deficit.

Commented [MS89]: Somewhere here or in text you need to note that steep drop at end of 2022 is a reset of the dendrometer band. Or perhaps don't even show 2022 as it is kind of irrelevant here, and it would be nice if your X axis range on the raw graph was exactly the same as on the processed graph.

Commented [SC90]: I would not order these by DOY. Instead order by date so the 2022 data come first

Commented [SC91]: what are the y-axis units?

Commented [SC92]: Needs to be on a separate plot as the magnitude is so small comparatively

Commented [MS93R92]: Or just do a second y axis on this graph

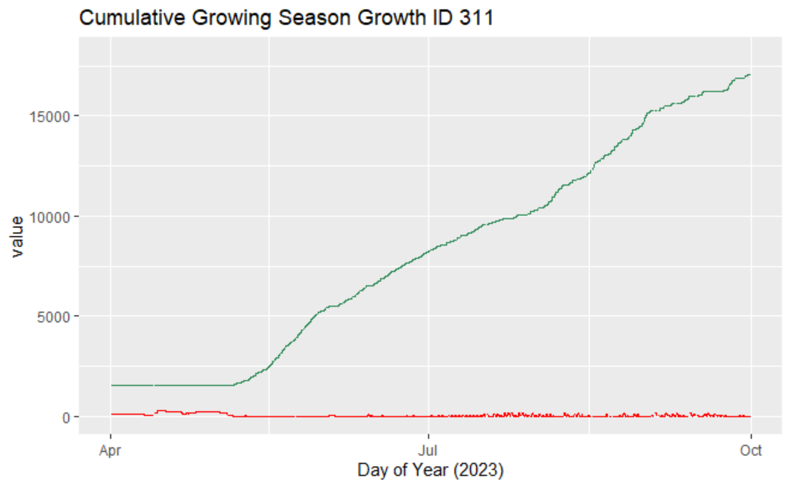

Figure 6C: Zoomed-in view of Figure 6B.

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.

Commented [SC94]: My above comments also apply to this zoomed-in plot

Commented [Gb95]: New figure to answer Loren's request for expected visualization of results

Commented [SM96]: You will probably need to convert this to relative (based on max and min values observed over the period of record) soil water content as there has not been a involved calibration to the specific soil, so you won't be able to infer plant available water except in a relative way.

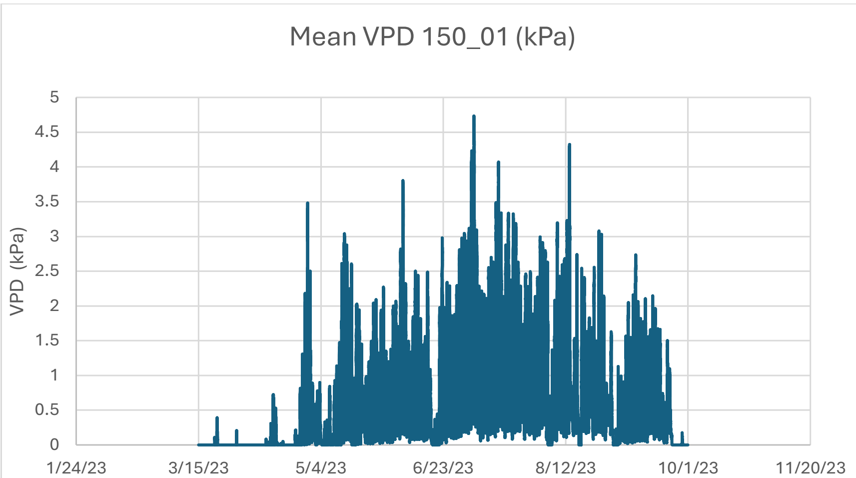

Figure 7: VPD (kPa) from March 15 - October 1, 2023. Data are from Still, 2023.

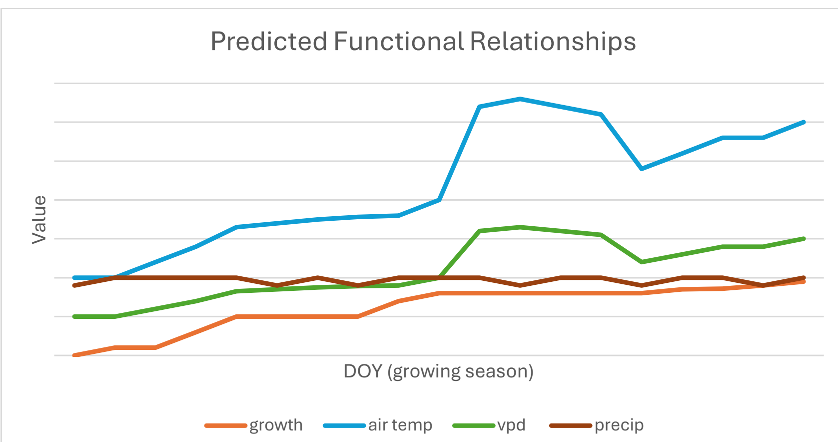

Figure 8: Conceptual model of relationships between tree growth, VPD, precipitation, and air temperature.

Chapter 2 Methodology

To expand the time period covered in my analyses, I will collect tree cores from the same trees used in chapter 1 as well as others (such as a nearby site with an elevation of 2,130 ft) to obtain a longer-term look into water use and stress among these trees, which—when paired with climate data at the area—can give key insights into prior heat wave responses (not just the June 2021 Heat Dome event). Inspired by similar methodologies found in the literature (e.g., Acosta-Hernández et al., 2020). I will aim to take 2 cores from 15

Commented [SC97]: This is from PRIMET? It's not from me.

Commented [SC98]: A functional relationship usually implies your response variable (tree growth) on the y-axis and an explanatory variable like VPD on the x-axis.

Commented [LA99R98]: I agree. This plot show predicted time series. I think plotting what you expect to see can be very helpful, and I encourage you to think a little more about what type of plot would answer your research questions. A time series plot like this could work well, but I'd add a label of "extreme heat event" to the time series to orient the reader. (Then it would also link to your first chapter in a more obvious way). As currently plotted, it looks like you predict growth would flatten for a few years after an extreme heat event?

Commented [SM100]: You won't have the luxury of holding precip constant while temp increases over the growing season. Just doesn't really happen that way in our climate. You could have different combinations of VPD and soil moisture, which reflects the longer term balance between precipitation inputs and evapotranspiration outputs. Which is probably the more interesting comparison in our climate. At a given VPD threshold do we see the same growth impact regardless of soil moisture status, or does it take a combo of high VPD and low soil moisture. You may also be able to find enough situations where temp is similar but VPD is different due to different RH values, but as Chris mentioned above, this is going to be driven more by temp than RH.

Commented [PM101]: Although your sample size might make this impractical statistically, I suggest also using metrics of the competitive environment and social position/tree characteristics for each cored tree as covariates in your analysis.

Commented [Gb102R101]: Added!

Commented [Gb103]: Bulked this section up to provide more methodological details and figures at Loren's request

Commented [SC104]: convert to meters

Commented [SM105]: Adding this here generates confusion I think. Ther most important others in this sentence are the replicates in the DT area that will give enough to really dive into these patterns of heat and drought stress and annual growth, and to tease part the scorch versus overall stress impact from the 2021 heat dome on WH. If you want to allude to the possibility of sampling the RS20 or PC17 site, do it in a sperate sentence that explains what the comparison would add to your analysis - e.g. RS20 is one of the most extreme sites on HJA for soil drought and heat, and RH; Pc17 is a ...

Commented [LA106R105]: Also, an estimated sample size from the 'others' would be useful.

individual trees of each species for a total of 60 cores per site. For each cored tree, I will also record characteristics such as dbh, tree height, elevation. If time allows, it will also be helpful to measure stand-level characteristics such as stand density to try and understand shade levels and site competition. Each core will be collected on-site then returned to OSU for drying, mounting, sanding, and eventually ring counting. Because latewood is added during the summer months—when heat waves are more likely to occur—latewood ring width will be especially valuable, as tree growth often ceases during heat waves and affects the thickness and even occurrence of latewood. Similarly to Chapter 1, Primet and the Discovery Tree will provide the meteorological data necessary for analysis.

The distribution of WH among this site results in varying levels of sun exposure due to gaps in the DF canopy, resulting in a clear gradient of foliar scorch of WH following the 2021 Heat Dome (Mark Schulze, personal communication). I will take special and additional care when analyzing cores from these trees to assess whether the degree of foliar scorch (recorded by M. Schulze) affected growth patterns. While the temperature and duration of exposure required to cause scorch varies by location and species, a general trend is that higher temperatures decrease the amount of time needed to cause foliar damage, which directly affects a tree's capacity for the leaf-level gas exchange that drives photosynthesis (Teskey et al., 2014).

If time allows, an allometric equation could be applied to these ring widths to estimate biomass and carbon accumulation to help quantify the value of trees for carbon storage. **Figures 9A and 9B** below show how one paper displayed these data (Acosta-Hernández et al., 2020).

Commented [SM107]: Tree height is good and we do have a laser you could use. Takes a bit of time. You could also use more relative indices like crown illumination index and relative crown position index.

Commented [SM108]: You could also probably derive some similar metrics from lidar if you don't have time for plots

Commented [SM109]: If you did sample RS20 you might want to expand the met data to include other stations. Or at least use the RS20 understory temp data to get a sense for how much hotter that site was on average than DT. Similar issue for PC17.

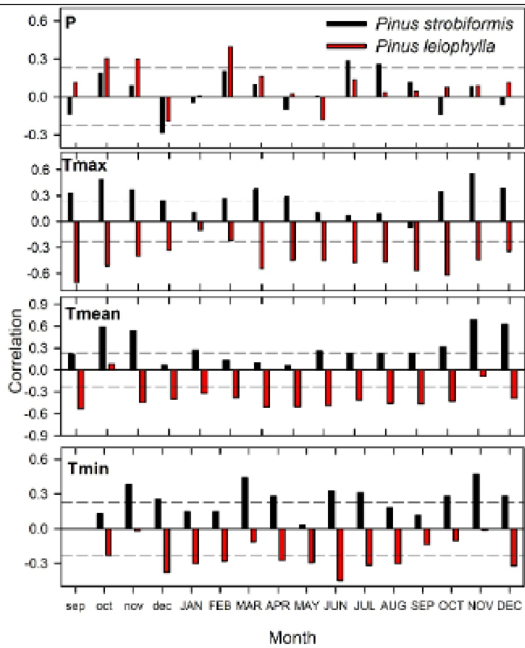

Figure 3. Correlation indexes between carbon accumulation and monthly data of the climatic variables for the two species studied. P = precipitation, Tmax = maximum temperature, Tmean = average temperature, Tmin = minimum temperature. The months in lowercase and uppercase correspond to the months of the previous year and the current year, respectively. The dashed horizontal lines show the $p = 0.05$ level of significance.

Fig. 10A

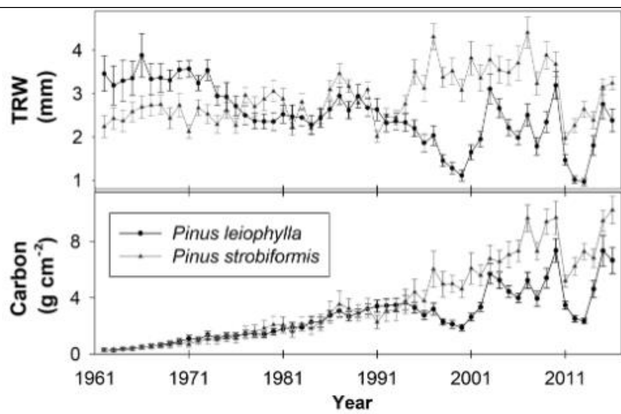

Figure 2. Average trends and standard error (mean ± SE) of the variables annual ring width (TRW) and annual carbon accumulation for the period 1962–2016.

Fig. 10B

Commented [LA110]: In science writing, we generally only show a figure if we also reference it in the text. I can't find a reference to Figure 10A in the text, so I'm a little confused about the 'take home message' of Fig 10A in relation to your proposed work. Are you proposing to use similar correlation indices as shown here? If so, I think you could describe that in text. If you want to make a point that is demonstrated well visually with this figure, please add some text about it in the main text.

TIMELINE

My proposed timeline is available in **Figure 10** below. This timeline accounts for field work, laboratory work, thesis writing, course enrollment, and data analysis. I plan to have collected all relevant data by the end of the summer 2024 field season. I will spend the next year analyzing the data and writing my thesis chapters so that I may graduate by the summer or fall of 2025.

Commented [SC111]: Nice figure!

Commented [SC112]: As we discussed today (May 29) you should update the summer 2024 timeline for collecting cores.

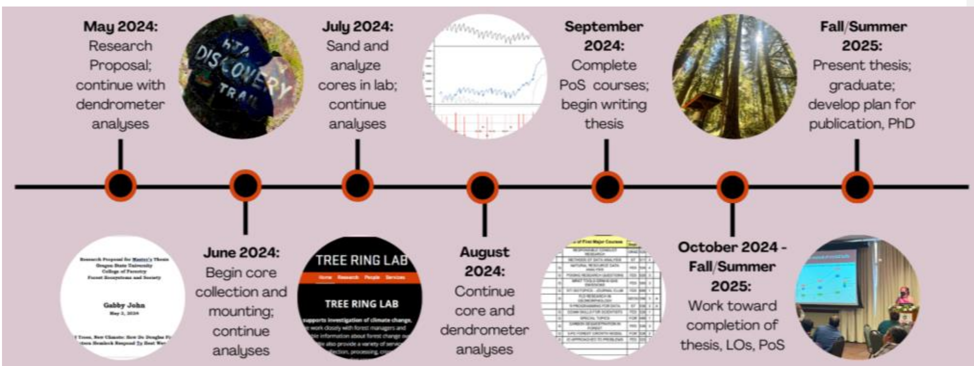

Figure 10: Timeline to achieve proposed thesis project. Made using Canva.com.

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