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Recent shifts from clearcutting to partial retention harvesting on many ownerships and the importance of microclimate dynamics on biotic responses to regional climate highlight the need to understand how microclimate conditions in forest understories differ across gradients of partial overstories. This study compares below-canopy near-surface temperatures at 2cm above ground to open-air temperature at 1.5m across a gradient of canopy cover and wildfire smoke. Findings are interpreted in the context how extreme events, such as the Northwest heat dome in Jun 2021 and large wildfires, as well as general warming trends may influence seedling performance and mortality. Overall, for every 10% increase in canopy cover, below-canopy air temperature at 2cm was 1.3°C lower and the odds of exceeding stress thresholds for conifer regeneration declined by a factor of 0.26. The reduction in temperature due to wildfire smoke was found to be equivalent to an additional 15% canopy cover. This study showed the benefits of residual canopy in lowering temperatures, but extreme events may overpower the ability of forest canopies and topography to provide microrefugia for temperature sensitive species and processes in managed forests. However, wildfire smoke may provide extra buffering during the hottest and driest conditions.

The Effect of Canopy Cover and Wildfire Smoke on Near-Surface Temperatures

by
Amanda Brackett

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Amanda Brackett, Author

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DEDICATION

This thesis is dedicated to my mom who instilled in me a love and curiosity for the natural world.

CHAPTER 1: GENERAL INTRODUCTION

Forest ecosystems have been and will continue to be impacted by global change. Scientists and managers around the world have been working to understand, predict, and adapt to effects of changing climate and disturbance regimes on forests for decades. A key component of this research is untangling the effect of increases in temperature, drought, and their combined effect on mortality of mature trees and seedlings (Allen et al., 2015). However, to do that we must match the scale at which we measure climate and the scale at which biota experience the climate. The study of microclimates has emerged as a way to bridge that gap and measure climate at ecologically relevant scales (De Frenne et al., 2021). Microclimates are driven by the regional climate, but are reflecting fine-scale variation in topography and forest structure creating a range of physical conditions, which then is reflected in temperature, moisture, and light levels (Jucker et al., 2018). Thus, microclimates can provide for growing conditions that are buffered from larger-scale climate extremes. Areas with such buffered microclimate will likely play a critical role in forest ecosystem responses to climate change (Ashcroft, 2010). Understanding the magnitude and drivers of microclimate buffering will allow researchers to create better predictions of biotic responses to macroclimate change, leading to more effective climate change adaptation strategies (De Frenne et al., 2019a; Maclean et al., 2017; Potter et al., 2013).

Within the last 10 years there have been significant advancements in understanding which structural elements drive variability in forest microclimates (Frey et al., 2016; Kovács et al., 2017; Sprugel et al., 2009; Von Arx et al., 2013, 2012). However, few studies have investigated the relationship between forest management actions and microclimate dynamics, and they mostly focus on specific management actions affecting microclimate conditions at the stand (average) scale. For example, studies have compared understory microclimates after thinnings of varying densities and group selection treatments (Baker et al., 2014; Bigelow and North, 2012; Childs et al., 1985; Ehbrecht et al., 2019; Heithecker and Halpern, 2007, 2006; Kovács et al., 2020; Ma et al., 2010; Peck et al., 2012; Rambo and North, 2009; Weng et al., 2007; Zheng et al., 2000) or a single treatment type such as shelterwoods to clearcuts (Baker et al., 2016; Childs et al., 1985; Latif and Blackburn, 2010; Raymond et al., 2006).

Results from these studies largely show patterns that would be expected given the basic thermodynamic principles governing the relationship between forest canopy and microclimate conditions. Stands with lower canopy density had increased understory air and soil temperature, soil moisture, light, and wind compared to stands with higher canopy densities (although not all microclimate variables were examined in each study). A major limitation of such studies is that they examined average microclimate conditions over time and space for a category of actions (e.g., thinning versus unthinned stands), which is not necessarily relevant for growth and survival of individual seedlings. Also, not investigating microclimates across a wide gradient of tree densities, makes it difficult to determine thresholds, e.g., the residual density at which thinning no longer provides microclimate benefits sufficient to have a biological impact (Halpern et al., 2012). For example, studies examining the variation in microclimate associated with dispersed and aggregated retention harvest in western Washington and Oregon demonstrated that, on average, compared to a clear-cut a 15% retention rate does not result in different microclimate conditions (Heithecker and Halpern, 2006). However, the study setup did not allow the investigation whether and how increases in the amount of tree retention provided a higher amount of microclimate buffering (Heithecker and Halpern, 2006). For aggregate retention there is evidence that on average, 1 ha aggregates retain microclimates conditions similar to undisturbed forests (Heithecker and Halpern, 2007). More research on the microclimate variation across a gradient of overstory retention is needed to determine how to design regeneration harvests to provide sufficient microclimate buffering.

Forest management practices have long capitalized on the buffering capacity of stand structure on microclimate conditions through implementing a variety of silvicultural practices. Shelterwood and uneven-aged silvicultural systems are the most widely used practices to specifically modify microclimate and provide suitable conditions for seedling growth and survival through retention of overstory trees (Ashton and Kelty, 2018). With novel conditions due to climate change, research and forest management practice should seek to operationalize what we have learned about the role of specific structural elements on microclimate conditions to mediate climate change effects on species. To achieve that, we need to understand how microclimate conditions in forest understories change across gradients of overstories, ideally from open clearcut conditions to dense fully stocked stands. This will also help managers when they have to balance multiple objectives. For example, understanding how the buffering capacity of forest canopy changes along a gradient of overstory retention can help managers develop prescriptions that maintain some buffering capacity while still meeting timber harvest objectives.

My research examines effects of a range of canopy cover on near-surface temperatures in recently thinned stands. The results provide insight into the potential for a variety of density management systems to at least partially buffer understory conditions under current regional climate conditions, 3^{o}C of warming, and heat wave conditions. Over the course of the study, the area was impacted by smoke from nearby wildfires allowing for me to also examine the effect of wildfire smoke on near-surface air temperatures. These two foci are represented in individual chapters. First, I present the effect of canopy cover on near-surface air temperature and discuss the implications for climate change and forest management. Then I present the effect of smoke on near-surface air temperatures with implications for plant physiological processes. Through-out both chapters I emphasize the importance of extreme events on seedling regeneration and thus forest ecosystem dynamics.

CHAPTER 2: CANOPY COVER AND CLIMATE CHANGE

Introduction:

Ecological, economic, and social concerns about forest management, the condition of forest ecosystems, and the threat of global change have led to the development and implementation of practices that support a wide variety of objectives and ecosystem services beyond maximizing timber production (Ashton and Kelty, 2018; Puettmann et al., 2009). As a result, on many ownerships there has been a shift away from clearcutting and towards retention of partial overstories during regeneration harvests, e.g., on federal lands of the United States (Franklin et al., 1997; Windmuller-Campione et al., 2020). Density management systems -including variable density thinning, aggregate retention, and gap thinning- have also been studied and proposed as an approach to meeting multiple objectives and increasing climate resilience in multiple regions around the globe (Gustafsson et al., 2012).

Within the research on partial retention and density management systems as a climate adaptation strategy, there has been an increasing interest in the effects of forest management activities on microclimate conditions (Aussenac, 2000; Ehbrecht et al., 2017) . It is well documented that forest canopy cover, in combination with topography, influences microclimate conditions by modifying processes such as interception and attenuation of incident solar radiation, air mixing, precipitation interception and throughfall, windspeed, and humidity (Aussenac, 2000; Geiger et al., 1995; Kovács et al., 2017). A fine scale variation in microclimates creates variety in the physical conditions experienced by forest biota, allowing selected spots to function as climate refugia - areas that are buffered from macroclimate extremes (Suggitt et al., 2018). Microclimates may provide favorable conditions for selected species or life stages sensitive to e.g., temperature extremes, even if macroclimate conditions become unfavorable due to climate change (Ashcroft, 2010; De Frenne et al., 2019; Lenoir et al., 2017).

Trees are typically more sensitive to climate extremes during germination and early establishment than in other life stages and the conditions near the ground are heavily influenced by microsite conditions (Anderson-Teixeira et al., 2013; Grubb, 1977; Schupp, 1995). Previous studies emphasized the importance of fine scale heterogeneity in climate conditions on seedling establishment and tree recruitment (Gray and Spies, 1997; Peck et al., 2012; Príncipe et al., 2019). For density management systems, especially those aimed at creating a multi-story stand, understanding how residual canopy cover influences microclimate conditions and affects regeneration success and performance is critical (Bauhus et al., 2009). Historically, forest management has evaded the regeneration bottleneck in many places through planting (Puettmann et al., 2009). However, with climate change the survival and performance of planted seedlings is also highly dependent on the microclimate conditions (Devine and Harrington, 2007; Harrington et al., 2013).

The physical principles driving forest microclimate variations are well understood and forest management practices have capitalized on the buffering capacity of stand structure on microclimate conditions by implementing a variety of silvicultural practices. For example, shelterwood and uneven-aged silvicultural systems have long been used to specifically modify microclimate and provide suitable conditions for seedling growth and survival through retention of overstory trees (Ashton and Kelty, 2018).

To provide information that can be operationalized in a variety of forestry settings, we need to understand how microclimate conditions in forest understories change across gradients of partial overstories, and how the specific location of the overstory canopy effects microclimate. We also need to understand whether the impact of overstory canopy shading changes under extreme events, e.g,. under novel conditions such as the Pacific Northwest heat dome in June 2021 (Puettmann, 2021). To predict how these relationships are relevant to biotic responses to macroclimate change, they need to be evaluated using physiologically relevant measurements and variables. Many microclimate studies use conditions at a height of 1.5-2m to examine the potential for micro-refugia, but conditions near the soil surface differ substantially from 1.5m (Geiger et al., 1995). For example, temperatures have been found to be up to 10°C hotter and vapor pressure deficit (VPD) was up to 2kPa higher at 10cm than at 2m (Davis et al., 2019b). Young plants and animals located near the forest floor are greatly affected by these differences (Geiger et al., 1995). Insight into microclimate dynamics close to the ground is crucial to understanding biotic responses to macroclimate change in terms of tree regeneration.

To address this issue, I set up a study in partially harvested stands with the following objectives: (1) to determine the effect of canopy cover on maximum temperature at 2cm above ground level; (2) to determine the effect of canopy cover on the probability and amount of temperature-induced stress that conifer seedlings and germinates may experience; and (3) to examine if the orientation of canopy cover relative to sun position throughout the day and summer would affect the relationships examined in objectives 1 and 2. Finally, (4) to use the results to predict how the relationships between canopy cover and understory microclimate conditions may change under projected climate changes.

Methods

Study Area

This study was conducted in 12 stands in the Upper Blue River Watershed on the McKenzie River district of the Willamette National Forest in western Oregon. The study sites range in elevation from 630m to 1086m. Based on data from Primary Meteorological Station (PRIMET) at 430m elevation at the H.J. Andrews Experimental Forest (located approximately 6.5KM south of study sites) mean monthly temperatures range from 0.6°C in January to 17.8°C in July and annual precipitation averages 2.30m (Bierlmaier, 1989). However, temperature and precipitation regimes have shifted, and conditions have been hotter and drier in more recent years. This area is also characterized by highly seasonal precipitation and a mostly dry growing season. During this study, June 29, 2021-September 25, 2021, the mean weekly temperature ranged from 11.3 °C to 22.2 °C at PRIMET. The study area experienced an unprecedented heat wave between June 25 and July 3rd 2021, with maximum open-air temperatures at 1.5m reaching 46 °C, as well as several other smaller heat waves where temperatures ranged from 38-40.5 °C. This area was also heavily impacted by smoke in early and mid-August due to the Middle Fork

Complex, and the Washington Ponds Fire. These conditions may be indicative of future climate conditions of this area given the predicted increase in duration and severity of heatwaves (Mazdiyasni and AghaKouchak, 2015) and large wildfires (Abatzoglou and Williams, 2016).

Study Design

All study sites are covered by approximately 50-year-old even-aged monoculture Douglas-fir (*Pseudotsuga menziesii*) stands. To ensure little interference of understory layers, stands selected for this study had been fairly dense until recent commercial thinnings, which occurred between 2015 and 2019. Thinning prescriptions included gap treatments to designation by description method with spacing distances of 14-18 feet. Designation by description aims at residual trees to be spaced a minimum of one spacing distance and a maximum of two spacing distances apart. In a stand with a DxD spacing of 14 feet the trees will be spaced from 14 feet to 28 feet apart. However, results may deviate depending on the spatial arrangement of the trees in the stand prior to thinning. These stands are representative of the typical first commercial treatment on federal forests in the PNW in terms of age, density, and thinning prescription. Additionally stands were only selected if they were within the path of a 2020 LiDAR flight conducted on and around the H.J. Andrews. To capture the microclimate conditions relevant to seedlings I used Tomst TMS-4 temperature sensors (Wild et al., 2019). TMS-4 data sensors are well suited to this study because they are designed to capture the climate and soil moisture conditions near ground level, i.e., as experienced by small plants, including germinants and tree seedlings. The sensors measure and record temperature 15 cm above the soil surface, near the soil surface (2cm), and soil temperature 8 cm below surface. The microclimate variables captured by the TMS sensor are relevant for tree regeneration processes and various ecological processes that occur near the ground or in upper soil layers (Ashcroft, 2018; Wild et al., 2019). For this analysis I focused on the 2cm air temperature measurements since all three temperature measurements were highly correlated. There was also too much fine-scale variation in soil texture that could not be controlled for and that confounded the comparison of soil temperature across sites. Additionally, the temperature at 2cm is heavily influenced by the soil and surface temperature and best represents the climate experienced by newly germinated seedlings which are the most susceptible to heat damage (Anderson-Teixeira et al., 2013; Bell et al., 2014; Grubb, 1977; Schupp, 1995).

I placed 20 TMS-4 sensors in the identified stands in locations selected by a stratified random sample and nested design. Sampling was stratified by overstory canopy cover and sensor locations were nested within harvest unit with a minimum distance of 100m between sensors. I limited locations to slopes less than 25 degrees, southern aspect (S or SW), elevations between 600-1100m, and a minimum distance between sensors of 100m. See Appendix A for more detail.

Temperature Data Processing

Prior to installation the study sensors were installed at PRIMET and the sensor data were compared to fan-aspirated temperatures at 1.5m to verify sensor accuracy (Appendix A). Data were retrieved from the sensors twice throughout the study period using TMS Lolly software and checked for quality. During the final field visit, the data were retrieved, and the sensors were removed.

The temperature data were summarized to weekly averages of daily maxima (^oC). To quantify heat stress for e.g., Douglas-fir seedlings, I also calculated weekly averages of daily accumulated stress degree hours. Using stress degree hours (SDH) to quantify heat stress is a novel application of the degree-day concept. Instead of calculating the accumulation of heating units above a minimum threshold for physiological processes, I used a temperature threshold where stress occurs in seedlings and calculated the accumulation of heating units above this threshold (Baskerville and Emin, 1969). I used a threshold of 40^oC based on metabolic responses of Douglas-fir seedlings to increased temperature (Marias et al., 2017). Studies have shown that higher temperatures as well as the accumulated time when temperatures are above 40^oC have negative effects on the photosynthetic capacity of seedlings (Duarte et al., 2016; Jansen et al., 2014; Marias et al., 2017).

Accumulation of SDH was calculated on an hourly basis by subtracting 40 °C from hourly average temperatures. Negative values were reassigned to 0 and the positive values were summed to a daily accumulation. The daily accumulation of SDH was then averaged for each week. The last two weeks of the study were removed since temperatures were significantly cooler and seedlings were not stressed based on our definition. The resulting variable used in the analysis was weekly average of the daily accumulation of SDH which represents not only the number of hours over 40°C, but how far over 40°C the hourly average temperature was.

Calculating explanatory variables

During the initial data exploration, I noticed a consistent pattern of short temperatures spikes occurring at the same time every day, but at different times for each sensor. The consistency of this pattern suggested the potential influence of canopy gaps and sun flecks on the timing and absolute value of the daily maximum, i.e., the importance of direct sunlight as influenced by the specific location of the shading trees. To capture this, I used LiDAR data from a June 2020 flight to isolate the canopy cover to the south (which is also downslope since all sensor locations were on south-facing slopes) to only capture trees that would be providing shade to the sensor. I then broke the canopy cover up into canopy that provides shade from 9am-12pm, 12pm-3pm, and 9am-3pm. This allowed me to examine not only how the canopy cover affects below-canopy air temperature but also to quantify the role of the specific location of canopy trees relative to the sun angle and thus the timing of the shade. I also used the canopy closure values from the convex spherical densiometer measurements, which integrate across the sky ignoring the azimuth. This measurement was included because it is suitable for practical applications by managers when more intensive measurements, such as LiDAR, direct measurements of solar radiation, hemispherical photos, or LAI are not available (Paletto and Tosi, 2009). Although the measurement accuracy and precision of spherical densitometers has been questioned, measures of canopy closure from spherical densiometers, hemispherical photos, and direct measurements of incoming solar radiation have been found to be broadly equivalent and correlated (Russavage et al., 2021).

To determine the area of the canopy cover to include in the shade calculation with the Lidar data for these three time periods, I calculated the maximum distance from each sensor at which a tree would still shade the sensor. This calculation was based on the average tree height and slope for each sensor location as well as the solar elevation (Figure 2.2). Since these stands are primarily composed of a single even aged canopy layer there is little variation in tree height and the average is representative of the stand. Since the sun position changes substantially between June and September, I calculated the areas that provides shades to the sensors on a weekly basis by using the solar azimuth and elevation in the middle of the week to represent the entire week. Using this distance and the solar azimuth at 9am, 12pm, and 3pm I calculated coordinates of the vertices of a triangle that would capture the area in which trees would potentially provide shade during the three time periods (Figure 2.2). Using these triangles, I then extracted the mean canopy cover pixel value per time period for each week at each sensor location from the LiDAR-derived canopy cover raster (5m resolution).

Additional explanatory variables that varied by sensor location included heatload (McCune 2007) and elevation. Elevation was determined using the digital elevation model (DEM) from the USGS. Heatload was calculated following McCune (2007) using latitude, slope, and aspect of each sensor location to represent the potential incoming solar radiation at each sensor in the absence of canopy cover. The weekly average of the daily maximum air temperature from Central Meteorological Station (CENMET) at the H.J. Andrews Experimental Forest was included to account for regional climate conditions and autocorrelation among weeks (Daly and McKee, n.d.). This station was chosen because it is close and most similar in elevation to the sites. After initial model fitting, autocorrelation was still present and was not resolved using a correlation structure, indicating the variables in the model were not sufficient to explain the trend through time. I hypothesized that this was due to nearby wildfires, as the study area was impacted by smoke throughout most of August. Smoke and high particulate concentrations in the air increase scattering of incoming solar radiation and decrease the amount of direct radiation on the sensor (McKendry et al., 2019; Rastogi et al., 2022). Since the TMS-4 only has a small radiation shield this change in conditions could affect the temperature recorded by the sensor, especially the maximum daily temperature. Additionally, temperature at 2cm is heavily influenced by the radiative heating of the soil surface and is likely impacted by changes in direct radiation (Campbell and Norman, 1998). The auto-correlation issue was resolved by the inclusion of weekly average daily accumulation of incoming short-wave radiation (W/m^2) measured at CENMET. Although heatload and incoming short-wave radiation both address the amount of solar radiation received, both variables were included in the analysis since heatload accounted for site differences while incoming short-wave radiation accounted for differences through time.

Statistical Analysis

The objective of the statistical analysis was to test the following three hypotheses associated with the four study objectives:

H1) There is a negative relationship between canopy cover and weekly average daily maximum temperature after accounting for elevation, heatload, incoming shortwave radiation, and open-air temperature.

H1.1) The strength of this relationship based on ΔAIC and pseudo R^2 values, differs based on whether canopy cover is determined by a static 360° measurement using a spherical densitometer or LiDAR-derived weekly average of average canopy cover shading sensors from 9am-12pm, 12pm-3pm, or 9am-3pm.

H2) There is a negative relationship between canopy cover and the probability of accumulating stress degree hours (SDH) and the magnitude of SDH accumulation after accounting for elevation, heatload, incoming shortwave radiation, and open-air temperature.

H2.1) The strength of these relationships, based on ΔAIC and pseudo R^2 values, differs based on which canopy cover estimate, listed in H1.1, is used.

H3) The relationships tested in H1 and H2 will be biologically relevant under varying regional climate scenarios including 30-year normal temperatures, 3°C of warming, the average conditions during the heat dome, and the hottest day of the heat dome.

To test H1 and H1.1 weekly average daily maximum temperature (°C) at 2cm above the ground was used as the response variable in four linear mixed models with canopy cover, open-air temperature, elevation, heatload, and incoming shortwave radiation as continuous explanatory variables, and sensor nested in harvest unit as a random effect. Each of the four models used a different canopy cover measurement (Table 2.1). Each linear mixed model was extended to allow for among-week correlations of the errors within sensor locations nested in harvest unit using an auto-regressive correlation of lag 1 (AR1). This correlation structure estimates a single correlation used to describe how errors within weeks become less similar with increasing time. Assumptions of constant variance and normality of errors for each model were assessed graphically using plots of the normalized residuals. No problems were noted. Sensor locations were assumed to be independent of each other due to the minimum distance of 100m (Baker et al., 2016).

For H1.1 differences in Akaike's information criteria values (ΔAIC) were used to compare the evidence of model support (Burnham et al., 2011). Pseudo R^2 and coefficients were also used to interpret model fit and the relationship between each response variable and the four canopy cover measurements. Pseudo R^2 was calculated for each model following Efron (1978). H1 was then evaluated using the model with the lowest ΔAIC value (Table 2.2, Figure 2.3).

To test H2 and H2.1 a log-normal hurdle model approach was used. The hurdle model approach used one model to examine how the explanatory variables of interest affect the odds of SDH accumulation (Table 2.1). The second model then examined how well the explanatory variables explain the accumulation of SDH when they are present. First, the SDH weekly average daily accumulation was transformed into a binary variable with values of 1 for weeks above 0.25 SDH and 0 for weeks below 0.25 SDH. Initially, a value of 1 for all weeks above 0 was used, but the presence of observations with very small values (i.e., <0.25) made the fitting of the second model in the hurdle approach difficult to interpret. To increase interpretability, values less than 0.25 were set to zero. From a plant physiological perspective these small values are basically negligible, allowing for increased interpretability of the results while keeping the variables based on plant physiological principles.

The binary variable of presence or absence of SDH was used as the response variable in four binomial generalized linear mixed models using a logit link and bobyqa optimizer with standardized canopy cover, open air temperature, elevation, heatload, and incoming shortwave radiation as continuous explanatory variables and sensor nested in harvest unit as a random effect (Table 2.1). The continuous fixed effects were standardized by subtracting the mean from each value and dividing by the standard deviation. This was necessary due to the difference in scales between variables. Plots of simulated residuals over fitted values were examined using the DHARma package and no unusual patterns or overdispersion were noted (Hartig, 2020). Coefficients and profile confidence intervals were calculated using standardized fixed effects on the model scale and then unstandardized and exponentiated to the odds scale for interpretation.

The weekly average daily accumulation of SDH for weeks when the average was greater than 0.25 was then log transformed and used as a response variable in a family of four linear mixed models with the same fixed and random effects as previous models (Table 2.1). Based on a graphical assessment of residual plots, a natural logarithm transformation of weekly average daily accumulation of SDH was found to adequately stabilize the variance and residuals were sufficiently symmetric and approximately normal. In both components of the hurdle model, the sensor locations were assumed to be independent of each other based on the minimum distance of 100m between sensors (Baker et al., 2016). All estimates and confidence intervals calculated on the model scale and were back transformed to the response scale for interpretation

For H2.1 a difference in Akaike's information criteria value (ΔAIC) was used to compare the evidence in support of the 4 models in both components of the log-hurdle approach- probability of SDH and accumulation of SDH (Burnham et al., 2011). Pseudo R^2 and coefficients were also used to interpret model fit and the relationship between each response variable and the four canopy cover measurements. Pseudo R^2 was calculated for each model following (Nakagawa and Schielzeth, 2013). H2 was then evaluated using the models with the lowest ΔAIC value (Table 2.2). H2 was then evaluated using the model with the lowest ΔAIC value (Table 2.2, Figure 2.3).

To evaluate H3 and the implications for climate change scenarios, the models containing canopy cover measured with a densiometer were used to estimate the relationship between canopy cover and the three response variables under four different climate scenarios: 30-year normal, 3°C of warming, the average conditions during the heat dome, and the hottest day of the heat dome (Figure 2.4). For each of these scenarios a prediction dataset was created. Canopy cover ranged from 20-80% (source data ranged from 16-85%), heat load and elevation at their median value for the 20 sensor locations (0.94 and 887m respectively), and the open-air temperature was set at 26°C, 29 °C, 35.0 °C, 41.8 °C for maximums and 17 °C, 20 °C, 26.5 °C, and 29 °C for means (30-year normal, 3 °C of warming, average heat dome, hottest day of heat dome respectively). To evaluate the effect of smoke incoming short-wave radiation was held at the value two weeks prior to the smoke event (July 27th (82915 w/m^2) and the value during the smokiest week of August 3rd (58833 w/m^2). The value for the week of July 27th was chosen to represent the non-smoke week since it was the closest to the week of August 3rd when there was no smoke and since incoming shortwave radiation is also affected by changes in daylength and sun-angle. These 24 prediction datasets were then used to predict the three response variables for each of the three response variables, four climate scenarios, and the presence/absence of smoke. To increase the ecological relevance of the results from H3 the maximum VPD for the predicted maximum temperatures under each of the three climate scenarios, but in the absence of smoke, was calculated with the conservative assumption of constant relative humidity of 20% (Table 2.4).

The nlme package was used to fit the linear mixed models (Pinheiro et al., 2022) and the lme4 package was used to fit the binomial generalized linear mixed models (Bates et al., 2015). Analyses were done with R version 4.1.2 (2021).

Results

Comparison of fit was done using AIC values and Pseudo R^2 are shown in Table 2.2. The low Δ AIC values (< 7) for models used to address H1 and H1.1 suggest that there is no difference in support for all models (Burnham et al., 2011). However, the model containing densiometer canopy cover better predicts the mean weekly average daily maximum air temperature at 2cm, as indicated by the slightly higher pseudo R^2. For H2 and H2.1, the Δ AIC (7.4) for the first component of the hurdle model also suggested there was no difference in model support in estimating the probability of SDH. Similar to the previous comparison for H1 and H1.1, the pseudo R^2 was slightly higher for the model containing densiometer canopy cover. For the second component of the hurdle model which examined SDH accumulation, the model with the densiometer measurement was better supported by the data than the LiDAR based measurements (Δ AIC 14.48). The difference in pseudo R^2 between models is also larger for this comparison.

Given these results, I highlight the management relevance by presenting the estimated relationship between canopy cover measured with a densiometer and the three response variables of interest to address H1 and H2. The results suggests that after accounting for elevation, heatload, incoming shortwave radiation, and open-air temperature, every 10% increase in canopy cover (measured using a densiometer) is estimated to decrease the mean weekly average daily maximum at 2cm by 1.3 °C (95% CI 0.4 ° to 2.2°), the odds of accumulating SDH by a factor 0.26 (95% CI 0.06 to 0.59), and the median weekly average daily accumulation of SDH by 40% (95% CI 20-55%) (Table 2.3; Figure 2.4).

The biologically relevant threshold of 40°C is crossed at higher canopy covers under the 3°C of warming and both heat dome scenarios compared to the 30-year normal. The amount of time and difference between mean temperatures and 40°C represented as SDH increased slightly under 3°C of warming and with a much larger increase under the heat dome scenarios. The presence of wildfire smoke reduces temperatures in all climate scenarios. Based on predicted mean weekly average daily maximum at 2cm under 30-year normal open-air temperatures, there is an estimated 16% (0.9kPa) decrease in VPD between 20 and 40% canopy cover, 14%(0.7kPa) between 40 and 60%, and 16% (0.7kPa) between 60 and 80% (Table 2.4). The absolute and relative difference in VPD across the range of canopy cover increases as climate change scenarios become harsher (3°C of warming to average heat dome conditions to hottest day of heat dome).

Discussion

The study results demonstrate that canopy cover- after controlling for the influences of topography- reduces near surface temperatures (2cm) enough to be relevant to ground level biological processes such as regeneration. As expected, I found a strong downward trend in maximum and mean temperatures at 2cm above ground with increasing canopy cover large enough to be biologically relevant. Separating the effect of canopy cover from the many other drivers of microclimate conditions allowed me to focus on how forest management actions can influence microclimate conditions. Previous studies have compared the average microclimate conditions at the stand level, e.g., in thinned versus fully stocked stands (Baker et al., 2016; Bigelow and North, 2012; Chen et al., 1999; Halpern et al., 2012; Heithecker and Halpern, 2006; Kovács et al., 2020; Latif and Blackburn, 2010; Ma et al., 2010; Rambo and North, 2009). In contrast, by sampling across a gradient of canopy cover from 16% to 85% and at a smaller spatial scale than previous studies, my findings can be used to inform decisions regarding a variety of density management systems, including treatments that result in higher spatial variability, such as variable density thinning, aggregate retention, or gap thinning (Ashton and Kelty, 2018; Franklin et al., 1997; Puettmann et al., 2009).

While this design is a major strength of my study, it makes direct comparison of my results to other studies difficult. At first glance, the 1.3°C increase in maximum temperatures with every 10% reduction in canopy cover found in this study is larger than effects found in most other studies. For example, in western Washington, a significant difference of roughly 4 °C for the 50% difference in overstory canopy cover between the unthinned control (90% canopy cover) and the 0% and 15% retention levels (~50% canopy cover) at 1m was found (retention level refers to proportion of trees over 45cm in diameter retained) (Heithecker and Halpern, 2006). My findings suggest a difference of 5.2°C in near-surface temperatures for the same 40% difference in overstory canopy cover. This difference is likely due difference in the ecological processes of interest between the two studies which is reflected in difference in sampling height (2cm vs 1-2m) and on my focus on south facing aspects (Geiger et al., 1995). Several other studies found a range of magnitudes from 0.6 °C to 5 °C in the difference of maximum air temperatures at 1-5m between closed-canopy and thinned stands or canopy-gaps (Bigelow and North, 2012; Kovács et al., 2020; Latif and Blackburn, 2010; Ma et al., 2010; Rambo and

North, 2009). It is worth noting that all these studies had different densities for both control and thinned stands, contributing to the wide range in values. Further highlighting the role of the exact measurement location heights , studies that examined the effect of thinning and shelterwood treatment on soil temperatures found a larger difference of ~7 ^{o}C between controls and treatments (Childs et al., 1985; Dunlap and Helms, 1983; Peck et al., 2012). My results provide support to these findings, as maximum temperatures near the surface are expected to be lower than soil temperatures due to the lower specific heat of air relative to soil but higher than air temperatures further from the ground due to the conductive heating near surface temperatures experience from the soil surface (Campbell and Norman, 1998; Geiger et al., 1995).

The results also quantify how higher canopy cover leads to lower heat stress near ground. The relationship between the probability of accumulating stress, as quantified by SDH, and canopy cover indicates that on south facing slopes, maintaining at least 60% canopy cover may likely avoid temperature stress in understories, e.g., for germinants under normal conditions. At the same time, retaining at least 60% canopy cover not only leads to lower probability of stress, it also limits the absolute amount of stress as seen by the accumulation of SDH. Thus, in stands with canopy cover greater than 60%, plant stress in the understory is less likely and less intense. The accumulation of SDH also provides context to the probability of SDH at lower canopy covers. For example, at 40% canopy cover the probability of SDH much higher than at 60% (~90%) but the median average daily accumulation of SDH is 4. The high probability, but low amounts of SDH at 40% canopy cover indicates that there may also be sufficient buffering at 40%. Another consideration is that higher levels of canopy cover may create a light limited environment in the understory which could prevent the regeneration of shade intolerant species. Managers now have information to balance potential temperature stress and light availability with their targeted composition and structure when making decisions.

The management relevance of this study is also highlighted by the finding that simple and available tools are basically just as good, and in some cases better at quantifying canopy cover as it relates to its impact on microclimate temperatures (Table 2.2). Thus, my results can be applied to stands in which canopy cover was measured with densiometers, a commonly used tool in forest management. The expense and expertise needed to collect and analyze LiDAR data (Paletto and Tosi, 2009; Russavage et al., 2021) will not improve the quality of predictions, based on our work. The high R^2 values for models fit using the densiometer canopy measurement indicated strong support of canopy cover modifying maximum and mean temperature at 2cm. Separating out and only use a slice of canopy cover by orientation and the time of day when it provides shade does not appear to be an improvement compared to 360^{o} measurements with a densiometer in terms of predicting microclimate temperature. This is counterintuitive, as previous research has found that the specific location of canopy cover, as related to azimuth, influences microclimate dynamics (Heithecker and Halpern, 2007; Oldén et al., 2019). Apparently, the study stands were sufficiently homogenous in terms of spatial distribution of residual trees that this effect was not statistically important in my models. Caution should be used in interpreting this aspect when applying the results to stands with high spatial variability, e.g. stands on north and south facing slopes, when gaps are created, or only a few small patches of residual trees are left (Palik et al., 2020).

While the objective of this study was to examine the relationship between near-surface temperatures and canopy cover, the presence of wildfire smoke during the study also resulting in lower near-surface temperatures. The particles in wildfire smoke reflect and absorb incoming solar radiation, reducing the amount that reaches the surface and subsequently the radiative heating of the soil-surface (Stone et al., 2011). My data show that this reduction in radiative heating affected near-surface temperature maximums and means (see chapter 3). Additionally, the 24,000w/m^2 reduction in incoming short-wave radiation from the wildfire smoke provided roughly the same reduction in maximum temperatures as an increase of 15% in canopy cover (Chapter 3). Wildfire smoke is temporally and spatially variable and should not be relied on to account for risk of reduced performance or mortality in the understory. However, it may provide additional buffering during the driest and hottest times of the year (Abatzoglou and Williams, 2016; Stone et al., 2011).

Implications of canopy cover in relation to climate change and extreme heat events

Under projected climate changes including increases in summertime open-air temperatures and extreme events such as the heat dome of June 2021 more canopy cover may be required to sufficiently modulate microclimate conditions for biological processes near the ground (i.e., to reduce amount of time near surface temperature is above 40^{o}C and the resulting VPD) (Figure 2.4). My data show that under 3 ^{o}C of warming, typical near-surface conditions are only slightly harsher across the range of canopy cover (~2^{o}C hotter). It is worth noting that the 30 year normal used in the study simulations (18 ^{o}C mean and 26 ^{o}C max) is based on summer temperatures from 1990-2020 at PRIMET (Daly and McKee, 2021), over which substantial warming and shifts in plant communities towards more heat and drought tolerant species occurred (De Frenne et al., 2013). General warming of regional conditions may continue to affect the composition, density, and growth rates of conifer regeneration and understory plants at similar rates. Additionally, thinning - independent of climate change - has been shown to increase cover of drought and heat-tolerant species due to changes in resource availability (Neill and Puettmann, 2013). In recently thinned stands with low canopy cover we would expect to see shifts in species composition due to increased temperatures and resource availability, which may improve ecosystem functioning and resilience (Neill and Puettmann, 2013).

While increasing regional temperatures have and will continue to impact forest ecosystems, extreme events pose a larger threat to forest health and the provision of ecosystem services (Allen et al., 2015; Puettmann, 2021). The June 2021 Northwest heat dome shattered temperature records and caused significant foliar damage and mortality throughout the Pacific Northwest. During the heat dome, the average temperature was 26.5 °C and the average maximum was 35 °C at CENMET. The hottest average daily temperature was 32 °C on June 27th while the maximum peaked at 42°C on June 28th. When open-air temperatures at 1.5m are this high, predicted Tmax at 2cm is estimated to be above 40 °C for the average daily maximum during the heat dome and above 45 °C for the hottest day of the heat dome across the range of canopy covers (Figure 2.4). Mean temperatures at 2cm are also well above thresholds for heat-stress impacts on plants (Jansen et al., 2014). Indicating that during extreme events, understory conditions will likely not be completely protected from damaging and potentially lethal temperatures on south facing slopes.

Heat waves are a current and future threat to tree mortality and ecosystem functioning (Allen et al., 2015; Breshears et al., 2021; Duarte et al., 2016; Teskey et al., 2015). They have already become more severe exemplified by the 2021 heat dome event in the Northwestern US and the 2019 heat wave in Europe, as well as the 2022 heat wave in India and are predicted to increase in intensity, duration, and frequency (Mazdiyasni and AghaKouchak, 2015). Heat waves have been shown to cause large-scale forest die-off of trees and shrubs (Matusick et al., 2013; Ruthrof et al., 2018) and affect tree regeneration through reduction in cone production as well as germination and survival of seedlings (Adams et al., 2017; Enright et al., 2015; Parmenter et al., 2018). The effect of heat waves has also been a recent focus of plant physiological research which has shown substantial heat-induced damage to photosynthetic machinery and eventual mortality especially in seedlings (Adams et al., 2017; Duarte et al., 2016; Jansen et al., 2014; Marias et al., 2017; Teskey et al., 2015). For example, in a study of Douglas-fir and Ponderosa Pine seedlings exposed to a heat treatment of 45°C for only 1 hour, there was substantial heat-induced damage (Marias et al., 2017). During the heat dome event, maximum near surface temperatures at my study sites was 44.1 °C on average and the absolute maximum temperature recorded was 57.4 °C. These conditions were more sustained than the simulated heat stress in Marias et al. (2017) and led to substantial seedling mortality in the region as well as damage to adult trees.

For a more comprehensive understanding of the implications of the canopy cover on germination and early growth of tree seedlings, it is important to keep in mind that growing conditions are influenced by complex interactions between temperature and atmospheric and soil moisture (Davis et al., 2019b; McLaughlin et al., 2017; Von Arx et al., 2013). My predictions assume that hydrologic and soil moisture conditions and the associated evaporative cooling remain constant in the future. Since drought occurrence and intensity are predicted to increase in the PNW, my predictions in terms of the benefits of canopy cover for young plants are likely conservative, as decreases in moisture will constrain evaporative cooling leading to non-linear increases in surface air temperatures (De Frenne et al., 2021; McLaughlin et al., 2017; Zellweger et al., 2020). This increase and co-occurrence of heat and drought will have significant negative impacts on physiologic processes in plants and could lead to increased mortality even during short droughts or heatwaves (Allen et al., 2015).

Even without changes to precipitation regimes, increases in near surface temperatures will lead to increases in soil moisture deficits and drought intensity, which increases mortality risk and decrease growth rates in trees (Allen et al., 2015). As temperatures increase so do respiration carbon costs, stomatal conductance, and risk of cavitation from critical water tension in the xylem (Allen et al., 2015; Grossiord et al., 2020). These effects on physiological process increase the risk of mortality during short-term droughts that may have been non-lethal under cooler temperatures (Adams et al., 2017; Allen et al., 2015). These effects have been thoroughly documented in theory as well as observational and experimental studies (Breshears et al., 2021). While the risks of mature tree mortality is high, the threat to regeneration is even higher because young trees have less control on physiological responses to drought and temperature leading to higher climate sensitivities (Anderson-Teixeira et al., 2013; Grubb, 1977; Schupp, 1995).

VPD is an important variable for understanding this relationships between temperature and moisture and their impacts on physiological processes (Breshears et al., 2021; Grossiord et al., 2020;

Zweifel et al., 2021). VPD is derived from temperature and relative humidity and increases exponentially with temperature. Under high VPD, photosynthesis and growth declines and the risk of damage and mortality due to carbon starvation and hydraulic failure increases (Grossiord et al., 2020). The non-linear relationship between temperature and VPD further highlights the potential benefits of higher canopy cover may be required to buffer understory conditions (Table 2.4). The estimated differences in VPD across the range of canopy cover is similar to differences found in other studies (Jucker et al., 2018; Kovács et al., 2020; Rambo and North, 2009; Von Arx et al., 2013). For example, in conifer forests in Oregon, Idaho, and Montana VDP at 5cm was found to be 0.73 kPa lower in open conditions compared to below-canopy and the difference increased to 1.1kPa when canopy cover was greater than 50% (Davis et al., 2019b). However, the effect of canopy cover on buffering both temperatures and VPD was dependent on soil moisture and that the buffering decreased with soil moisture declines (Davis et al., 2019b). Thus, the buffering potential of canopy cover is decreased at the critical times when water availability is lowest (Allen et al., 2015; Drake et al., 2018; Grossiord et al., 2020).

The lowering of mean and maximum temperatures at near ground level found in this study do not prevent near surface temperatures from reaching damaging and potentially lethal temperatures during extreme heatwaves, leading to important implications for understory species and forest succession (Rother et al., 2015; Will et al., 2013). At low canopy covers, temperature and moisture conditions under heat waves are likely to lead to seedling mortality (Jansen et al., 2014; Marias et al., 2017). However, these results do not mean that we would expect to see complete regeneration failure during heatwaves everywhere in the region. I sampled in the harshest microclimate conditions (i.e. south-facing slopes) and controlled for the effect of micro-topographic variation. Macro and micro topography greatly affect the spatial variability in near-surface temperatures and are one of the main drivers of climate refugia (Jucker et al., 2018; Suggitt et al., 2018; Wolf et al., 2021). Within that spatial variability in near-surface temperatures In recently thinned stands the level and pattern of retention, amount of course woody debris, and understory cover add additional spatial variability in physical conditions leading to increased spatial variability in seedling mortality due to extreme temperatures (Heithecker and Halpern, 2006; Jucker et al., 2018; Kovács et al., 2017).

Management Implications

Sampling below-canopy temperature at 2cm across a gradient of canopy cover demonstrated that in south-facing stands with low canopy cover near-surface temperatures are likely to reach extremely stressful or lethal levels for understory plants. These findings have implications for management strategies that target low stand densities either to promote drought resilience in the residual trees (North et al., 2022) or to develop structural diversity (Bauhus et al., 2009). By sampling at a smaller spatial scale and across a gradient of canopy cover, my findings can be used to inform decisions regarding a variety of density management systems, including treatments that result in higher spatial variability (Ashton and Kelty, 2018; Franklin et al., 1997; Puettmann et al., 2009). These insights can help managers make informed decisions and balance trade-offs. For example, if managers want to encourage the development of a multi-aged stand on south facing slopes, higher retention will likely be necessary to protect regeneration from heat and moisture induced stress. However, higher levels of retention results in less profitable harvest and can limit regeneration growth due to low light levels (Bauhus et al., 2009). Additionally, at higher levels of retention the understory plant composition is typically less heat-tolerant and provides fewer ecosystem functions (Neill and Puettmann, 2013). There are many factors that go into management decisions and the buffering capacity of canopy cover should be considered, especially given the climate sensitivity of regeneration and the projected increases of heatwaves and VPD. This study provides the necessary information for managers to consider the impact of density management systems on understory climate conditions and the implications for regeneration and understory plant growth.

Thinning to or maintaining low density stands is also a commonly proposed climate adaptation strategy to prevent mortality in mature trees by reducing competition for water resources (D'Amato et al., 2013; Puettmann, 2011). This presents managers with another tradeoff between buffering understory conditions or increasing the resilience of the overstory. Additionally, high density may increase competition for water through transpiration, negatively effecting seedlings and understory plants but also decreasing evaporation and VPD so the net effect on water availability may be low. As previously mentioned, managers will also need to find a local balance between buffering of temperatures and creation of a light-limited environment that depends on the desired species composition of the understory. I highlight these selected trade-offs not as an exhaustive list, but instead to demonstrate how the findings from this research could impact management decisions. The relationships between canopy cover and the probability and amount of SDH provide information that managers can use to determine an acceptable level of risk for seedling stress following thinning based on other objectives such as timber production and wildlife habitat.

Limitations and Future Research

This study is limited in terms of inference scope since the data was collected during a single unique summer and therefore absolute values from the data may not be generalizable to more typical years. However, since the general trends follow trends that are predictable based on thermodynamic physical principles, they are generalizable across years. Additionally, the conditions from the study period may be analogous to future conditions under global change (Abatzoglou and Williams, 2016; Mazdiyasni and AghaKouchak, 2015). As mentioned previously, I only examined south facing slopes where temperatures are likely to be the most extreme. At a landscape scale there is much more variability in microclimate temperatures not captured in this study largely due to topography and forest structure and composition (Jucker et al., 2018; Wolf et al., 2021). The scope was intentionally limited to recently thinned, even-aged Douglas-fir stands to isolate the effect of canopy and highlight the potential for shifts in density management systems to buffer below-canopy air temperatures near the surface. Since canopy height and structure affects air mixing the results may not be applicable to younger stands (Kovács et al., 2017). However, the stands selected for this study were representative of the age class and structure at which the first commercial entry is typically conducted on federally managed forest in the PNW as well as other non-industrial managed forests. As the first plants regenerated in the understory in response to the thinnings, they will experience these conditions. If their establishment is successful, the additional shading by understory vegetation and advance regeneration will increase the amount of near surface temperature reduction (Kovács et al., 2017; Prévosto et al., 2020). However, with increasing temperatures it is possible that a negative feedback loop could be developed where the increase in temperature and moisture stress immediately after thinning slows or prevents the establishment and growth of understory and shrub layers, leading to arrested succession driven by maintenance of high temperatures and evaporation that further effect growth and establishment of understory layers (Soto and Puettmann, 2020).

Finally, other important variables influence vegetation responses to daytime temperatures but are not directly examined in this study, including nighttime temperatures and moisture. Previous work has found that overstory thinning leads to large decreases in nighttime temperatures due to decreases in the reflection of long-wave radiation (Rambo and North, 2009). Nighttime temperatures affect plants physiological processes and their ability to recover from extreme day-time temperatures and cooler night time temperatures may provide some benefit to understory plants when canopy cover is low (Zweifel et al., 2021). As discussed, moisture is an incredibly important resource for understanding the ecological relevance of climate data and is not directly measured in this study (Grossiord et al., 2020). The sensors used in this study do have a soil moisture sensor, but due to fine scale variation in soil texture and sensor error the data were not useable (Susha Lekshmi et al., 2014).

Conclusion

My study demonstrated that higher canopy covers resulted in lower maximum temperatures and less accumulation of time and degrees (quantified as stress degree hours), that were large enough to be ecologically relevant to seedlings and other understory plants. However, under extreme heat-waves stress, tissue damage, and mortality are still likely to occur even at the highest canopy covers, highlighting the importance of extreme events and the need to promote and maintain buffering of understory conditions through management.

This study isolated the effect of varying levels of retention but understanding how different drivers of microclimate conditions interact with overstory conditions warrants additional attention. Given the climate sensitivity and ecological importance of regeneration (Anderson-Teixeira et al., 2013), evaluating the combined influence of these factors on microclimate temperature and moisture dynamics and their impact on seedling performance and survival may help forest managers promote and maintain understory conditions that at least partially protect seedlings from regional climate variation and extremes.

Forest managers whose goal is to create structural diversity through lower stand densities and understory regeneration will need to develop decision and risk analysis tools that can incorporate the buffering capacity of higher residuals and topography to create sufficient spatial variability in microclimate conditions for regeneration success to occur at the stand and landscape level. These tools should also accommodate the effects of extreme events such as heat waves and droughts – independently and concurrently- as well as general warming (Allen et al., 2015; Breshears et al., 2021; Puettmann, 2021). My findings suggest that typical conditions on south facing slopes will be unfavorable for regeneration under climate change and extreme heat events , however, the spatial variability in conditions as well as variability in species and individual responses to heat and moisture stress indicate that while growth and survival rates may decline a complete regeneration failure is unlikely (De

Lombaerde et al., 2022; Franks et al., 2014; Jucker et al., 2018). Additionally, although tree regeneration may be reduced the understory plant composition following thinning may support other ecosystem services such as food sources for wildlife and climate resilience through increased cover of drought and heat resistant species (Neill and Puettmann, 2013).

Thinning to low residual density is one of the current recommendations for increasing the resilience of mature trees to drought and heat induced stress (North et al., 2022). There are many complex interactions between residual density and temperature and water stress in mature trees. For example, at lower densities competition for water is lower but higher evaporative demand would be expected as well. Plus a higher density of shrubs and understory plants may amplify both competition and reduced evaporative demand (Kovács et al., 2017; Riegel et al., 2013). These may also play out in interactions between seedlings and mature trees (e.g., increased competition for water, but lower temperatures leading to lower VPD). This highlights the challenge of managing for climate adaptation across spatial scales and through time. The best answer to this challenge based on our current understanding is to create variability and reduce connectivity across and within scales. One way to achieve this is by promoting and maintaining variability in microclimate conditions allowing for selected spots to serve as climate refugia, while others may shift towards more heat and drought adapted species.

Table 2.1 Model parameters of the 3 different model types and 12 models fit in the analysis to address the first two hypotheses. Each model type had 4 individual models with the same response variable. These four models only differed in which measurement of canopy cover was used (360° measurement from spherical densiometer and LiDAR-derived canopy cover for three time periods). AM time period corresponds to shade from 9am-12pm, PM time period corresponds to shade from 12pm-3pm, and AM + PM is 9am to. Refer to Figure 2.2 for how these variables were calculated. For each response variable the open-air temperature used in the models was summarized to match the response variable.

<table>
<tr><th>Hypothesis</th><th>Response Variable</th><th>Model Type</th><th>Canopy Cover</th><th>Continuous Fixed effects</th><th>Random Effects</th></tr>
<tr><td>1</td><td>Weekly average daily maximum</td><td>Linear Mixed Model with AR1 Correlation Structure</td><td>360°
AM
PM
AM + PM</td><td rowspan="3">1. Canopy Cover (%)
2. Open air temperature (°C)
3. Elevation (m)
4. Heatload
5. Weekly average daily accumulation of incoming shortwave radiation (w/m²)</td><td rowspan="3">Sensor nested in harvest unit</td></tr>
<tr><td>2</td><td>Presence/absence of Stress Degree Hours</td><td>Binomial Generalized Linear Mixed Model with Logit Link</td><td>360°
AM
PM
AM + PM</td></tr>
<tr><td>2</td><td>Log of Weekly average daily accumulation of Stress Degree Hours</td><td>Linear Mixed Model with Log Transformation and AR1 Correlation Structure</td><td>360°
AM
PM
AM + PM</td></tr>
</table>

Table 2.2: Results of model comparison using Δ AIC and pseudo R^2 to evaluate which model and associated canopy cover variable better predicted each of the three response variables (Ho 1.1 and 2.1). The model with the lowest Δ AIC was then used to test Ho 1 and 2. For each of the three response variables this was the 360° measurement from a convex spherical densiometer.

H	Response Variable	Model Type	Canopy Cover	AICc	Δ AIC	Pseudo R^2
1	Weekly average daily maximum	Linear Mixed Model with AR1 Correlation Structure	360°	1084.67	0.00	0.82
			AM + PM	1086.15	1.48	0.76
			AM	1088.38	3.71	0.74
			PM	1091.72	7.05	0.76
2	Presence/absence of Stress Degree Hours	Binomial Generalized Linear Mixed Model with Logit Link	360°	146.59	0.00	0.72
			AM + PM	153.33	6.74	0.62
			AM	153.72	7.13	0.62
			PM	154.01	7.42	0.62
2	Log of Weekly average daily accumulation of Stress Degree Hours	Linear Mixed Model with Log Transformation and AR1 Correlation Structure	360°	339.85	0.00	0.50
			AM + PM	353.26	13.44	0.26
			AM	353.52	13.67	0.25
			PM	353.95	14.09	0.17

Table 2.3: Estimates and 95% confidence intervals for relationships between the three response variables (weekly average daily maximum, presence/absence of SDH, and amount of SDH accumulated) associated with the two hypotheses. Ho column connects estimates to hypotheses and provides context to what relationship the estimate applied to. For the binomial GLMM estimates and confidence intervals were exponentiated from the link scale (log odds) to the odds scale

	Hypothesis	**Model Type**	**Canopy Cover**	**Lower 95% CI**	**Estimate**	**Upper 95% CI**
1	Change in mean weekly average daily maximum temperature at 2cm for 10 % change in canopy cover	Linear Mixed Model with AR1 Correlation Structure	**360°**	**0.41**	**1.32**	**2.24**
			AM + PM	0.48	1.25	2.03
			AM	0.26	0.95	1.63
			PM	0.08	0.64	1.20
2	Factor for the multiplicative change in odds of accumulation of SDH for a 10% change in canopy cover	Binomial Generalized Linear Mixed Model with Logit Link	**360°**	**0.07**	**0.26**	**0.62**
			AM + PM	0.12	0.48	1.48
			AM	0.13	0.53	1.51
			PM	0.27	0.65	1.59
2	Factor for the multiplicative change in median weekly average daily accumulation of SDH for a 10% change in canopy cover	Linear Mixed Model with Log Transformation and AR1 Correlation Structure	**360°**	**0.46**	**0.61**	**0.81**
			AM + PM	0.68	0.96	1.36
			AM	0.70	0.91	1.18
			PM	0.84	1.06	1.33

Table 2.4: Estimated maximum near-surface VPD (kPa) for different canopy covers and climate change scenarios. Calculations were based on predicted maximum temperature at 2cm and an assumed constant relative humidity of 20%

Canopy cover	**30-year normal**	**3^{o}C warming**	**Heat dome**	**Hottest day of heat dome**
20	6.6	7.4	9.3	12.0
40	5.7	6.5	8.2	10.5
60	5.0	5.6	7.1	9.2
80	4.3	4.9	6.2	8.1

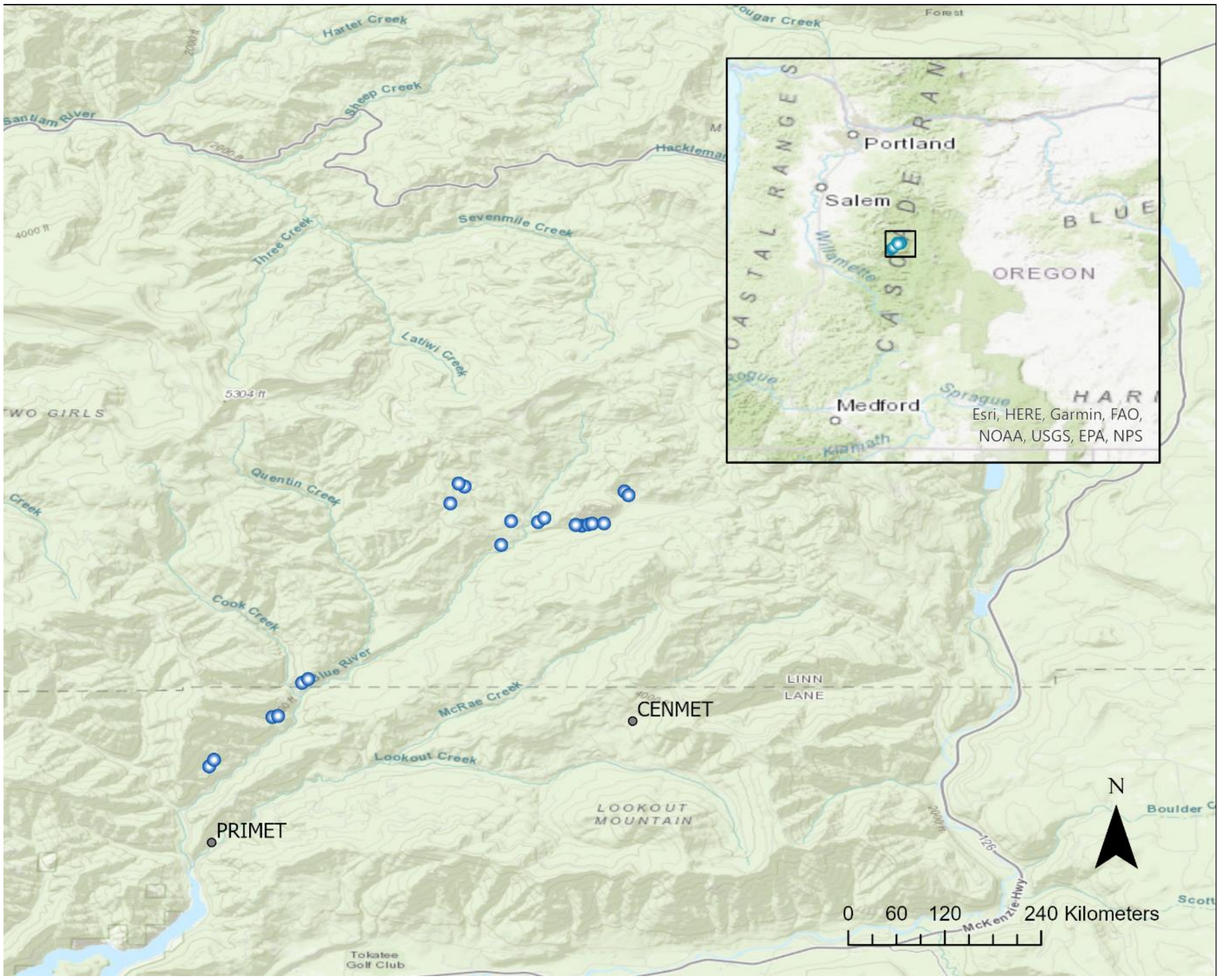

Figure 2.1: Study area map with 20 sensor locations and PRIMET and CENMET stations

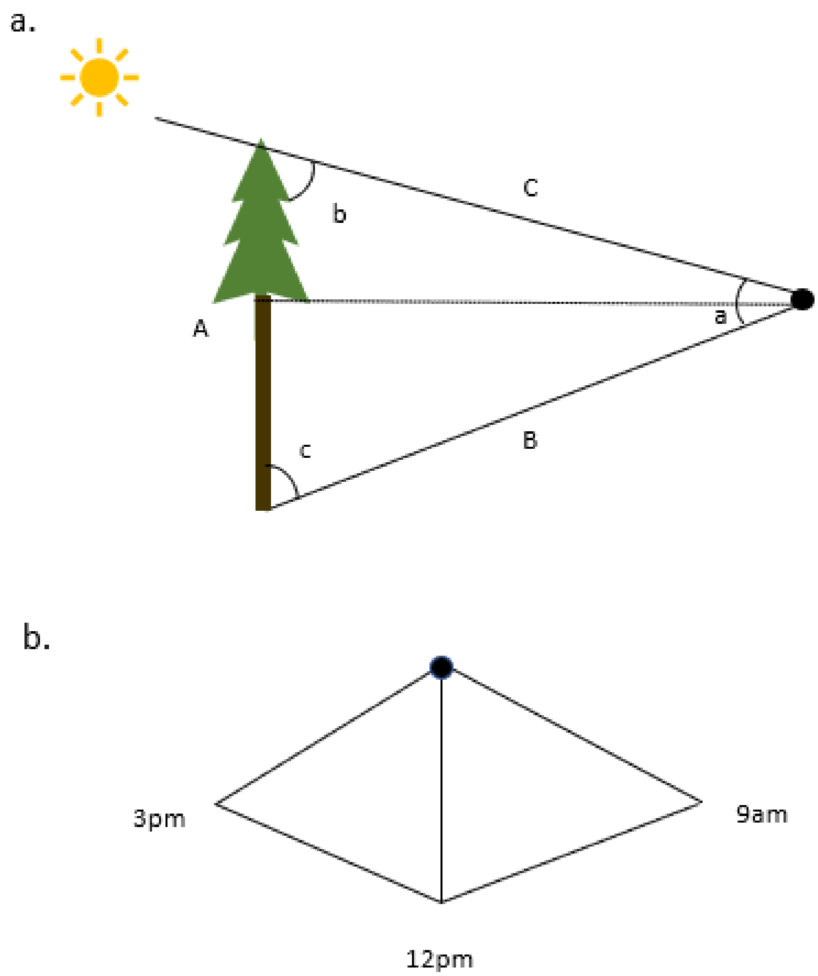

Figure 2.2: Schematic of how the area in which trees could shade a sensor for each time period was calculated. The top (a) shows a cross section of a sensor location while the bottom shows an overhead view where the black dot is the sensor. In the cross-section, angle a is equal to the slope plus the solar elevation, angle c is equal to 180-90-slope (dotted line makes right triangle used to calculate this angle), angle b is then equal to 180- (angle a + angle b). The length of side A is equal to the average tree height. Then the length of side B can be calculated as the using the law of sines (A*(sin(b))/sin(c)). Side B is the maximum slope distance a tree can be while still shading the sensor. This calculation was done for the start and end of each of the three time periods (9am, 12pm, and 3pm) for each sensor location (20) and each week of data collection (13). Solar elevation changed weekly and slope changed by sensor location. The length of side B was then slope corrected and used in combination with the solar azimuth for the start and end of the three time periods for each week to determine the area potentially providing shade for each time period (b).

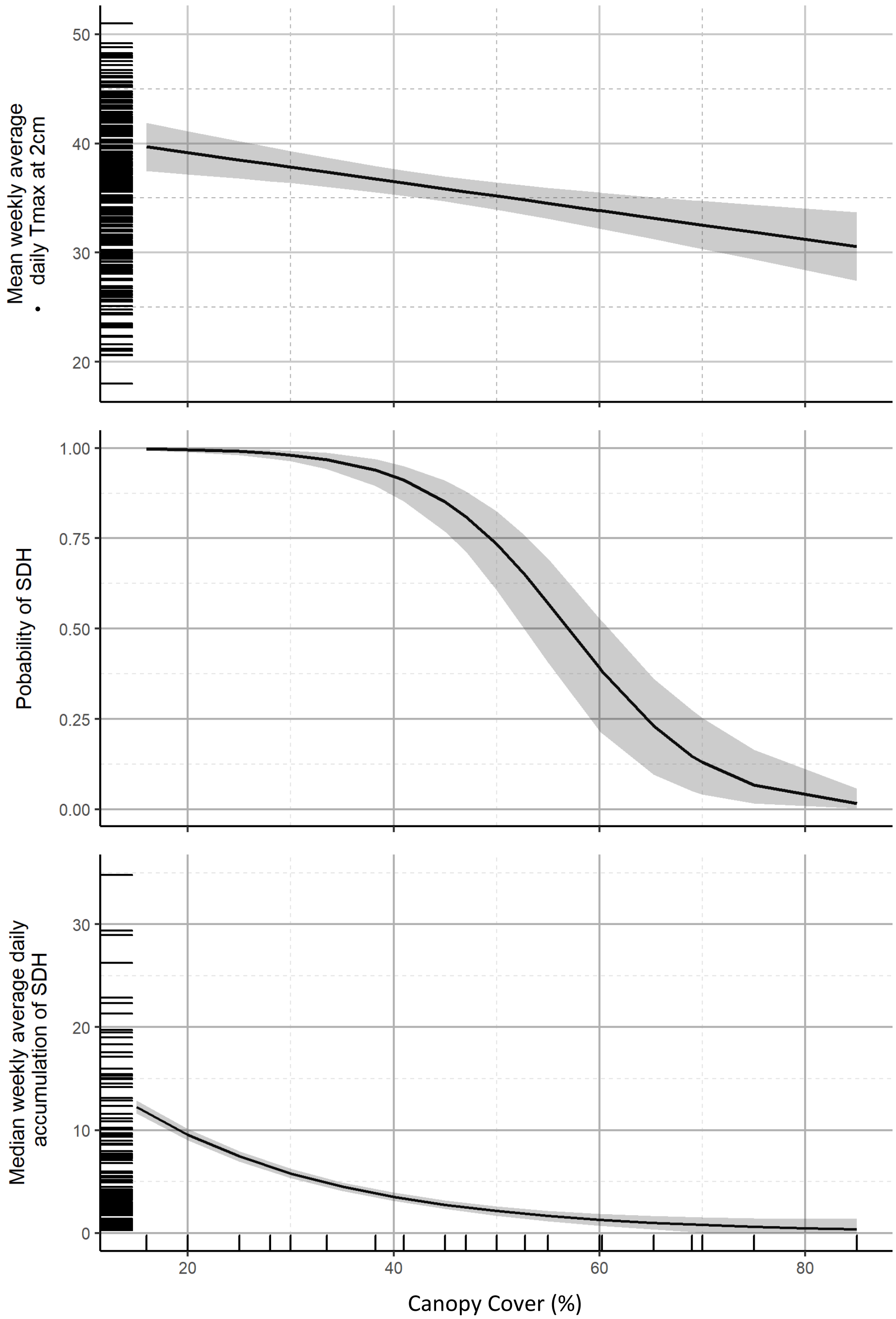

Figure 2.3: Estimated relationship and associated 95% confidence intervals between the three response variables and canopy cover. To isolate the effect of canopy cover, all other fixed effects (see table 1) were held at their observed median.

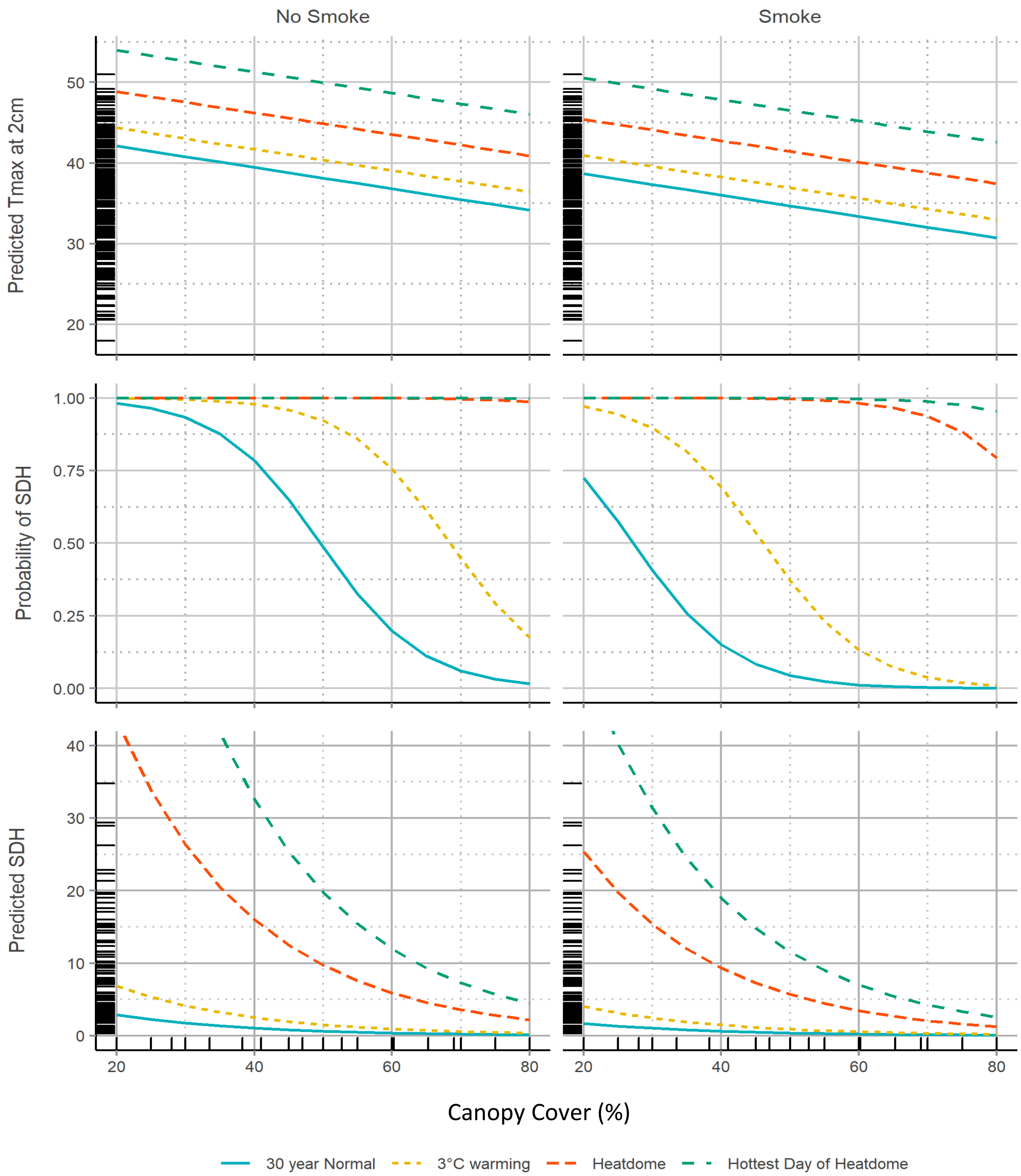

Figure 2.4: Estimated relationships between the three response variables and canopy cover for 4 different climate scenarios and the presence/absence of smoke. To examine the estimated relationships between the three response variables and canopy cover I used the models fit using the densiometer derived canopy cover measure and a prediction dataset where all elevations and heatloads were held at their observed median while open-air temperature was held at different values for the 4 climate change scenarios and incoming shortwave radiation was held at the value for the week of July 27th without the presence of smoke and the smoke used the value from the week of August 3rd.

CHAPTER 3: THE EFFECT OF SMOKE

Introduction:

Wildfires, which emit large quantities of smoke, are projected to increase in frequency, severity, and duration in western North America (Abatzoglou and Williams, 2016). The aerosols present in wildfire smoke scatter and absorb incoming solar radiation as well as outgoing long-wave radiation and thus can modify the Earth's radiative budget (Stone et al., 2011). The interactions between the high aerosol content in wildfire smoke and radiative fluxes can be complex and are driven by the particle composition and reflective properties, as well as topography, latitude and time of year which effect the solar angle (Kochanski et al., 2019; McKendry et al., 2019). At smaller scales, wildfire smoke can profoundly impact radiation and these atmospheric-smoke interactions have been found to reduce daytime surface temperatures leading to temperature inversions that slow the dispersion of smoke and further increasing smoke accumulation amplifying the inversion (Kochanski et al., 2019). This positive feedback loop can trap smoke for up to several weeks, particularly in mountain valleys. While interactions between smoke and atmospheric processes have been extensively studied, the focus has largely been on the bottom 100s of meters of atmosphere known as the surface layer at regional or global scales and with an emphasis on air quality (Calvo et al., 2010; Liang et al., 2021; McKendry et al., 2019; Stone et al., 2011; Zhang et al., 2016).

Given the future projections of wildfire frequency and severity and the effect of smoke on radiative fluxes, we need to understand how wildfire smoke affects climate at ecologically relevant scales. Microclimates represent the physical conditions experienced by biota and can provide insight into the impact of regional climate changes on biota (Carnicer et al., 2021; De Frenne et al., 2021). To my knowledge, no studies have examined the effect of wildfire smoke on microclimate dynamics which is necessary to fully understand the potential impacts of fires on tree seedlings, understory plants, and soil-dwelling organisms.

During my study on microclimate temperature dynamics under a gradient of canopy cover, the study area was impacted by smoke from the Washington Ponds fire and the Middle Fork Complex (see chapter 2) providing a unique opportunity to study the impact of smoke on near surface temperature measured at 2cm. After seeing the impact of smoke, quantified indirectly by incoming short-wave radiation, in the previous chapter, there clearly was a need to examine the impact more directly. To address this need I developed the following research questions:

1) How does wildfire smoke affect maximum and mean below-canopy air temperature at 2cm?
2) How do wildfire smoke and canopy cover interact to affect the difference between maximum and mean below-canopy temperature at 2cm and open-air temperature at 1.5m (ΔT)?

Methods

The Middle Fork Complex started on July 29th, 2021, just north of Oakridge, Oregon, about 45 KM south of the study site (described in chapter 2). The complex burned into October and affected just over 12,000 hectares of forest. The Washington Ponds fire started on August 2nd, 2021, just west of Sisters, Oregon, about 23km east of the study site. This fire was much smaller, only burned 10.5 ha over two weeks, and probably resulted in minor smoke contributions. The study site was heavily impacted by smoke during the week of August 3rd and the week of September 7th, 2021 (Figure 3.1). The influence of smoke from these fires was detected in the analysis for chapter 2 and examined using incoming short-wave radiation. Here, I quantified smoke using aerosol optic depth (AOD) data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle implementation of Atmospheric Correction (MAIAC). AOD represents how far into the atmosphere light reaches and has been used to extensively to examine wildfire smoke (Calvo et al., 2010; David et al., 2018; Sena et al., 2013; Zhang et al., 2016). Average AOD values for each week and sensor location were then calculated from MODIS band B3 (0.47μm) at a 1km resolution. Canopy cover was quantified using measurements from a convex spherical densiometer. For more detail on the study location and measurement of all variables, see chapter 2.

Statistical Methods

The main objectives of the statistical analysis were to determine 1) the relationship between increases in AOD due to wildfire smoke on maximum and mean below-canopy temperature at 2cm and 2) the combined effect of smoke and canopy cover on the difference between maximum and mean below-canopy temperature at 2cm and open-air temperature at 1.5 (ΔT).

To achieve these objectives, weekly average daytime temperature maxima and means were used as response variables in two linear mixed models with canopy cover, heatload, elevation, weekly average aerosol optic depth, and open-air temperature at 1.5m as fixed effects and sensor nested in harvest unit as a random effect. Both linear mixed models were extended to allow for among-week correlations of the errors within sensor locations nested in harvest unit using an auto-regressive correlation of lag 1(AR1). This correlation structure estimates a single correlation used to describe how errors within weeks become less similar with increasing time. Assumptions of constant variance and normality of errors for each model were assessed graphically using plots of the normalized residuals. No problems were noted. Sensor locations were a minimum of 100m apart and assumed to be independent of each other. Models were fit using nlme package and all analyses were done using R version 4.1.2 (2021) (Pinheiro et al., 2022).

To evaluate the estimated relationship between AOD and below-canopy air temperature likelihood ratio tests (LRT) were used to test the null hypotheses of no relationship between AOD maximum and mean below-canopy temperature at 2cm. While the individual effect of canopy cover is not the focus of this analysis, the combined effect of wildfire smoke and canopy cover is of interest. LRTs were also used to test the null hypothesis of no relationship between canopy cover and maximum and mean below-canopy air temperature at 2cm. Given the exploratory nature of this study more conservative tests than LRTs were not considered necessary.

Results:

My results show that smoke results in lower maximum and mean below-canopy air temperatures at 2cm and that reduction leads to a smaller ΔT between below-canopy temperatures at 2cm and open-air temperatures at 1.5m. This reduction in absolute magnitudes and relative differences is consistent across the range of elevation, heatload, open-air temperature, and canopy cover used in this study. Additionally, increases in canopy cover, in combination with smoke, result in a further reduction in below-canopy temperatures at 2cm and decrease in ΔT.

AOD peaked at an average of 0.90 for the study area during the week of August 3rd 2021 compared to an average of 0.28 for the previous week. During the week of September 7th AOD values for the study site averaged 0.74. For the week prior to August 3rd the observed ΔT of maximum temperatures (ΔTmax) across sensor locations was 13.22 °C (39.05 °C average below-canopy at 2cm and 25.83 °C open air at 1.5m). In contrast, during the smoke event the ΔTmax was 8.8 °C (36.5 °C below-canopy versus 27.7 °C open air). Even though the maximum open-air temperature at 1.5m was slightly higher during the smoke event, the observed decrease in maximum below-canopy temperature at 2cm averaged across all sensors was larger (3.4 °C).

Model results show that after accounting for the effect of canopy cover, heatload, elevation, and open-air temperature the observed increase in AOD from 0.28 to 0.79 is estimated to reduce mean below canopy weekly average daily maximum temperature at 2cm by 1.9 °C (95% CI 1.5 to 2.3 °C) while mean below canopy weekly average daily mean temperature at 2cm is estimated to decrease by 0.36 °C (95% CI 0.20 to 0.52°C). This study found evidence to reject the first null hypothesis that there is no relationship between below canopy weekly average daily maximum or mean at 2cm and AOD after accounting for elevation, heatload, open air temperature, and canopy cover ($\chi^2_1 = 70.13$, $p < 0.0001$ and $\chi^2_1 = 18.20$, $p < 0.0001$ respectively).

To examine the combined effect of wildfire smoke and canopy cover I estimated the relationship between canopy cover and mean below-canopy maximum and mean air temperature at 2cm. After accounting for all other fixed effects, a 10% change in canopy cover is estimated to change mean weekly average daily maximum at 2cm by 1.3 °C (95% CI 0.3 to 2.3 °C) and mean weekly average daily mean at 2cm by 0.7 °C (95% CI 0.11 to 1.3 °C). This study also found no evidence supporting the second null hypothesis that there is no relationship between below-canopy weekly average daily maximum or mean temperature at 2cm and canopy cover after accounting for elevation, heatload, open air temperature, and AOD ($\chi^2_1 = 9.10$, $p = 0.0026$ and $\chi^2_1 = 7.39$, $p = 0.0066$ respectively).

To answer the second research question regarding the effect of wildfire smoke and canopy cover on ΔT, I estimated that on average, ΔTmax is 10.06 °C after accounting for all other fixed effects (95% CI 8.60 to 11.72 °C). These estimates are consistent with theory (Campbell and Norman, 1998). When AOD values are 0.8, mean ΔTmax is estimated to be 7.99 °C (95% CI 6.44 to 9.70°C). On average, ΔTmean is estimated to be 5.66 °C after accounting for all other fixed effects (95% CI 3.38 to 8.32 °C). When AOD values are 0.8, mean ΔTmean is estimated to 5.44 °C (95% CI 3.12 to 8.17 °C).

Discussion:

This study found compelling evidence that the presence of wildfire smoke results in cooling of below-canopy near-surface temperatures (2cm) and a reduction in the difference between near-surface temperature under a forest canopy and open-air temperatures at 1.5m. The strong impact of wildfire smoke on near-surface temperatures, although not previously documented, is supported by the literature on the effect of smoke on radiative budgets and larger scale atmospheric processes (Calvo et al., 2010; Chubarova et al., 2012; Stone et al., 2011). The substantial reduction of ΔTmax in smoky conditions and the moderate reduction of ΔTmean is supported by our understanding of near-surface heating (Campbell and Norman, 1998; Geiger et al., 1995). The scattering and absorption of short-wave radiation by particles in the smoke reduce the radiative heating of the surface (McKendry et al., 2019; Stone et al., 2011). The heating of air near the surface through conduction is then also reduced causing it to become more similar to air temperatures at 1.5m which are less affected by surface conditions and processes (Campbell and Norman, 1998; Geiger et al., 1995).

Based on previous microclimate work, our estimate of a decrease of up to 2.3^{o}C in maximum below-canopy surface air temperature could be ecologically significant, especially for temperature-sensitive biota. (Breshears et al., 2021; Puettmann, 2021; Zellweger et al., 2020). However, this body of literature typically examines the effects of static local conditions, mainly vegetation and topography, on long-term reductions in microclimate temperatures compared to regional climate, often referred to as buffering. The consistency of microclimate buffering through time is a key component in the creation of long-term micro-refugia, which are small areas that are buffered from regional climate variation and warming (Wolf et al., 2021). Although this buffering may somewhat protect temperature-sensitive biota from increases in average regional temperatures, extreme events such as heatwaves may overwhelm the buffering capacity of topography and overstory canopy cover (Frey et al., 2016; Puettmann, 2021; Wolf et al., 2021; Zellweger et al., 2020; also see chapter 2). While wildfire smoke is more episodic and likely to only impact microclimates for short periods of time, on a scale of days to weeks, it may provide additional buffering during extreme temperature events when fires are more likely to occur.

Wildfires are typically more frequent and severe under hot and dry settings which are also the harshest conditions for most understory plants (Abatzoglou and Williams, 2016; Breshears et al., 2021). Wildfire smoke may provide additional buffering when it is most needed could make the difference between survival or mortality during extreme events when combined with the effect of topography and overstory canopy cover. For example, during the heat dome event open-air temperatures at 1.5m reached 46 °C while the observed average maximum below-canopy temperature near the ground was 57.4 °C (ΔT of 11.4) which is well above the temperature thresholds for foliar damage and mortality for most species (Allen et al., 2015; Boanares et al., 2021; Lancaster and Humphreys, 2020; Marias et al., 2017). Based on the results of this study, wildfire smoke and at least 50% canopy cover could have reduced maximum below-canopy temperature at 2cm to a maximum of 53.5 °C (ΔT of 7.5 °C) (Figure 3.2). While 53.5°C is still above thresholds for damage and mortality of understory plants, the chance of survival is higher than the modeled 60 °C under 20% canopy cover and clear sky conditions (Breshears et al., 2021; Marias et al., 2017).

The higher climate sensitivity of seedlings compared to mature trees (Cranston and Hermanutz, 2013; Davis et al., 2019a; Lloret et al., 2012) and the impact of extreme events on forest ecosystems (Breshears et al., 2021; Puettmann, 2021) indicates that the reduction in maximum below-canopy air temperature due to smoke may affect long-term succession and forest regeneration under global change. The effect of smoke may be particularly relevant for shade intolerant but temperature sensitive species or ecological process such as regeneration of early-successional species. I estimated a decrease of 1.9°C under smoky conditions compared to clear conditions which is roughly equivalent to adding 15% canopy cover. Thus, wildfire smoke could potentially allow for beneficial temperature buffering during extremes without creating a light limited environment as is the case with higher canopy cover. Higher cover reduces germination and growth rates of regeneration and subsequently the creation of multi-layered stands that are often desired for biodiversity (Bauhus et al., 2009; Carter and Klinka, 1992).

Plant stress and mortality is not driven solely by extreme temperatures, but is also heavily dependent on water availability which often interacts with temperature (Davis et al., 2019b; Drake et al., 2018; Grossiord et al., 2020). Understanding the complex interactions among aerosols, near-surface temperatures, water fluxes, and physiological responses is key to determining the ecological relevance of the temperature buffering found in this study. These interactions are likely controlled by ecosystem and site specific characteristics making generalizations and comparisons difficult and demonstrating the need for further research on the effect of wildfire smoke on ecosystem processes (McKendry et al., 2019; Rastogi et al., 2022; Steiner et al., 2013).

I found a reduction in maximum temperature and ΔT in the presence of wildfire smoke and under increasing canopy cover assuming constant relative humidity this would lead to decreases in VPD and resultant plant stress (Grossiord et al., 2020). Unlike under forest canopies where minimum relative humidity has been shown to be higher than open conditions (Von Arx et al., 2012), wildfire smoke has been shown to decrease relative humidity and increase evapotranspiration and VPD creating dryer conditions in the understory (McKendry et al., 2019; Rastogi et al., 2022; Steiner et al., 2013). The aridity of wildfire smoke could negate any ecological benefits of a smoke driven temperature reduction-and the associated increase in relative humidity. Future research should focus on the interactions between smoke, temperature, and moisture availability to gain a fuller understanding of the ecological impacts of smoke.

My results suggest that patterns found among wildfire smoke, ecosystem fluxes, and atmospheric processes at regional scales also may apply at the microclimate scale. The reduction in ΔT found in this study is driven by the scattering and absorption of short-wave radiation by particles in the smoke leading to large reductions in the amount of radiation reaching the surface (McKendry et al., 2019; Stone et al., 2011). These radiative impacts of smoke are well documented at larger spatial scales and have been found in North America (McKendry et al., 2019; Stone et al., 2011), South America (Moreira et al., 2017; Rosário et al., 2013; Sena et al., 2013), Africa (Schafer et al., 2002), Europe (Calvo et al., 2010) and Asia (Chubarova et al., 2012; Wang et al., 2007). Cooling of the atmospheric surface layer has also been found consistently although the magnitude differs. Robock (1991) found 1.5-7 °C of cooling in mountain valleys across Northern California, 3.5°C of cooling was documented in Siberia (Youn et al., 2011), and 2-5 °C was found in Colorado (Stone et al., 2011).

This study, to my current knowledge, is the first to investigate the effect of smoke on microclimate (specifically, near-surface) temperature and demonstrates the need for more research on the effect of wildfire smoke on microclimate dynamics. Wildfire smoke has been demonstrated to have complex feedbacks with weather patterns affecting ecologically important climate variables including air mixing, relative humidity, temperature, and vapor pressure deficit near the surface (Kochanski et al., 2019; Rastogi et al., 2022; Stone et al., 2011). While some work examining the effect of those interactions on ecosystem processes has been conducted (Rastogi et al., 2022; Rosário et al., 2013; Steiner et al., 2013) much more work is needed to better understand the impacts of smoke on temperature and moisture conditions near the surface.

When interpreting the study results, it is important to note that this study only used sites with a mid-slope position on south facing aspects which receive the most direct radiation during clear conditions. The impacts of smoke on incoming radiation may be less pronounced on e.g., north-facing slopes that typically receive less direct radiation. Additionally, there may be an interaction between smoke and canopy cover since forest structure reduces air mixing potentially preventing the dissipation of smoke (Geiger et al., 1995; Kovács et al., 2017). This interaction would likely lead to smoke being present longer and not an increase in the amount of smoke and therefore is not expected to affect my results. The data was also summarized to the week level which may be too long of a time period to address the episodic nature of smoke. However, this means our estimates may be conservative and that at smaller time scales the magnitude of the temperature reduction at 2cm may be higher. At smaller time scales the potential for an interaction between canopy cover and smoke should be considered as smoke may be present below the canopy longer than captured by satellite imagery. Finally, this study does not address the issues of moisture availability which would improve the ecological relevance. The sensors used in this study did also collect soil moisture and I had planned on including moisture in the analysis, however, due to fine scale variations in soil texture and instrument error the data were not useable (Susha Lekshmi et al., 2014).

Conclusion

My study advances an understanding of the effects global change, mainly increases in intentisy of heat-waves and wildfire smoke, on near-surface temperature dynamics under a range of overstory canopy cover. Wildfire smoke reduces near-surface below-canopy air temperatures and has the potential to provide temperature buffering during the harshest conditions for plants since wildfires are most likley to occur when conditions are hot and dry (Abatzoglou and Williams, 2016). During the smoke event we observed a decrease in below-canopy near surface temperatures, but an increase in open-air temperatures at 1.5m. Smoke induced increases in aersol particles (quantified using AOD values from satelitte imagery) was estimated to provide similar temperature buffering capabilties as an increase in residaul canopy cover of 15%. While I observed a decrease in temperature that would lead to decreases in relative humidity, wildfire smoke typically has lower absolute water content which may increase water stress enough to negate benefits of reduced temperatures on physiological processes (Grossiord et al., 2020; McKendry et al., 2019; Steiner et al., 2013). Given the projected increase in wildfire activity and smoke, this novel finding highlights the need to understand how wildfire smoke, temperature, and moisture interact and influence the physiological responses of plants under global change.

My research also emphasizes that conditions at ground level are harsher than at 1.5m. The large difference in temperature between these two heights, and previously documented differences between below-canopy conditions and regional gridded climate predictions (Frey et al., 2016; Wolf et al., 2021) highlights the need to measure climate at ecologically relevant scales to understand potential impacts on biota. This is an area of expanding research and recent efforts to create global databases of spatial explicit soil and near-surface temperature data to reduce the gap between current large scale climate data and the fine-scale resolution at which biota experience climate are promising (Lembrechts et al., 2020).

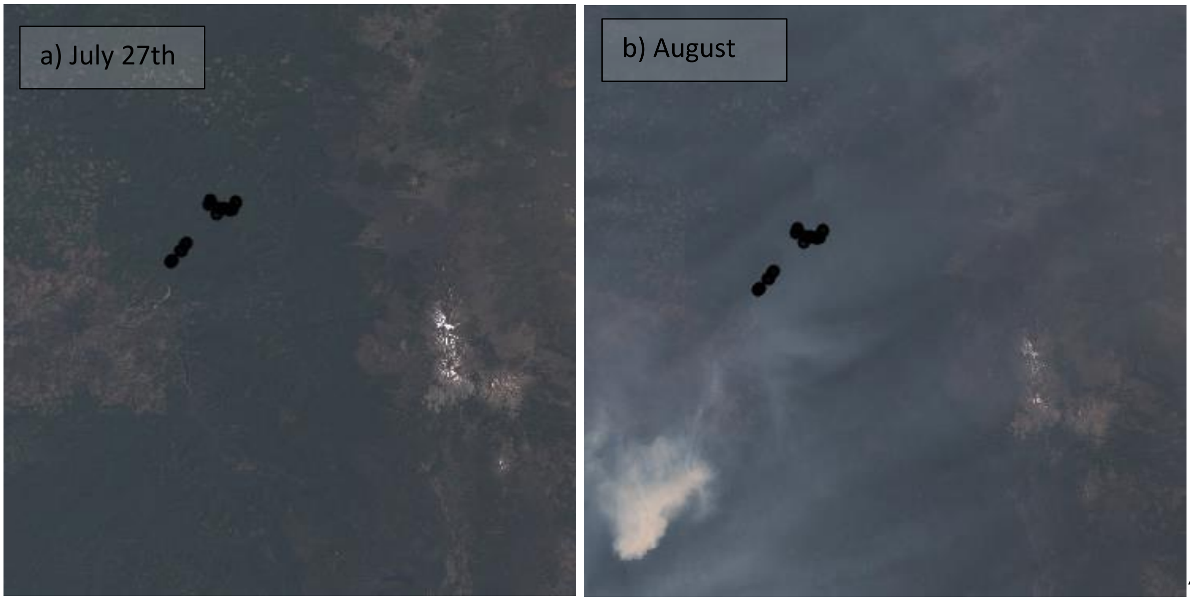

Figure 3.1: Satellite imagery from July 27th (a) and August 3rd (b) showing the amount of smoke over the study sites (circles).

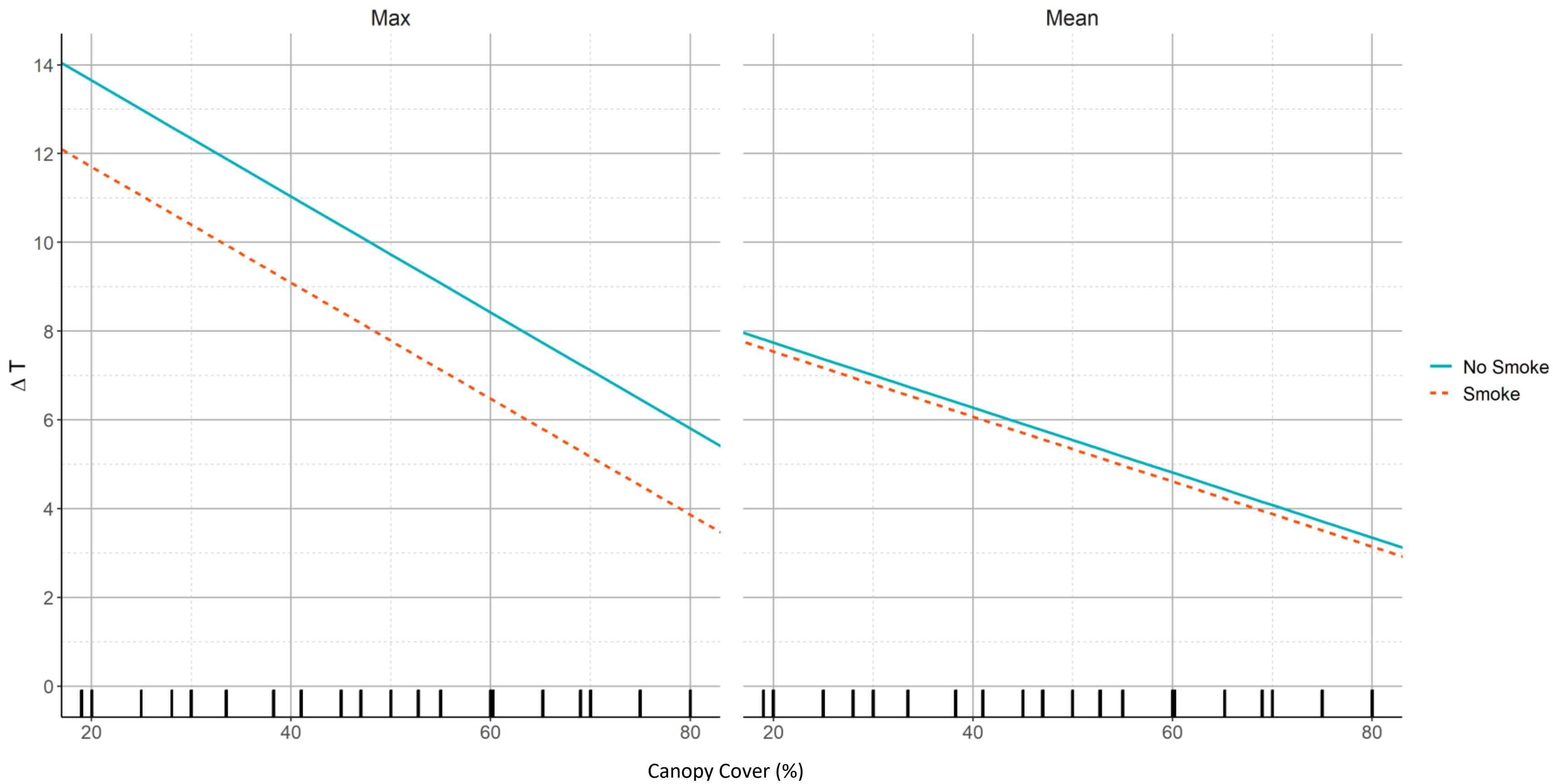

Figure 3.2: Difference between estimated mean below-canopy weekly average daily maximum (a) and mean (b) and open-air maximum at 1.5m across a gradient of canopy cover under clear and smoky conditions. The models were used to estimate mean weekly average daytime maximums and means across a range of canopy covers for smokey (AOD=0.8) and clear conditions (AOD=0.27). All other fixed effects were held constant at their median values from the original dataset

Chapter 4: General Conclusion

At a landscape scale variability in topographic conditions and canopy cover allow for heterogenous below-canopy microclimate conditions create areas that are at least partially buffered from regional climate variation and can reduce the risk of damage or mortality in regeneration and understory plants. The presence of buffering under forest canopy has been well-documented in managed forests, but there was not a good understanding of how that buffering varies across a gradient of canopy cover. The approach used in this research allowed me to estimate the slope of the relationship between canopy cover and below-canopy near surface air temperature over a canopy density gradient making the results relevant to a variety of density management systems. The buffering capacity quantified here provides additional insight into management impacts on microclimate conditions on a smaller spatial scale (Baker et al., 2016; Fleming et al., 1998; Heithecker and Halpern, 2006; Peck et al., 2012; Zheng et al., 2000). This study also adds to the literature on the effect of smoke on atmospheric processes by providing the first documentation of the effect of wildfire smoke on near-surface air temperature relative to open-air conditions.

While I only analyzed temperature data, the implications for microclimate conditions on biota are tied to interactions between temperature and moisture. This may have led to conservative estimates of understory temperature stress across a range of canopy cover and over the four climate scenarios examined. VPD, which is driven by temperature and relative humidity, affects plant physiological processes and increases non-linearly with temperature. Therefore, changes in canopy cover that lead to relatively small changes in temperature will lead to larger changes in VPD that can greatly affect plant functioning. I estimated VPD using a conservative assumption of constant relative humidity of 20%, therefore my estimates of VPD are also likely conservative. Additionally, data on the relative humidity during smoke conditions would provide additional insight into the potential buffering capacity of smoke.

While smoke reduces the amount of incoming solar-radiation, it also typically has low moisture content which could negate and temperature reductions in terms of plant stress.

My research presents evidence that temperature buffering from forest canopies has benefits, but also limits and may not be sufficient during extreme heat events on south-facing slopes in even-aged forests, but wildfire smoke may provide extra buffering during the hottest and driest conditions. While there is a substantial body of experimental research on the effect of heat waves on physiological processes the magnitude and duration of the simulated heat waves are much smaller than recent heat waves (Breshears et al., 2021; Jansen et al., 2014; Marias et al., 2017). Future experimental research on the effects of heat waves lasting for several days is necessary to fully understand the impacts of heat-waves and the ability of canopy cover to buffer microclimate conditions sufficiently to protect regeneration and other understory species (Breshears et al., 2021).

My results also highlight the potential impact of extreme heat waves on plant physiological processes which may have cascading effects on forest health (Breshears et al., 2021). For example, hotter droughts and heat waves can increase susceptibility to insect attacks as well as fuel loads and decrease fuel moisture (Allen et al., 2015). There are also likely multiplicative interactions between previous disturbances that may increase or decrease heat wave impacts or the likelihood and severity of an additional disturbance following a heat wave. However, extreme events are difficult to predict (Puettmann, 2021) and therefore manage for (Allen et al., 2015). The impact of extreme events may be minimized by reducing connectivity across and within scales (Puettmann, 2021). For heat waves, which affect forests at a landscape scale this means promoting and maintaining a mix of microclimate conditions as well as a mix of species with different sensitivities to temperature and VPD. This could be done by increasing canopy cover in already topographically buffered areas to achieve maximum protection in selected locations, or increasing canopy cover in topographically vulnerable places to achieve a lower magnitude of buffering but at a broader scale. On the landscape scale this would allow managers to utilize a variety of climate adaptation strategies based on the buffering potential of topography and canopy cover. For example, when topographic buffering potential is high such as on higher elevation north facing slopes with a lot of fine scale topographic variation, managers may opt for lower stand densities to allow shade intolerant species to regenerate. On lower elevation south facing slopes higher canopy cover could be retained to add additional buffering to the understory conditions or stands could be transitioned to more drought and heat tolerant species. Basing management decisions for climate adaptation or mitigation on these conditions would allow for potential climate refugia for temperature sensitive native species, continued timber production, and plant community shifts towards more heat and drought tolerant species to coexist on the landscape. Landscape scale variability in stand conditions and management approaches allows the ecosystem and managers the necessary flexibility to respond to an uncertain future.

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APPENDIX

Site selection

Using a GIS approach I generated 100 points that fit within the identified topographic conditions and were stratified across a gradient of canopy cover. To determine canopy cover I used the LiDAR data from the H.J. Andrews flight. I first classified points as ground or vegetation, then classified the vegetation by height. To calculate canopy cover I divided the number of hits classified as vegetation of 20m by the total number of hits for each $2m^2$ cell. To verify the canopy cover raster, I visually compared the canopy cover layer to satellite imagery taken after the thinning treatments.

Since low and high overstory cover allow for less spatial variability the 100 random points were distributed unevenly with 25 locations for less than 30% cover, 25 locations for greater than 60% cover, and 50 locations between 30 and 60% with the goal of achieving the same proportions in the selected 20 locations. Within the stratification each location was randomly assigned into five groups (20 locations per group). These groups determined the order in which the 100 locations were visited to select 20 suitable final locations.

In the field, I first visited sites in group 1 and if the location was suitable a sensor was installed. If the location was unsuitable (due to too much slash, understory vegetation, or it did not meet the slope, aspect, or topographical position criteria) the location was dropped and a location from the next group with similar canopy cover was visited and evaluated on the same criteria. Site suitability assessment included taking and recording a canopy cover measurement using a spherical densitometer to ensure the overstory canopy cover was similar to the LiDAR-derived measure and we were capturing the desired gradient in overstory conditions (Lemmon, 1957). This process was repeated until 20 sensors were installed underneath a wide range of overstory densities but with similar topographical and understory conditions. This method was used to minimize the effects of fine-scale conditions - such as slash, density of shrub layer, or microtopographic conditions on the measured microclimate (Kovács et al., 2017). To isolate the effect of canopy cover these needed to be controlled for, however, this could not be done systematically with the spatial data available and needed to be done in the field.

Once a location was determined suitable and a sensor was installed, I took photographs and notes of the sensor location, its immediate neighborhood, and of surrounding stand. I also recorded the convex spherical densiometer canopy cover measurement. The location of each sensor was also recorded using short-term waypoint averaging for a minimum of 5 minutes with a Garmin etrex 20. I took 3 additional short-term samples and used the multi-point averaged locations for analysis.

Data processing

Prior to installation at the study sites, I conducted pre-deployment accuracy and precision checks. Precision check was completed by comparing temperature measurements between the sensors for 5 days when in a homogenous temperature environment. The sensors were placed in a plastic bin in a cool dark closet to prevent drafts or differing levels of light from affecting the temperature measurements. I compared each sensor measurement to the average measurement and ensured each sensor was within the 0.5°C precision level of the sensor. To determine the accuracy of the sensor I installed the sensors at PRIMET for 7 days. I then compared the sensor measurements to PRIMET data (Daly and McKee, n.d.). The data are not totally analogous due to difference in measurement height and instrumentation, but this comparison provides insight into strengths and weakness of the sensors used in this study. The TMS-4 measurements are taken much lower to the ground (2cm and 15cm) making them more variable compared to the measurements at 1.5m for PRIMET. The air temperature measurements taken at PRIMET are also fan aspirated and have more solar shielding than the TMS-4 sensors used in this study. Because of these factors the diurnal temperature range recorded by the sensors was much higher than the PRIMET data, which was expected. The temperatures recorded from both sites followed the same temporal trends, indicating that although the data from the TMS-4 sensors is more variable and is more affected by solar radiation, the trends should be reliable.

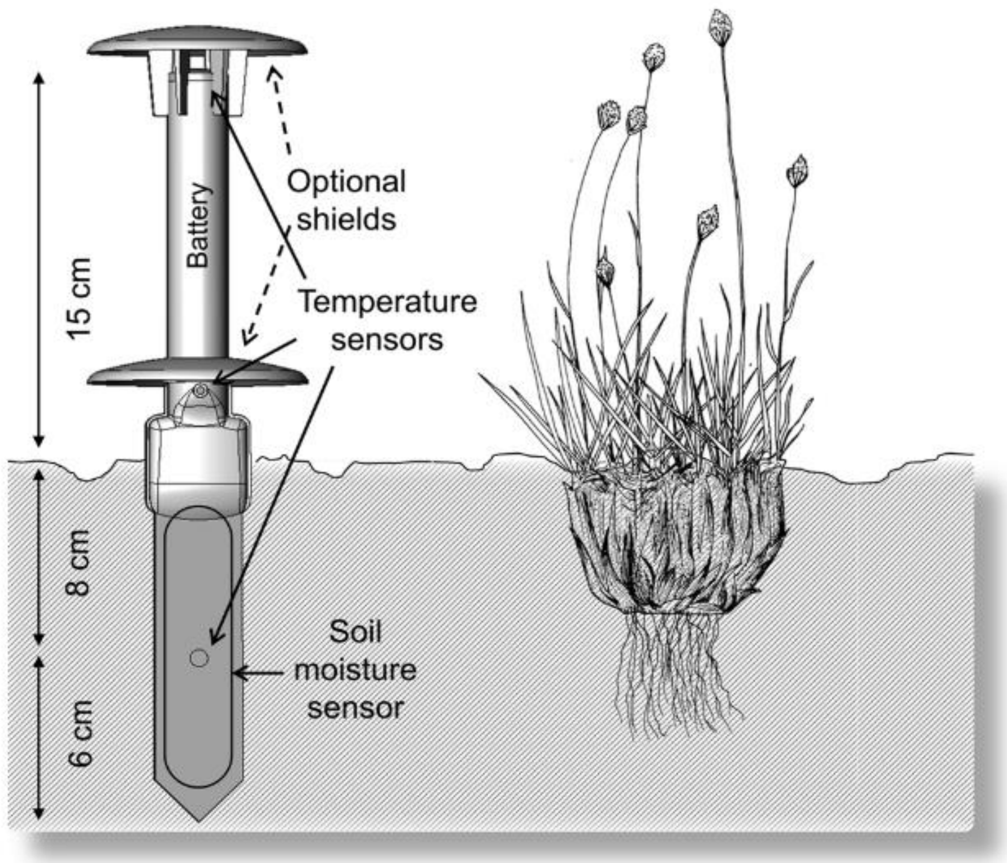

Figure A1: Sensor used in the study. Image from Wild et.al, (2019)

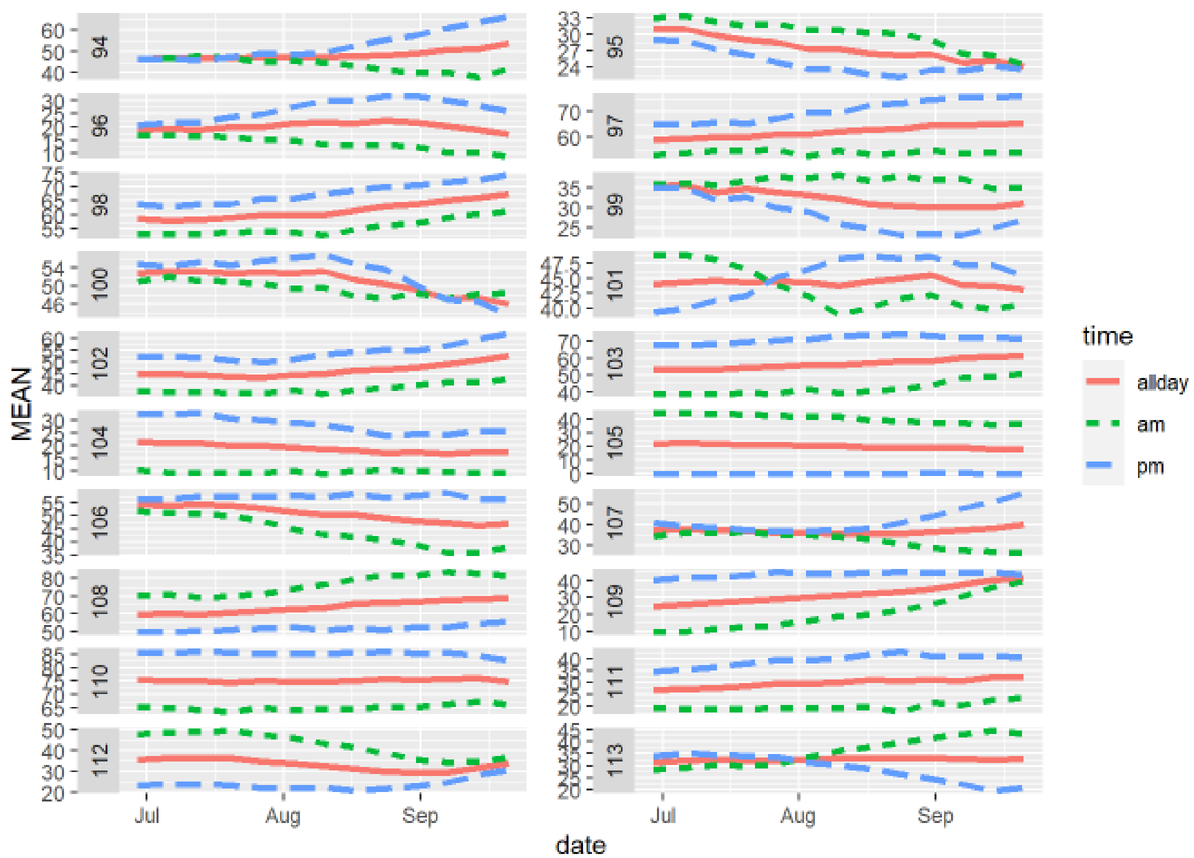

Figure A2: LiDAR derived canopy cover values for the three time periods (9am-12pm, 12pm-3pm, 9am-3pm) through time for each of the sensor locations. See table A1 for comparison to densiometer measured canopy cover.

Table A1: Sensor level variables. Percent canopy cover in the table is the densiometer measurement. Elevation, slope, and aspect are derived from the digital elevation model.

Sensor	Canopy Cover (%)	Elevation (m)	Slope (°)	Aspect(°)
96	16	1056	9.88	175
109	20	874	6.06	153
94	25	631	10.18	173
111	28	1049	27.89	175
105	30	925	28.37	177
113	34	759	4.84	274
108	40	970	19.52	195
104	41	919	16.65	173
102	45	866	20.73	164
107	47	1053	14.71	168
101	50	661	17.41	178
99	53	646	15.13	165
97	55	862	13.79	182
98	60	637	23.75	176
100	61	650	12.57	202
106	61	1057	20.25	231
95	69	661	18.92	197
103	70	901	14.52	194
112	75	1086	13.30	191
110	85	907	13.86	191

Table A2: Week level variables. Average daily open-air maxima and mean are from CENMET as well as the average daily incoming shortwave radiation. Average daily maxima and mean at 2cm is from the sensors and averaged across all sensors each week. Aerosol optic depth (AOD) measures the aerosols present in the atmosphere below 4.2km and is derived from satellite imagery.

Week	Date	Average daily open-air max (°C)	Average daily open-air mean (°C)	Average daily max at 2cm (°C)	Average daily mean at 2cm (°C)	Average daily incoming shortwave radiation (w/m^2)	Average AOD
1	6/29/2021	28.58	22.24	41.22	23.00	89815.95	0.24
2	7/6/2021	29.26	22.38	42.63	21.41	92929.54	0.11
3	7/13/2021	27.80	21.23	40.96	19.28	89873.57	0.16
4	7/20/2021	25.82	19.48	39.05	22.43	82915.11	0.12
5	7/27/2021	30.17	23.63	38.87	24.46	67048.81	0.27
6	8/3/2021	27.70	22.30	36.54	22.65	58833.17	0.79
7	8/10/2021	29.62	23.23	40.77	20.12	69299.66	0.35
8	8/17/2021	24.42	16.65	33.50	16.19	56845.94	0.65
9	8/24/2021	21.64	15.37	31.51	22.76	61296.43	0.43
10	8/31/2021	24.41	16.96	34.65	16.48	63211.48	0.16
11	9/7/2021	24.51	19.10	31.40	15.04	41966.73	0.74
12	9/14/2021	22.80	15.38	30.96	13.33	55229.30	0.09
13	9/21/2021	16.59	11.31	24.31	18.99	30395.28	0.08