

Forest Ecosystems and Society Graduate Program Research Proposal Approval Form

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

By signing below, I acknowledge that I have reviewed this research proposal and judge it to be an acceptable and actionable part of this student's degree program.

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GRADUATE COUNCIL REPRESENTATIVE (PRINT)	SIGNATURE	DATE

Please attach a copy of this fully-signed form to your research proposal and submit it to the FES Graduate Program Coordinator in the FES Department Office.

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

Gabby John
May 3, 2024

**“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
Research Gap
Research Questions and Hypotheses
Proposed Methodology
Timeline
Literature

BACKGROUND, MODELS, AND BROADER SIGNIFICANCE

General background

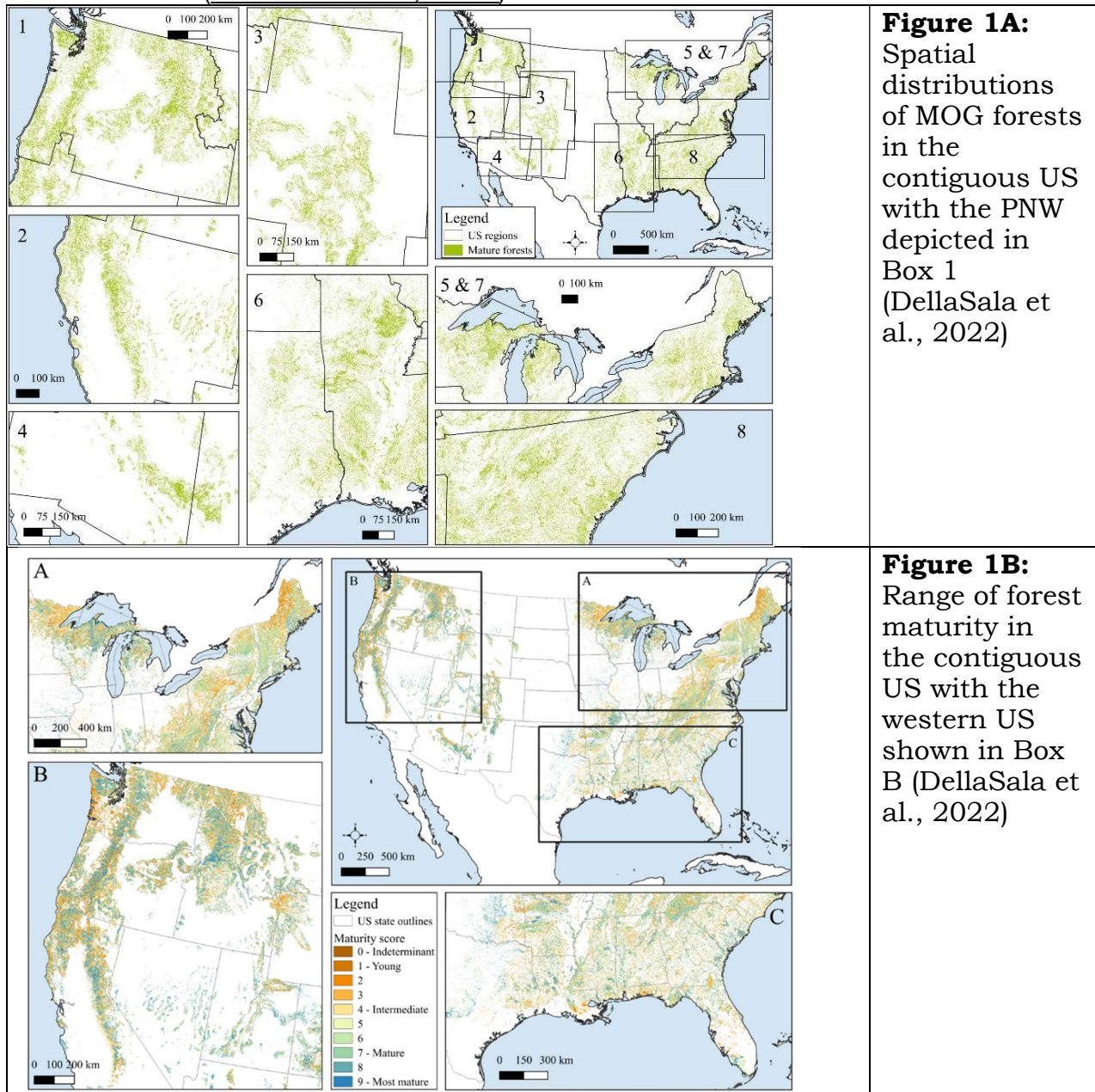
Forests all over the world are sequestering less carbon from the atmosphere due to stressors imposed by anthropogenic climate change, namely drought, heat, increased pathogens, and more ([Davis et al., 2023](#)). Climate change encompasses events such as acute periods of extremely high temperatures, 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 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).



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](#)).



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."

Because of the mounting stressors climate change imposes on forests, it

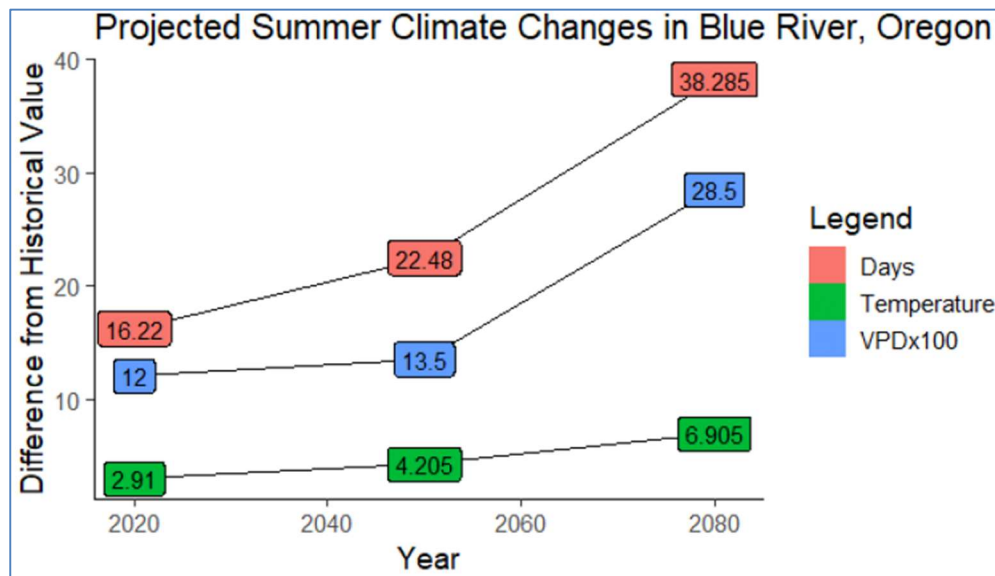


Figure 3: Projected differences in maximum daily temperature, number of days above 86 °F, and 100 times the vapor pressure deficit (original units kPa) compared to historical values in Blue River, Oregon ([Hegewisch and Rangwala](#)).

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.

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. 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.

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).

RESEARCH QUESTIONS AND HYPOTHESES

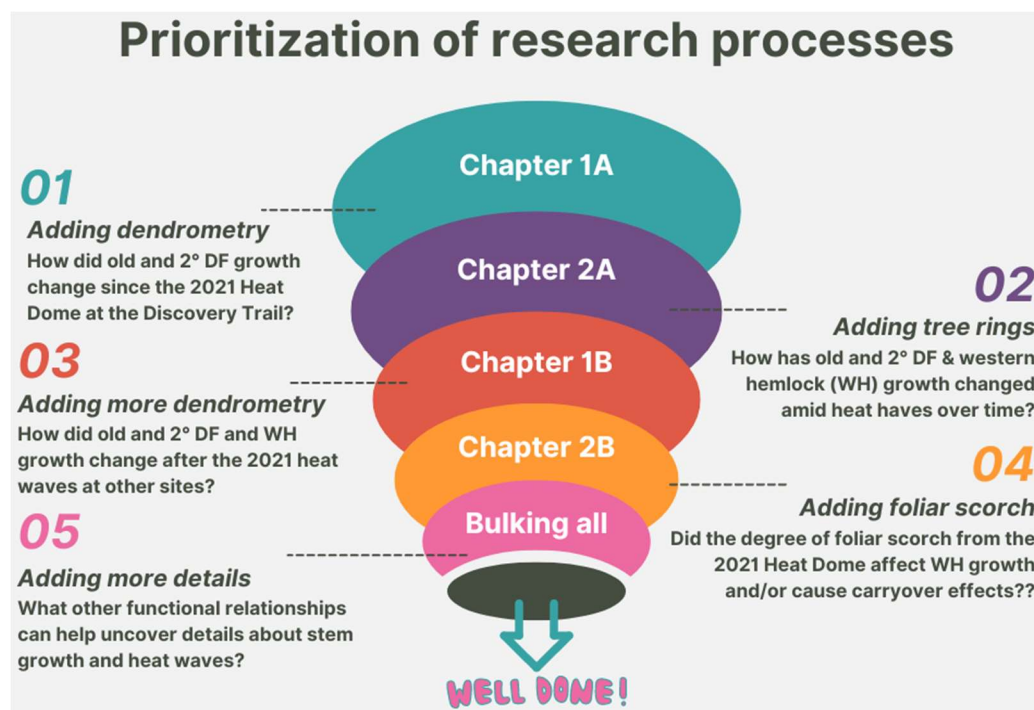


Figure 5: Flowchart demonstration my priorities for research questions in this project.

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?
- **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-scorched 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.

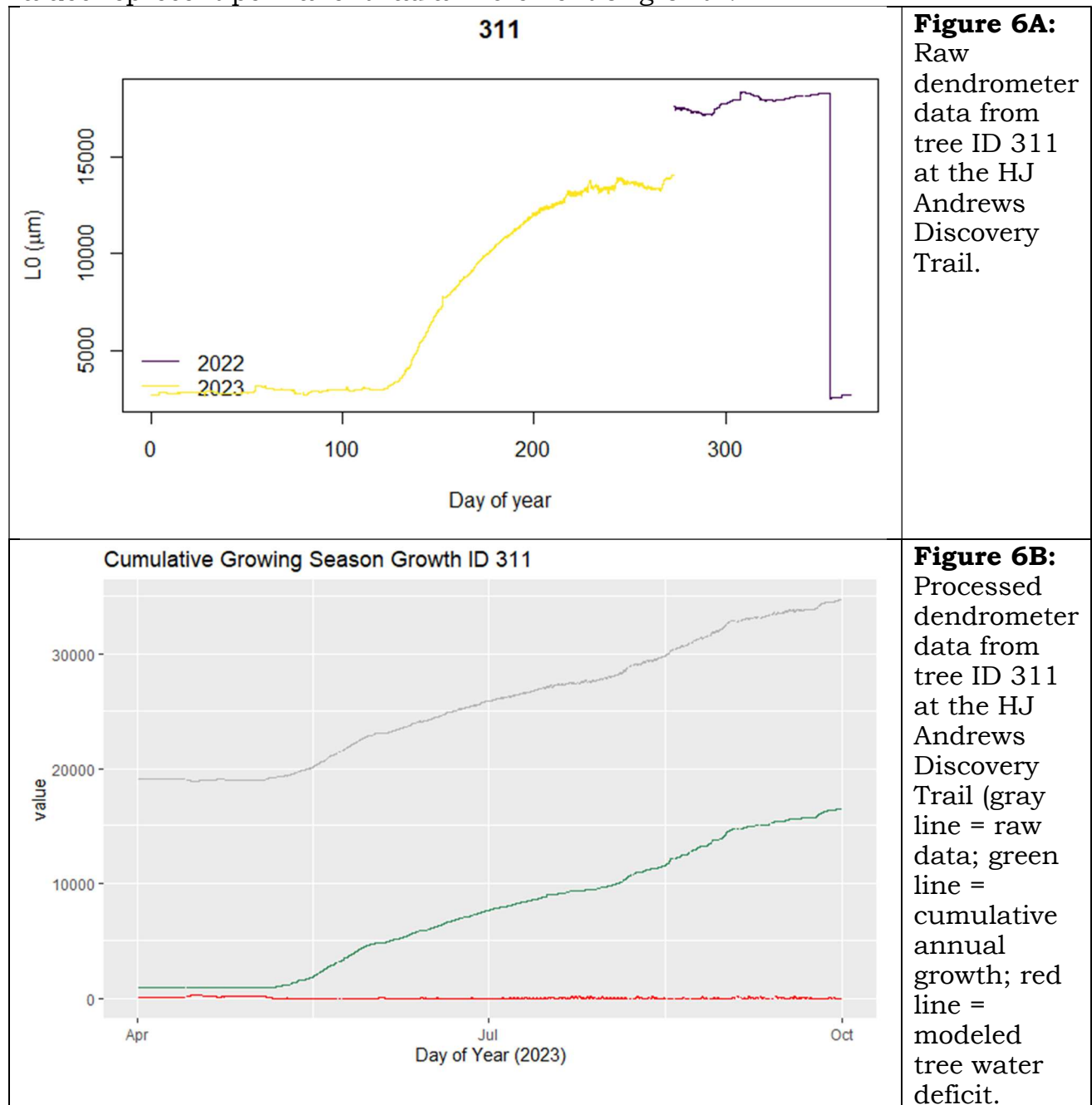
Chapter 1 Methodology

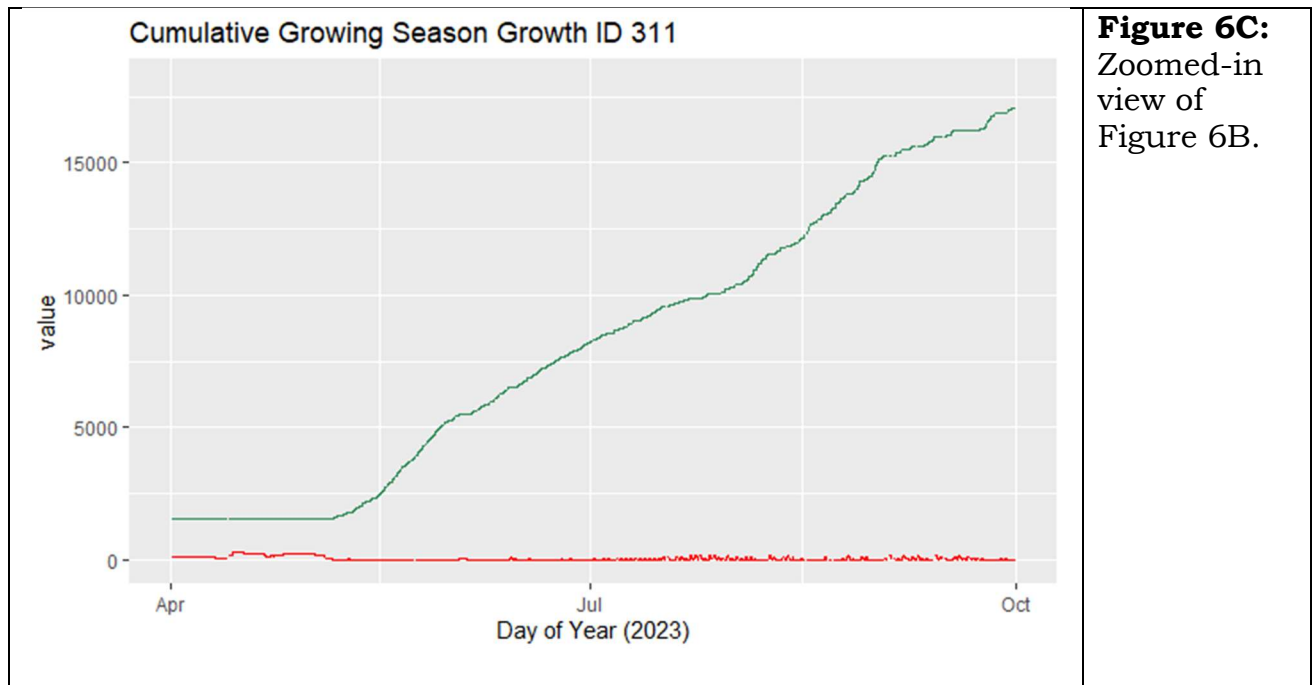
To answer the question reserved for chapter 1, I will use shrinking and swelling data (in microns or micrometers) from automated dendrometers (Ecomatik DC3) already installed on OG and secondary-growth DF and WH trees near the Discovery Tree Trail in the Andrews. This site is located in the moist valley 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 on just the green and red lines of **Figure 6B**. Non-oscillating increases in values represent permanent radial increment or growth.





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.

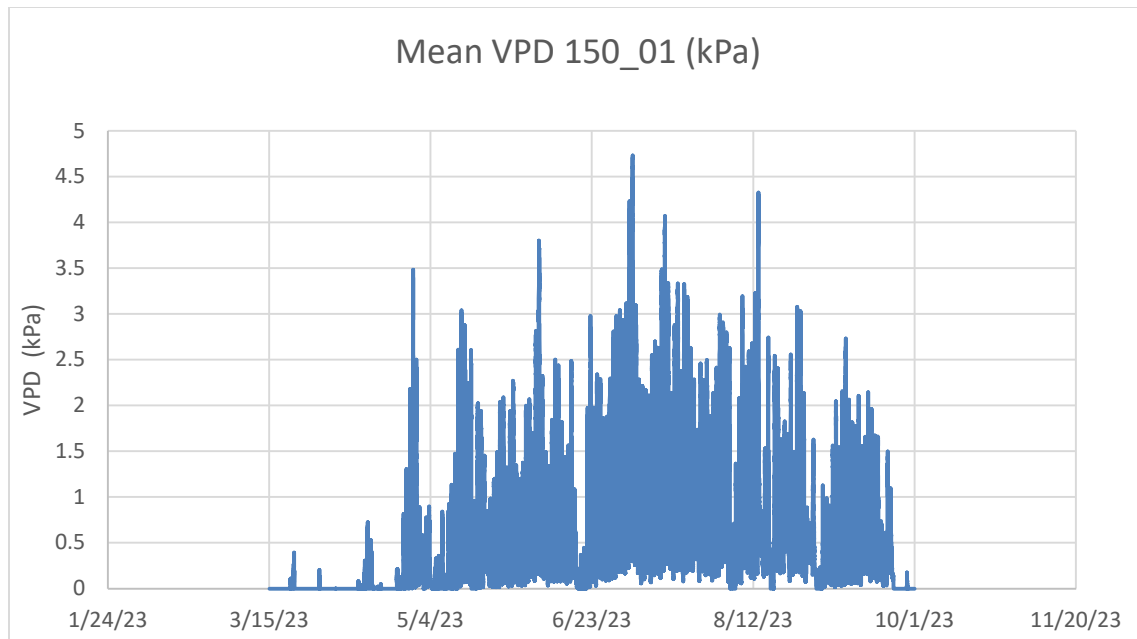


Figure 7: VPD (kPa) from March 15 - October 1, 2023. Data are from Still, 2023.

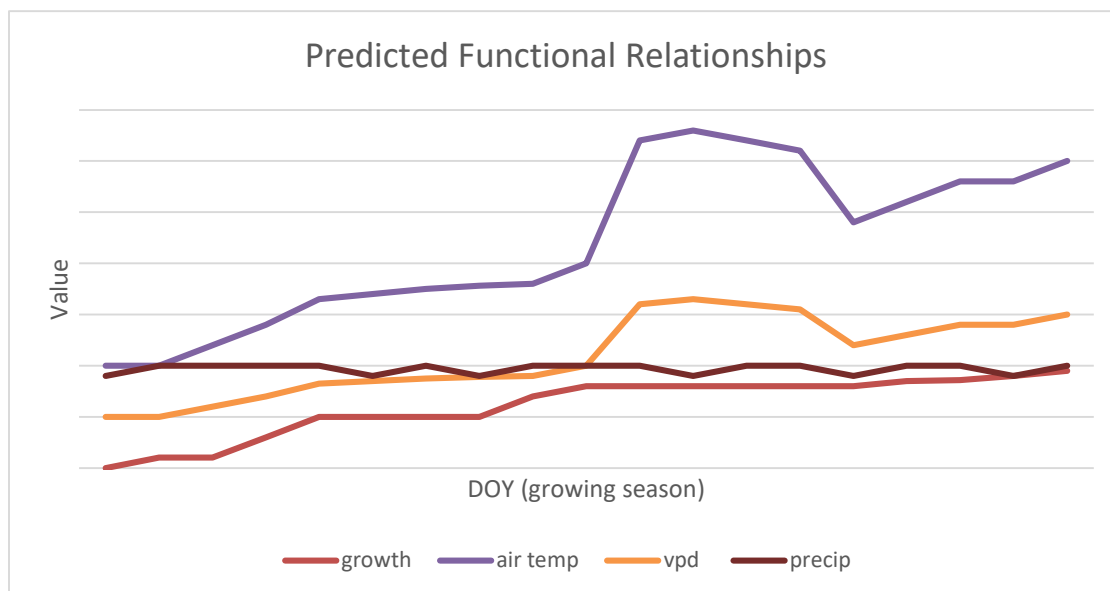


Figure 8: Conceptual model of relationships between tree growth, VPD, precipitation, and air temperature.

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

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).

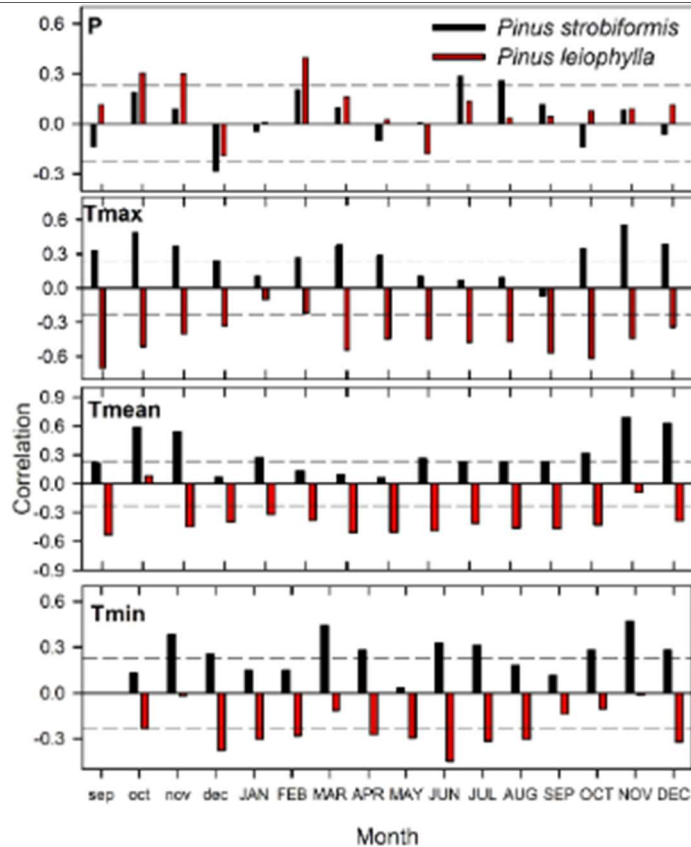


Figure 3. Correlation indexes between carbon accumulation and monthly data of the climatic variables for the two species studied. P = precipitation, Tmax = maximum temperature, Tmean = average temperature, Tmin = minimum temperature. The months in lowercase and uppercase correspond to the months of the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

Fig. 10A

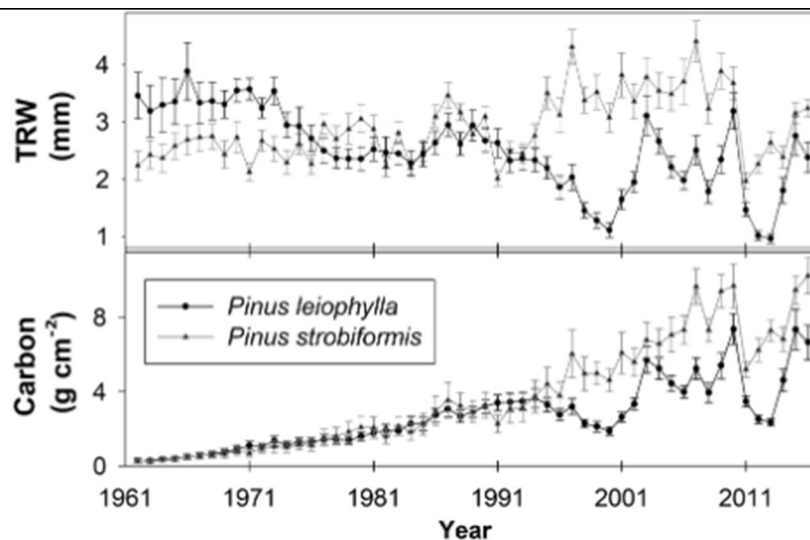


Figure 2. Average trends and standard error (mean \pm SE) of the variables annual ring width (TRW) and annual carbon accumulation for the period 1962–2016.

Fig. 10B

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.

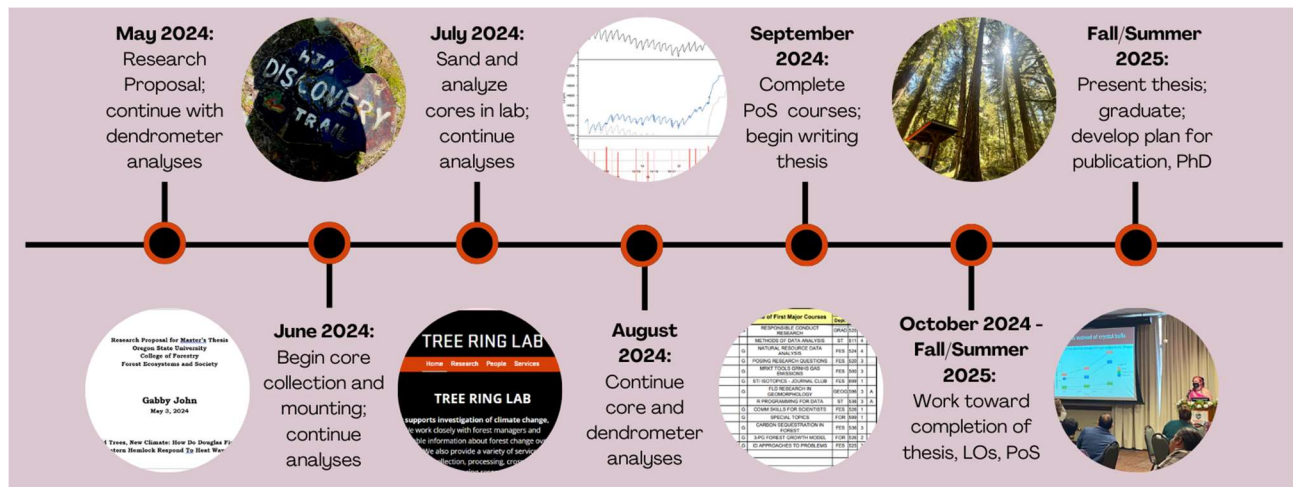


Figure 10: Timeline to achieve proposed thesis project. Made using Canva.com.

LITERATURE

- Acosta-Hernández, AC, Padilla-Martínez JR, Hernández-Díaz JC, Prieto-Ruiz JA, Goche-Telles JR, Nájera-Luna JA, Pompa-García M (2020) Influence of Climate on Carbon Sequestration in Conifers Growing under Contrasting Hydro-Climatic Conditions. *Forests* 11:1134. <https://doi.org/10.3390/f11111134>
- Allen, C. D., A. K. Macalady, H. Chenchouni, D. Bachelet, N. G. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D. D. Breshears, E. H. Hogg, P. González, R. J. Fensham, Z. Zhang, J. Castro, N. Demidova, J. H. Lim, G. Allard, S. W. Running, A. Semerci, and N. S. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259:660–684. <https://doi.org/10.1016/j.foreco.2009.09.001>
- Balducci, L., Deslauriers, A., Rossi, S., & Giovannelli, A. (2019). Stem cycle analyses help decipher the nonlinear response of trees to concurrent warming and drought. *Annals of Forest Science*, 76(3). <https://doi.org/10.1007/s13595-019-0870-7>
- Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rödenbeck, C., Arain, M. A., Baldocchi, D., Bonan, G. B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H. A., Oleson, K. W., Rouspard, O., . . . Papale, D. (2010). Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and

- Covariation with Climate. *Science*, 329(5993), 834–838.
<https://doi.org/10.1126/science.1184984>
- Chang, M., L. Erikson, K. Araújo, E.N. Asinas, S. Chisholm Hatfield, L.G. Crozier, E. Fleishman, C.S. Greene, E.E. Grossman, C. Luce, J. Paudel, K. Rajagopalan, E. Rasmussen, C. Raymond, J.J. Reyes, and V. Shandas, 2023: Ch. 27. Northwest. In *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC. <https://doi.org/10.7930/NCA5.2023.CH27>
- Dai, L., Jia, J., Yu, D., Lewis, B., Zhou, L., Zhou, W., Zhao, W., Jiang, L. (2013). Effects of climate change on biomass carbon sequestration in old-growth forest ecosystems on Changbai Mountain in Northeast China. *Forest Ecology and Management*, 300: 106–116.
<https://doi.org/10.1016/j.foreco.2012.06.046>
- Davis, S.J., R.S. Dodder, D.D. Turner, I.M.L. Azevedo, M. Bazilian, J. Bistline, S. Carley, C.T.M. Clack, J.E. Fargione, E. Grubert, J. Hill, A.L. Hollis, A. Jenn, R.A. Jones, E. Masanet, E.N. Mayfield, M. Muratori, W. Peng, and B.C. Sellers, 2023: Ch. 32. Mitigation. In *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC. <https://doi.org/10.7930/NCA5.2023.CH32>
- DellaSala, D. A., Mackey, B., Norman, P., Campbell, C., Comer, P. J., Kormos, C. F., Keith, H., & Rogers, B. M. (2022). Mature and old-growth forests contribute to large-scale conservation targets in the conterminous United States. *Frontiers in Forests and Global Change*, 5.
<https://doi.org/10.3389/ffgc.2022.979528>.
- Downes GM, Beadle CL, Worledge D (1999) Daily stem growth patterns in irrigated *Eucalyptus globulus* and *E. nitens* in relation to climate. *Trees* 14:102–111. <https://doi.org/10.1007/pl00009752>
- Duarte, A. G., G. Katata, Y. Hoshika, M. Hossain, J. Kreuzwieser, A. Arneth, and N. K. Ruehr. 2016. Immediate and potential long-term effects of consecutive heat waves on the photosynthetic performance and water balance in Douglas-fir. *Journal of Plant Physiology* 205:57–66.
<https://doi.org/10.1016/j.jplph.2016.08.012>
- Filewood, B. and Thomas, S. (2013). Impacts of a spring heat wave on canopy processes in a northern hardwood forest. *Global Change Biology*, 20(2): 360–371. <https://doi.org/10.1111/gcb.12354>
- Grossiord C, Buckley TN, Cernusak LA, Novick KA, Poulter B, Siegwolf RTW, Sperry JS, McDowell NG (2020b) Plant responses to rising vapor pressure deficit. *New Phytologist* 226:1550–1566.
<https://doi.org/10.1111/nph.16485>
- Haeni, M., Knüsel, S., Wilhelm, M., Peters, R. L., and Zweifel, R. (2020). Treenetproc - Clean, Process and Visualise Dendrometer Data. R Package Version 0.1.4. Github Repository.
<https://github.com/treenet/treenetproc>

- Hammond, W.M., Williams, A.P., Abatzoglou, J.T. et al. (2022). Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. *Nat Commun* 13, 1761. <https://doi.org/10.1038/s41467-022-29289-2>
- Heeter KJ, Harley GL, Abatzoglou JT, Anchukaitis KJ, Cook ER, Coulthard BL, Dye LA, Homfeld IK (2023) Unprecedented 21st century heat across the Pacific Northwest of North America. *npj Clim Atmos Sci* 6:1–9. <https://doi.org/10.1038/s41612-023-00340-3>
- Hegewisch, K.C., and I. Rangwala. (n.d.). Future Climate Scenarios web tool. Climate Toolbox. <https://climatetoolbox.org/future-climate-scenarios>.
- Italiano SSP, Camarero JJ, Colangelo M, Borghetti M, Castellaneta M, Pizarro M, Ripullone F (2023) Assessing Forest Vulnerability to Climate Change Combining Remote Sensing and Tree-Ring Data: Issues, Needs and Avenues. *Forests* 14:1138. <https://doi.org/10.3390/f14061138>
- Jarecke, KM, Hawkins LR, Bladon KD, Wondzell SM (2023) Carbon uptake by Douglas-fir is more sensitive to increased temperature and vapor pressure deficit than reduced rainfall in the western Cascade Mountains, Oregon, USA. *Agricultural and Forest Meteorology* 329:109267. <https://doi.org/10.1016/j.agrformet.2022.109267>
- Johnson, K. Norman; Swanson, Frederick J. 2009. Historical context of old-growth forests in the Pacific Northwest--policy, practices, and competing worldviews. In: Spies, Thomas A.; Duncan, Sally L., eds. *Old growth in a new world: a Pacific Northwest icon reexamined*. Washington, DC: Covelo, CA: Island Press: 12-28. Chapter 2.
- Jones, J., and Driscoll, C. (2022). Long-Term Ecological Research on Ecosystem Responses to Climate Change. *BioScience*, 72(9): 814-826. <https://doi.org/10.1093/biosci/biac021>
- Knüsel, Simon, Richard L. Peters, Matthias Haeni, Micah Wilhelm, and Roman Zweifel. 2021. "Processing and Extraction of Seasonal Tree Physiological Parameters from Stem Radius Time Series" *Forests* 12(6): 765. <https://doi.org/10.3390/f12060765>
- Kunert, N., Hajek, P., Hietz, P., Morris, H., Rosner, S. and Tholen, D. (2022), Summer temperatures reach the thermal tolerance threshold of photosynthetic decline in temperate conifers. *Plant Biol J*, 24: 1254-1261. <https://doi.org/10.1111/plb.13349>
- "Maps". (n.d.). Andrews Forest Research Program. <https://andrewsforest.oregonstate.edu/data/map?topnav=157>
- Mo, L., Zohner, C. M., Reich, P. B., Liang, J., De Miguel, S., Nabuurs, G., Renner, S. S., Araza, A., Herold, M., Mirzaghali, L., Ma, H., Averill, C., Phillips, O. L., Gamarra, J. G., Hordijk, I., Routh, D., Abegg, M., Adou Yao, Y. C., Alberti, G., . . . Crowther, T. W. (2023). Integrated global assessment of the natural forest carbon potential. *Nature*, 624(7990), 92-101. <https://doi.org/10.1038/s41586-023-06723-z>
- Novick, KA, Ficklin DL, Grossiord C, Konings AG, Martínez-Vilalta J, Sadok W, Trugman AT, Williams AP, Wright AJ, Abatzoglou JT, Dannenberg MP, Gentine P, Guan K, Johnston MR, Lowman LEL, Moore DJP, McDowell NG The impacts of rising vapour pressure deficit in natural and managed

- ecosystems. *Plant, Cell & Environment* n/a.
<https://doi.org/10.1111/pce.14846>
- Rastogi, B., Berkelhammer, M., Wharton, S., Whelan, M. E., Meinzer, F. C., Noone, D., and Still, C. J. (2018), Ecosystem fluxes of carbonyl sulfide in an old-growth forest: temporal dynamics and responses to diffuse radiation and heat waves, *Biogeosciences*, 15: 7127–7139. <https://doi.org/10.5194/bg-15-7127-2018>
- Reich, P.B., Luo, Y., Bradford, J.B., Poorter, H., Perry, C.H., and Oleksyn, J. (2014). Temperature drives global patterns in forest biomass distribution in leaves, stems, and roots. *PNAS* 111 (38) 13721–13726. <https://doi.org/10.1073/pnas.1216053111>.
- Salomón, R. L., Peters, R. L., Zweifel, R., Sass-Klaassen, U., Stegehuis, A. I., Smiljanić, M., Poyatos, R., Babst, F., Cienciala, E., Fonti, P., Lerink, B., Lindner, M., Vilalta, J., Mencuccini, M., Nabuurs, G., Van Der Maaten, E., Von Arx, G., Bär, A., Akhmetzyanov, L., . . . Steppe, K. (2022). The 2018 European heatwave led to stem dehydration but not to consistent growth reductions in forests. *Nature Communications*, 13(1).
<https://doi.org/10.1038/s41467-021-27579-9>
- Stephenson, N. L., Das, A. J., Condit, R., Russo, S. E., Baker, P. J., Beckman, N. G., Coomes, D. A., Lines, E. R., Morris, W. K., Rüger, N., Álvarez, E., Blundo, C., Bunyavejchewin, S., Chuyong, G., Davies, S. J., Duque, Á., Ewango, C. N., Flores, O., Franklin, J. F., . . . Zavala, M. A. (2014). Rate of tree carbon accumulation increases continuously with tree size. *Nature*, 507(7490), 90–93. <https://doi.org/10.1038/nature12914>
- Still, C. J., 2023. Meteorological data from the Discovery Tree at the Andrews Experimental Forest, 2015 to present ver 3. Environmental Data Initiative. <https://doi.org/10.6073/pasta/88040f52946c09c74ac0bfc2a3167717>
- Still, C. J., Sibley, A., Depinte, D., Busby, P. E., Harrington, C. A., Schulze, M., Shaw, D. R., Woodruff, D. R., Rupp, D. E., Daly, C., Hammond, W. P., & Page, G. (2023). Causes of widespread foliar damage from the June 2021 Pacific Northwest Heat Dome: more heat than drought. *Tree Physiology*, 43(2), 203–209. <https://doi.org/10.1093/treephys/tpac143>
- Strittholt, J. R., Dellasala, D. A., and Jiang, H. (2006) Status of Mature and Old-Growth Forests in the Pacific Northwest. *Conservation Biology* 20:363–374. <https://doi.org/10.1111/j.1523-1739.2006.00384.x>
- Swanson, F.J. (2023). The H.J. Andrews Experimental Forest Long-Term Ecological Research Program, Oregon, USA: A Historical Biocultural Perspective. In: Rozzi, R., Tauro, A., Avriel-Avni, N., Wright, T., May Jr., R.H. (eds). *Field Environmental Philosophy. Ecology and Ethics*, vol 5:32, 532–554. doi: https://doi.org/10.1007/978-3-031-23368-5_32
- Teskey, R, Wertin T, Bauweraerts I, Ameye M, Mcguire MA, Steppe K (2015) Responses of tree species to heat waves and extreme heat events. *Plant, Cell & Environment* 38:1699–1712. <https://doi.org/10.1111/pce.12417>
- Wang, Y., Xing, C., Gu, Y., Zhou, Y., Song, J., Zhou, Z., Song, J., and Gao, J. (2023). Responses and Post-Recovery of Physiological Traits after

- Drought–Heatwave Combined Event in 12 Urban Woody Species. *Forests*, 14:1429. <https://doi.org/10.3390/f14071429>
- Wickham, H., François, R., Henry, L & Müller, K. (2019). *Dplyr: A Grammar of Data Manipulation*. R package version 0.8.3. <https://CRAN.R-project.org/package=dplyr>
- Williams, A. P., Allen, C. D., Macalady, A. K., Griffin, D., Woodhouse, C. A., Meko, D. M., Swetnam, T. W., Rauscher, S. A., Seager, R., D., H., Dean, J. S., Cook, E. R., Gangodagamage, C., Cai, M., & McDowell, N. G. (2013). Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, 3(3), 292–297. <https://doi.org/10.1038/nclimate1693>
- Yi, C, Hendrey G, Niu S, McDowell N, Allen CD (2022a) Tree mortality in a warming world: causes, patterns, and implications. *Environ Res Lett* 17:030201. <https://doi.org/10.1088/1748-9326/ac507b>
- Zweifel R, Haeni M, Buchmann N, Eugster W (2016) Are trees able to grow in periods of stem shrinkage? *New Phytologist* 211:839–849. <https://doi.org/10.1111/nph.13995>