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Effects of Thinning and Climate on Stem Radial Fluctuations of *Pinus ponderosa* and *Pinus lambertiana* in the Sierra Nevada

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Abstract

Due to the multiple ecosystem benefits that iconic large, old growth trees provide, forest managers are applying thinning treatments around these legacy trees to improve their vigor and reduce mortality, especially in the face of climate change and other forest health threats. One objectives of this study was to analyze sub-hourly stem fluctuations of legacy ponderosa (*Pinus ponderosa* Dougl. Ex P. & C. Laws) and sugar pines (*Pinus lambertiana* Dougl.) in the mixed-conifer forests of the Sierra Nevada in multiple different radius thinning treatments to assess the short-term effects of these treatments. Thinning treatments applied were: R30C0 (9.1 m radius), R30C2 (9.1 m radius leaving 2 competitors), and RD1.2 (radius equaling DBH multiplied by 1 ft/in multiplied by 1.25). The other objective was to assess climatic drivers of hourly stem fluctuations. Using the dendrometeR package, we gathered daily statistics (i.e. daily amplitude) of the stem fluctuations, as well as stem cycle statistics such as duration and magnitude of contraction, expansion, and stem radial increment. We then performed correlation analyses to assess the climatic drivers of stem fluctuations and to determine which radial thinning treatment was most effective at improving growth. We found an important role that mean solar radiation, air temperature, and relative humidity play in stem variations of both species. One of the main findings from a management perspective was that the RD1.2 treatment group allowed both species to contract less on warmer and higher solar radiation days. Furthermore, sugar pine put on more stem radial increment on higher solar radiation days. These findings suggest that the extended radius RD1.2 thinning treatment may be the most effective at releasing legacy sugar and ponderosa pine trees compared to the other forest management treatments applied.

Key Words: climate change, dendrometer, radial release, restoration, Sierra Nevada

Introduction

It is expected that global surface temperatures will rise under all future climate change emission scenarios, otherwise called Shared Socio-economic Pathway (SSP) (IPCC 2021). SSP are characterized by the underling socio-economic trends of each scenario and the level of radiative forcing resulting from the scenario (in watts per square metre, or W m-2) (IPCC 2021). Relative to 1850-1900, the global temperature in 2081-2100 is expected to increase by 1.0°C to 1.8°C under the low emissions scenario (SSP1-1.9), 2.1°C to 3.5°C under the intermediate emissions scenario (SSP2-4.5), and 3.3°C to 5.7°C under the very high emissions scenario (SSP5-8.5) (IPCC 2021).

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The forests of the Sierra Nevada region of California are facing multiple stressors due to climate change issues, such as increasing temperatures, earlier melting of snowpack (Eriksson and Alexandersson 1990), and previous fire suppression. During the dry growing seasons (April to September) in the Sierra Nevada, increased stem densities have likely intensified tree stress and competition (Fecko et al. 2008). Management of density via thinning treatments (releases) is a common mitigation technique to limit competition and moisture stress of the residual focal trees (Fecko et al. 2008). Since large, old growth trees provide multiple ecosystem benefits such as wildlife habitat, carbon sequestration, and structural diversity, new thinning treatments designed to thin a certain radius around these trees are being implemented to improve vigor and reduce mortality of these legacy trees. Hood et al. (2018) found that, for legacy *Pinus ponderosa* (ponderosa pine) and *Pinus jeffreyi* (Jeffrey pine), radial thinning treatments that removed stems less than 25.4 cm diameter at breast height (DBH) within the width of the legacy tree crowns were not sufficient to cause an increase in basal area increment (BAI). However, there are other benefits to these thinning treatments in general than just increased growth. Thinning treatments may limit drought induced mortality (Bradford and Bell 2017), mitigate wildfire risk through the creation of heterogeneous canopy conditions (Fulé et al. 2012; Hood et al. 2018), and lower the likelihood of bark beetle attacks (Fettig et al. 2007; Bentz et al. 2010; Zhang et al. 2019). Though prior and current methods attempting to improve vigor of large trees involve thinning to a common radius around them (i.e., Hood et al. 2018), there is little information on variations in the thinning radius and its impact on tree growth in the Sierra Nevada region.

The use of dendrometers to measure tree stem fluctuations—often in sub-hourly intervals—can provide useful short-term results of thinning treatments such as tree water status and stem radial growth (Vieira et al. 2013). In addition, comparing sub-hourly tree stem measurements with multiple climate variables can provide key insights as to what climate variables are driving stem fluctuations throughout the day. This can help to highlight which forest structural conditions that managers can alter via thinning treatments to improve growth and vigor. Most studies which use dendrometer readings to assess stem size fluctuations use methods of analysis that either summarize the readings using a daily approach (i.e. daily amplitude, mean, minimum, and maximum values) (Duchesne and Houle 2011) or using a stem cycle approach (Deslauriers et al. 2003; Vieira et al. 2013; Ziaco and Biondi 2018). The stem cycle approach breaks down the dendrometer readings into contraction, expansion, and stem-radius increment and can analyze cycles that last longer than a day (van der Maaten et al. 2016). Contraction occurs as the stem variation goes below the previous maximum, expansion occurs as the stem goes above the previous minimum, and stem-radius increment occurs when the stem expands further than the previous maximum. A study in the Sierra Nevada found that thinning treatments caused the stems of residual Jeffrey pine trees to contract more on a daily basis—especially during the latter (and drier) part of the growing season (Fecko et al. 2008). They attributed this to the trees in the thinned treatments having more available water to recharge their stems (Fecko et al. 2008). A study done by Vieira et al. (2013) on maritime pine (*Pinus pinaster*) in the Mediterranean climate region of the west coast of Portugal found that daily variations in stem radius were mainly controlled by transpiration, and therefore stem fluctuations were most influenced by temperature and tree water status. Other applications of dendrometer studies include examining tradeoffs between resource partitioning between reproductive growth and radial growth in California oaks (Barringer et al. 2013). Dendrometers have been used to track phenology of *Pinus longaeva* in California (Hallman and Arnott 2015) and water storage relationship in the trunks of Sequoiadendro giganteum (Lindley) J. Bucholz. (Williams et al. 2021). However, there are limited studies specific to the Sierra Nevada region (Fecko et al. 2008). Similarly, there have been no studies looking at the effects of variations in radial-release thinning treatments on daily stem fluctuations of the retained large/legacy trees within the Sierra Nevada region.

To address this research gap, one objective of this current study is to analyze sub-hourly stem fluctuations of ponderosa and sugar pines in multiple different radius thinning treatments to assess the short-term effects of these treatments. This will help to provide guidance earlier to managers as to what thinning radius, whether it be diameter-based or a fixed radius, improves tree health and vigor of the remaining legacy trees. The other objective of this study is to analyze the sub-hourly dendrometer data collected on the ponderosa and sugar pines within those varying radial thinning treatments to assess climatic drivers of hourly stem fluctuations.

Materials and Methods

Study site

The study took place in the Lassen National Forest in the northern Sierra Nevada range of California at an average elevation of 1,530 m (Fig. 1). The ecoregion of the Lassen National Forest is categorized as the M261 Sierran Steppe—Mixed Forest—Coniferous Forest—Alpine Meadow Province (Bailey 1994). The northern Sierra Nevada region in general is described as having warm, dry summers and cool, moist winters with most of the yearly precipitation generally happening in the winter (between October and March). Furthermore, most precipitation at higher elevations in the winter comes in the form of snow and is usually an important resource for moisture during the growing season as the snow melts (Yeh and Wensel 2000). The main soils found in this region are ultisols on mountain slopes with humid air, dry alfisols at lower elevations, and entisols in the narrow floodplains and alluvial parts of the valley (USDA Forest Service 1999).

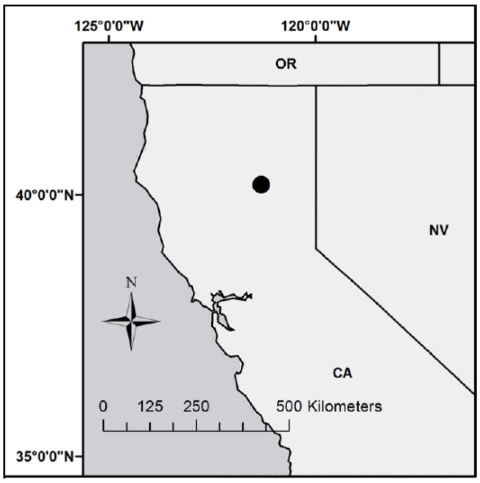


Fig. 1. Map of study area—located in the southern portion of Lassen National Forest in northern California, just southwest of Lake Almanor. Map courtesy of Johnson et al. (2017).

Site selection & field methods

The study sites were selected based on criteria that includes containing a large pine which was defined as having a breast height diameter of at least 63.5 cm. These large pines were designated as the plot centers in which operational radial thinning treatments were then applied around them, removing all mid and understory trees except healthy pines greater than 40.6 cm in diameter. A total of 16 plots were selected for this study; 11 of those plots had an old-growth sugar pine as the plot center and 5 plots had an old-growth ponderosa pine as the plot center.

Treatment types for sugar pine consisted of:

1) 3 control plots with no thinning (referred to as Con)
2) 3 plots with a thinning radius of 9.1 m around the focal tree with zero competitors left within the radius (referred to as R30C0) (this is the common radial thinning radius in the Lassen National Forest (John Zarlengo, USDA Forest Service, personal communication))
3) 2 plots with a thinning radius of 9.1 m keeping two competitors within the radius (R30C2)
4) 3 plots with a radius based on the old-growth pine diameter multiplied by 1 ft/in of DBH and then multiplied by 1.25 which ranged from 14.0-18.0 m (RD1.2)

Dendrometer units were attached to three sugar pines in the control treatment group with an average dbh 81.8 cm, three sugar pines in the R30C0 treatment group with an average dbh of 88.1 cm, two sugar pines in the R30C2 treatment group with an average dbh of 99.1 cm, and three sugar pines in the RD1.2 treatment group with an average dbh of 111.3 cm (Tables 1, 2).

Treatment types for ponderosa pine consisted of:

1) 2 control plots with no thinning (Con)
2) 3 plots with a thinning radius of the diameter multiplied by 1 ft/in of DBH and then multiplied by 1.25 which ranged from 11.3-14.0 m (RD1.2)

Dendrometer units were attached to two ponderosa pines in the control treatment with an average dbh of 89.4 cm and three in the RD1.2 treatment group with an average dbh of

Table 1. Summary table of trees that were measured with dendrometers

Focal species	Treatment category	Plot ID	Plot radius (m)	Focal tree DBH (cm)
PILA	Control	Con230	9.1	64.0
PILA	Control	Con234	9.1	63.8
PILA	Control	Con240	16.9	117.6
PILA	R30C0	122R30	9.1	96.0
PILA	R30C0	126R30	9.1	92.2
PILA	R30C0	138R30	9.1	75.9
PILA	R30C2	135R30C2	9.1	106.2
PILA	R30C2	141R30C2	9.1	91.9
PILA	RD1.2	C2RD1.2	18.0	120.7
PILA	RD1.2	C4RD1.2	17.4	115.6
PILA	RD1.2	C8RD1.2	14.0	97.5
PIPO	Control	Con226	10.7	73.4
PIPO	Control	Con259	13.4	105.4
PIPO	RD1.2	C6RD1.2	11.3	78.0
PIPO	RD1.2	C7RD1.2	13.4	86.9
PIPO	RD1.2	C11RD1.2	14.0	98.0

The control treatment category did not have any radial thinning done; R30C0 had a constant radial thinning radius of 9.1 m regardless of DBH; R30C2 had the same treatment as R30C0 but two competitor trees were left within the 9.1 m radius; lastly, the RD1.2 treatment radius was determined by multiplying the DBH in inches by 12 by 1.25 to get a radius (in feet) that was dependent on the DBH.
PIPO, *Pinus ponderosa* (ponderosa pine); PILA, *Pinus lambertiana* (sugar pine).

Table 2. General descriptive statistics of the combined species-treatment groups

Species and treatment group	Mean plot radius (m)	Mean focal tree DBH (cm)
PILA_Con	11.7	81.8
PILA_R30C0	9.1	88.1
PILA_R30C2	9.1	99.1
PILA_RD1.2	17.7	111.3
PIPO_Con	12.0	89.4
PIPO_RD1.2	12.9	87.6

The mean plot radius for the control treatments is just for the measurement plots since there were no radial thinning treatments applied to them. The other mean plot radii were the actual mean radii of the radial thinning treatments applied.

87.6 cm (Tables 1, 2). All radial thinning treatments mentioned above were applied approximately one and a half years before dendrometer measurements were taken for this study.

Automatic point dendrometers were made using methods from Wang and Sammis (2008) (Fig. 2). Dendrometers were then connected to the trees by scraping off some of the outer bark to have a clean surface for the dendrometer to mount to. Care was taken to avoid exposure of cambium layer (not all bark was removed). The point dendrometer was placed in the C-clamp making sure the sensor's resistor slider (plunger) was pushed in to a depth of approximately 3 mm. The dendrometer was then connected to an Onset HOBO datalogger (Bourne, MA, USA). Other climate data were downloaded from the Chester, CA RAWs weather station (https://raws.dri.edu/cgi-bin/rawMAIN.pl?caCCHS). This included hourly measurements of mean air temperature, mean relative humidity, total solar radiation, and total precipitation (Fig. 3). HOBO data and Chester RAWs weather station data were then combined for analysis purposes.

Analysis methods

Combining and running data through dendrometeR

As for the HOBO data, the dendrometer unit recorded data in voltages rather than actual units. To convert the voltages from the dendrometer unit to radial distance in mm, a regression equation was made by manually pushing in the sensor's plunger at 0.2 mm increments and recording the respective voltage at each increment.

Any gaps in measurements due to technical issues were filled in with “NA” so that the data could be run through the dendrometeR package (Version 1.0.0) (van der Maaten et al. 2016) in program R (Version 4.0.4). Once initial compiling and cleaning of the data was finished, outliers were located by calculating Z-scores, and if Z-scores for a given sub-hourly dendrometer measurement were ≥2 or ≤-2, “NA” values were substituted (Ziaco and Biondi 2018).

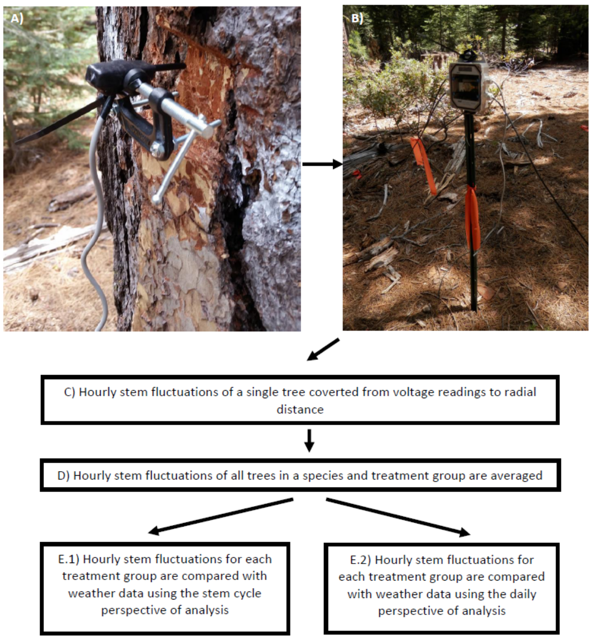
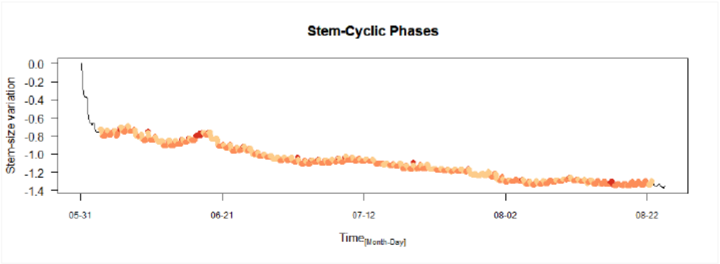


Fig. 2. Flow chart showing key stages of field data collection and data analysis steps. Close-up of point dendrometer (A) and HOBO data logger (B). Photos in A) and B) taken by Sophan Chhin.

The raw dendrometer data with all “NA” values added in as previously mentioned was then used as input for the dendrometeR package (van der Maaten et al. 2016). Any “NA” values in the dendrometer data were gap filled using the “fill_gaps” function (van der Maaten et al. 2016) to ensure gaps were estimated primarily by data adjacent to the gaps. Once gaps were filled, hourly averages of the dendrometer data were calculated. Then this data was combined with the Chester, CA RAWS station data (https://raws.dri.edu/cgi-bin/rawMAIN.pl?caCCHS).

The dendrometer datasets needed to be combined by species-treatment group to assess the treatment effects and climatic drivers of stem variation. Dendrometer data sets were standardized for each focal tree using a locally weighted quadratic regression via the “loess” function in the pro-

A. 126R30 stem cyclic phases



B. PILA_R30C0 stem cyclic phases

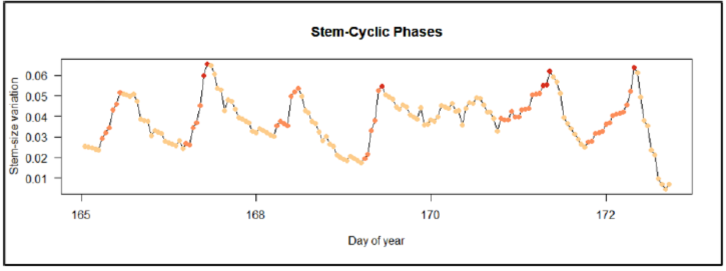


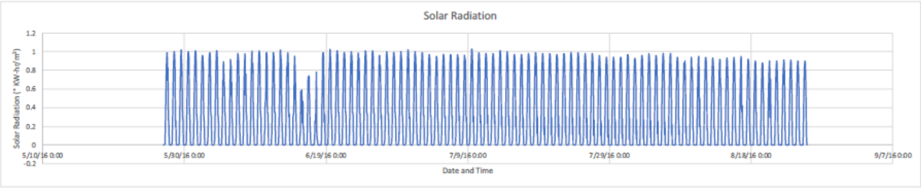
Fig. 3. Example output of the actual dendrometer data stem cyclic phases for an individual sugar pine tree, 126R30 (A), and for a portion of the normalized dendrometer data showing stem cyclic phases of the PILA_R30C0 treatment group (B). Yellow indicates contraction (phase 1), orange indicates expansion (phase 2), and red indicates stem radial increment (phase 3). Stem radial increment occurs when the stem expands further than the previous maximum.

gram R (Chhin et al. 2010). Once the dendrometer datasets were standardized, the initial residuals were averaged across the whole species-treatment group for each hourly increment, then cumulative values were calculated at each successive hour. These cumulative standardized dendrometer measurements will be further referred to as normalized stem variation.

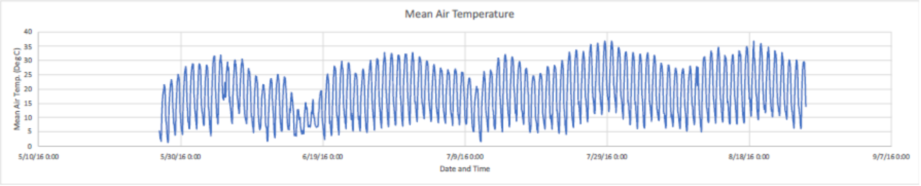
Three distinct stem cycle phases (contraction, expansion, stem radial increment) were identified using the "phase_def" function (van der Maaten et al. 2016) (Fig. 3). This function first looks within a specified daily time window, and offsets the original dendrometer series to ensure the initial extrema identified are the actual extrema of each cyclic phase (van der Maaten et al. 2016). The output from the "phase_def" function was used as input for the "cycle_stats" function in which cycles were defined based on the previously identified phases. A full stem cycle is denoted by a contraction, expansion, and a stem radial increment phase (if any increment occurs). Statistics such as magnitude (of normalized radial change), duration, and timing for each phase and cycle were then calculated (van der Maaten et al. 2016). The smoothing parameter for the "cycle_stats" function was set according to Deslauriers et al. (2007). The "climate_seg" function was then used to calculate the mean, min, max, and sum of all the environmental parameters for each given stem cyclic phase and cycle. The main stem cycle statistics from the dendrometeR package consisted of magnitude and duration of each stem cyclic phase as well as the mean and sum of the environmental variables during that respective phase (sum is only applicable to precipitation data).

Daily statistics were also calculated for the environmental and normalized stem variation data. The "daily_stats" function from the dendrometeR package calculated the following: amplitude of normalized radial change, timing of min and max of the normalized stem variation data, as well

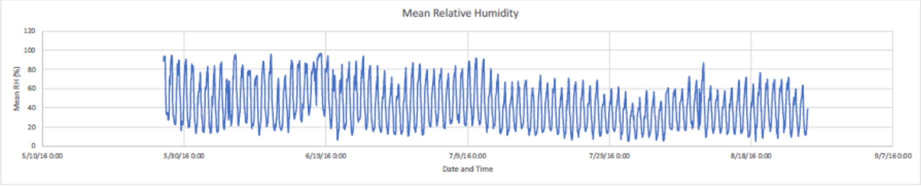
A. Solar radiation



B. Mean air temperature



C. Mean relative humidity



D. Total precipitation

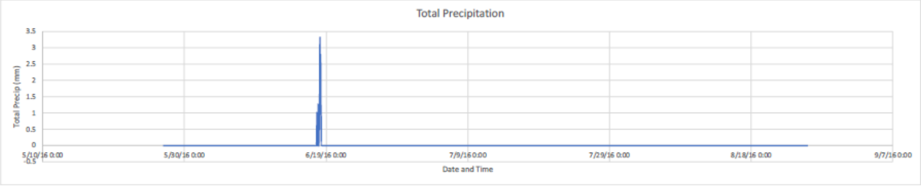


Fig. 4. Chester RAWs weather station for the measurement period. Data shown here is from the time of the first dendrometer measurement to the last dendrometer measurement.

as mean and sum of each environmental variable (sum only applicable to precipitation data).

Analyzing output from the dendrometeR package

To analyze dendrometeR package output for the stem cycle approach, Pearson correlations were run to determine the association between each climate variable and the magnitude and the durations of standardized stem fluctuations for each cyclic phase. In addition, a correlation matrix was developed on growth parameters (magnitude and duration) to assess if there was any correlation between magnitude and duration for all combinations of phases for a total of 15 separate Pearson correlations (i.e. magnitude of phase 1 vs. duration of phase 1, magnitude of phase 1 vs. magnitude of phase 2, etc.). Correlations and bootstraps were done separately for each climate variable versus phase duration, for each climate variable versus phase magnitude, and for each pair of variables in the correlation matrix. For the daily ap-

Table 3. Significant correlations between growth variables

Treatment group	Variable	Duration_1	Magnitude_1	Duration_2	Magnitude_2	Duration_3
PILA_Con	Magnitude_1		-	-	-	-
	Duration_2			-	-	-
	Magnitude_2			0.61^{a}	-	-
	Duration_3					-
	Magnitude_3					
PILA_R30C0	Magnitude_1		-	-	-	-
	Duration_2	-0.32^{b}		-	-	-
	Magnitude_2			0.41^{a}	-	-
	Duration_3					-
	Magnitude_3					0.83^{a}
PILA_R30C2	Magnitude_1		-	-	-	-
	Duration_2			-	-	-
	Magnitude_2				-	-
	Duration_3		-0.64^{b}			-
	Magnitude_3					
PILA_RD1.2	Magnitude_1	0.33^{a}	-	-	-	-
	Duration_2			-	-	-
	Magnitude_2		0.85^{a}		-	-
	Duration_3					-
	Magnitude_3					0.85^{a}
PIPO_Con	Magnitude_1		-	-	-	-
	Duration_2			-	-	-
	Magnitude_2	-0.30^{b}	0.76^{a}	0.30^{a}	-	-
	Duration_3					-
	Magnitude_3					
PIPO_RD1.2	Magnitude_1		-	-	-	-
	Duration_2			-	-	-
	Magnitude_2		0.29^{a}		-	-
	Duration_3					-
	Magnitude_3					

The underscore and number indicate a given phase (1=contraction, 2=expansion, 3=radial increment). Magnitude is the absolute value of the difference between the highest and lowest normalized stem growth for a given phase, whereas duration is how long that phase lasted. Values considered significant if after 1,000 bootstrapped correlations the 95% confidence interval did not include zero. Hyphens (-) are noted in cells where comparisons were not made or to avoid duplicate correlations. ^{a}Indicates a significant positive correlation between the variables whereas. ^{b}Indicates a significant negative correlation (mean correlation noted in cells with significant correlations).

proach, Pearson correlations were calculated to determine the association of each individual climate variable with amplitude of daily standardized stem radial variation. Variables were considered significantly correlated if after 1,000 bootstrapped correlations the 95% confidence interval of their correlation coefficient did not include zero, similar to Vieira et al. (2013).

Results

Climate data

The overall mean hourly solar radiation recorded from May 27th to August 25th, 2016 was 0.32° KW-hr/m^2 with a standard deviation of 0.36° KW-hr/m^2 (Fig. 4A). Mean air temperature was 18.55°C with a standard deviation of 8.54°C (Fig. 4B). The mean relative humidity for that time span of the measurement period was 42.40% with a standard deviation of 22.79% (Fig. 4C). The total amount of precipitation during the three months of field recordings was 18.02 mm (Fig. 4D).

Growth variable relationships

One of the most common significant correlations for the sugar pine groups was the positive correlation between magnitude and duration of the same phase (Table 3). For example, as magnitude of contraction increases, so would the duration of contraction, and this significant positive correlation was seen in PILA_RD1.2. The most common occurrence of the positive relationship was also found between the magnitude of expansion and duration of expansion, and this was observed in both the PILA_Con, and PILA_R30C0 treatment groups. There was also a very strong positive correlation between magnitude of radial stem increment and duration of radial increment for PILA_R30C0 and PILA_RD1.2. The other positive correlation found between growth variables was the positive correlation between magnitude of expansion and magnitude of contraction seen in PILA_RD1.2. We also found the strongest negative correlation between duration of stem-radius increment and magnitude of contraction for the PILA_R30C2 treatment group.

The most common significant correlation for the ponderosa pine groups was the positive correlation between magnitude of expansion and magnitude of contraction seen in PIPO_Con and PIPO_RD1.2 (Table 3). There was also a significant negative correlation between magnitude of expansion and duration of contraction for PIPO_Con. This was the only significant correlation found in the ponderosa pine group that was not found in the sugar pine group. Lastly, a significant positive correlation was found between magnitude of expansion and duration of expansion for the PIPO_Con treatment group.

Daily perspective

The most common and strongest significant correlations for the sugar pine treatment groups were seen between daily amplitude and daily mean solar radiation for PILA_R30C0 and PILA_R30C2 (Table 4). Only one significant positive correlation was found between daily amplitude and mean relative humidity, occurring in the PILA_RD1.2

Table 4. Daily approach analysis

Species and treatment group	Variable	Mean solar radiation (W/m^2)	Mean air temperature (°C)	Mean RH (%)	Sum precipitation (mm)
PILA_Con	Daily amplitude				
PILA_R30C0		0.23^a			
PILA_R30C2		0.44^a			
PILA_RD1.2				0.24^a	
PIPO_Con				0.32^a	
PIPO_RD1.2			-0.37^b	0.25^a	

Significant correlation values after running 1,000 bootstrapped correlations for each variable. If there is a significant correlation, the mean correlation value is indicated within the cell. ^{a}Indicates a significant positive correlation between the variables whereas. ^{b}Indicates a significant negative correlation (mean correlation noted in cells with significant correlations).

treatment group.

The most common significant correlation for the ponderosa pine treatment groups was the positive correlation between daily amplitude and mean relative humidity for both the PIPO_Con and PIPO_RD1.2 treatment groups. The only significant negative correlation found in the ponderosa pine groups was the negative correlation between amplitude of daily stem variation and daily mean air temperature for the RD1.2_PIPO treatment group.

Table 5. Stem cycle approach analysis

Species and treatment group	Variable	Mean Solar radiation (W/m^2)	Mean air temperature (°C)	Mean RH (%)	Sum precipitation (mm)
PILA_Con	Duration of contraction				
PILA_R30C0			-0.55^b	0.60^a	
PILA_R30C2		-0.91^b			
PILA_RD1.2		-0.40^b	-0.35^b	0.34^a	
PIPO_Con		-0.45^b	-0.43^b	0.40^a	
PIPO_RD1.2		-0.64^b	-0.42^b	0.53^a	
PILA_Con	Duration of expansion				
PILA_R30C0		-0.20^b			
PILA_R30C2		0.80^a			
PILA_RD1.2			0.28^a	-0.28^b	
PIPO_Con		0.39^a	0.53^a	-0.39^b	
PIPO_RD1.2					
PILA_Con	Duration of radial increment				
PILA_R30C0					
PILA_R30C2		-0.71^b	-0.72^b	0.83^a	
PILA_RD1.2					
PIPO_Con					
PIPO_RD1.2		-0.38^b			
PILA_Con	Magnitude of contraction				
PILA_R30C0		0.41^a			
PILA_R30C2					
PILA_RD1.2		-0.49^b	-0.40^b	0.45^a	
PIPO_Con		0.29^a	0.27^a		
PIPO_RD1.2		-0.33^b	-0.44^b	0.40^a	
PILA_Con	Magnitude of expansion				
PILA_R30C0					
PILA_R30C2		0.41^a			
PILA_RD1.2		0.71^a	0.42^a		
PIPO_Con					
PIPO_RD1.2					
PILA_Con	Magnitude of radial increment				
PILA_R30C0					
PILA_R30C2		-0.65^b	-0.68^b	0.76^a	
PILA_RD1.2		0.35^a			
PIPO_Con					
PIPO_RD1.2					

Significant correlation values after running 1,000 bootstrapped correlations for each variable. Mean correlation noted in cells with significant correlations. [a]Indicates a significant positive correlation between the variables for that species-treatment group. [b]Indicates a significant negative correlation.

Stem cycle perspective

In general, the stem variation of the sugar pine treatment groups was most often negatively correlated with mean solar radiation and mean air temperature (Table 5). Furthermore, the sugar pine groups that had the radial thinning treatments applied to them were more often correlated to the environment variables than the control treatment groups were. The duration of contraction for both the PILA_R30C2 and PILA_RD1.2 treatment groups was negatively correlated with mean solar radiation. The duration of contraction for both the PILA_R30C0 and PILA_RD1.2 treatment groups was negatively correlated with mean air temperature and positively correlated with mean relative humidity. The magnitude of contraction followed a similar pattern for PILA_RD1.2 in which the magnitude of contraction was negatively correlated with mean solar radiation and mean air temperature but positively correlated with mean relative humidity.

One notable finding for the sugar pine group was that the duration of expansion was positively correlated with mean air temperature and negatively correlated with mean relative humidity for PILA_RD1.2 (Table 5). The duration of expansion for PILA_R30C2 was positively correlated to mean solar radiation. All correlations between magnitude of expansion and the environmental variables for the sugar pine group were positive. There were also significant positive correlations between magnitude of expansion and mean solar radiation for both the PILA_R30C2 and PILA_RD1.2 treatment groups. The only other correlation found with the magnitude of expansion was the significant positive correlation with magnitude of expansion and mean air temperature for the PILA_RD1.2 treatment group.

There was a very similar pattern between the significant correlations found for the duration of stem radial increment and the magnitude of stem radial increment for the sugar pine treatment groups. Most of these correlations were found for the R30C2_PILA treatment group. In this case, the duration of radial increment and the magnitude of radial increment were both negatively correlated to mean solar radiation and mean air temperature but positively correlated to mean relative humidity. Both duration and magnitude of stem radial increment had fairly strong mean correlation values for those significant correlations mentioned. The other significant correlation found for the radial increment phase was the positive correlation between magnitude of radial increment and mean solar radiation for the PILA_RD1.2 group.

For the ponderosa pine group and for correlations with the contraction phase, both the PIPO_Con and PIPO_RD1.2 treatment groups had the same correlations with duration of contraction. In this case, they both were significantly negatively correlated to mean solar radiation and mean air temperature and positively correlated to mean relative humidity. Interestingly, the magnitude of contraction was positively correlated with mean solar radiation and air temperature for PIPO_Con, whereas the duration of contraction was negatively correlated with those same variables for the PIPO_Con treatment group. Lastly, the magnitude of contraction for PIPO_RD1.2 was positively correlated to mean relative humidity.

There were not many significant correlations identified for the ponderosa pine groups for the expansion phase. The PIPO_Con treatment group had a positive correlation between duration of expansion and both mean solar radiation and mean air temperature. There was a negative correlation between duration of expansion and mean relative humidity for the PIPO_Con treatment group. There were no significant correlations found between the magnitude of expansion and the environmental variables for the ponderosa pine groups. In addition, there were limited significant correlations found between the stem radial increment phase and the environmental variables. In this case, the only significant correlation found between the ponderosa pine groups and the stem radial increment phase was the negative correlation with duration of radial increment and mean solar radiation for the PIPO_RD1.2 group.

Discussion

Growth variables

The significant relationship between magnitude and duration of the same phase—especially for the expansion and radial increment phases—is a common finding in other studies (Deslauriers et al. 2007; Vieira et al. 2013; Biondi and Rossi 2015). The study done by Vieira et al. (2013) on maritime pine (*Pinus pinaster*) in the Mediterranean climate of Portugal attributed the relationship between magnitude and duration of expansion and radial increment in pre-summer (late June to August) to the long days that occur during this time. Since the days are longer and most expansion (also referred to as recovery) occurs during the night when transpiration slows or even ceases, the magnitude of expansion is highly dependent and restricted by the duration of time the tree has during the night to expand (Vieira et al. 2013). This is similar for radial increment since most radial increment occurs during the night when the tree stem is recovering; for example, if the stem can recover long enough to expand more than it contracted during the day, then a radial increment will occur. Hence, since nights are shorter during the summer, radial increment usually does not occur and rather an overall decrease in stem size often occurs throughout the summer in Mediterranean climates, as seen in Fig. 3A in the current study and in Vieira et al. (2013). The significant positive correlation between magnitude of contraction and magnitude of expansion can most likely be linked to the negative water potential that is created inside the stem when transpiration rates exceed the rate of water uptake—which also leads to stem shrinkage (contraction) (King et al. 2013). Therefore, as the stem contracts, water potential becomes more negative within the stem because it is losing more water to transpiration without being able to replenish it, therefore creating a stronger pull at the roots (Pallardy 2008). This stronger pull created at the roots would then likely pull up more water throughout the night when the stem is recovering during the expansion phase (compared to if the stem shrank less and therefore had a less negative water potential). This is likely why the magnitude of expansion is strongly positively correlated to the magnitude of contraction. Liu et al. (2017) also had a similar finding in which they found a positive relationship between amplitude of recovery and magnitude of contraction and highlighted the interdependency of these two phases—this relationship occurred even under drought conditions in the Liupan Mountains of Northwest China.

Daily perspective

Similar findings regarding the significant correlations between daily amplitude and solar radiation and relative humidity were also found in Biondi and Rossi (2015) in *Pinus monophylla* in the Great Basin Desert of North America. However, they compared those variables to the daily stem variations computed from daily averages and daily maxima and did not explicitly state the sign of the correlation. There were some findings that were unique to each species group, however. Regarding the sugar pine groups, PILA_R30C0 and PILA_R30C2 both had a positive correlation between daily amplitude and mean solar radiation, while there were no significant correlations found between these variables for the ponderosa pine group. It is unclear why only sugar pine would have that correlation and not ponderosa pine as well. A study done by King et al. (2013) on larch and spruce trees in the central Swiss Alps also observed increased daily amplitude on days with greater amounts of sunshine. They attributed these observations to the greater evaporative demand on days with stronger solar radiation (King et al. 2013). It is important to note that amplitude is an absolute value calculation for the daily approach—a possible disadvantage regarding the use of the daily approach. Therefore, any value for daily amplitude can mean an overall increase in stem size or an overall decrease in stem size for that day. In this case, it is most likely that the stem size decreased more on those sunnier days.

A finding that was unique to the ponderosa pine group was the negative correlation between daily amplitude and mean air temperature for the PIPO_RD1.2 treatment group. However, King et al. (2013) observed an increase in daily stem amplitude on days with higher temperatures. They attributed this to the increased canopy transpiration and water demands that are required on hotter days. This finding does not align with this study in which we observed a negative correlation with daily amplitude and mean air temperature for the RD1.2_PIPO group. This could be attributable to differences in species and climate patterns between the two study areas. The area where King et al. (2013) conducted their study is also relatively dry, but precipitation is distributed evenly throughout the year. This is different from the Mediterranean climate of the Lassen National Forest, characterized by warm and dry summers with most precipitation occurring during the winter. In this case, it is more likely that the ponderosa pine in the Sierra Nevada closed their stomata on those hotter days to avoid xylem cavitation since they are isohydric species that close their stomata quickly during periods of high water stress

(McDowell et al. 2008), whereas there may be enough moisture in the summer in that region of the Swiss Alps to allow trees to keep their stomata open and therefore transpire and contract more. The positive correlation between daily amplitude and mean solar radiation unique to PILA_R30C0 and PILA_R30C2 treatment groups, this could be related to how isohydric or anisohydric sugar pines are. Though information is lacking regarding how isohydric (or anisohydric) sugar pines are, this finding may allude that sugar pines are more likely to keep their stomata open on sunnier (possibly drier) days than ponderosa pines and therefore be more anisohydric than ponderosa pine (therefore closing their stomata less readily during periods with high water stress (McDowell et al. 2008)). If that is the case, sugar pine may be keeping its stomata open on those sunnier days, causing the stem to contract more and have a larger amplitude (though we can only assume the direction of growth when given just the daily amplitudes). A future study to determine if sugar pines are isohydric or anisohydric may help to explain more of the differences in responses to climate between these species.

Stem cycle perspective

The magnitude and duration of contraction being negatively correlated with air temperature and solar radiation is expected when considering the climate of the Sierra Nevada. Since the climate is already warm and dry in the summers (Yeh and Wensel 2000; Bigelow et al. 2014), it is more likely that stomata of the sugar pine and ponderosa pines closed on these hotter days since there is limited water. Vieira et al. (2013) had a similar finding in which magnitude of contraction was negatively correlated with maximum temperatures during the summer in the Mediterranean region of Portugal. They attributed this to the high temperatures and low soil water content during the summer causing the trees to control transpiration more—thus causing the stem to contract less on hotter days when the stem is controlling transpiration even more. The duration of contraction and magnitude of contraction being positively correlated to mean relative humidity (RH) does not seem to be a growth response covered in other dendrometer studies. This finding is opposite to what is expected when considering the effect of relative humidity on transpiration rates. Since the water vapor concentration gradient between the leaf and the atmosphere on high RH days is lower, the tree would not transpire as much compared to a low RH day (Pallardy 2008) when just considering the concentration gradient that is pulling water from the leaf into the atmosphere to drive transpiration. If that is the case, the stem should actually contract less on these days because it would be losing less water relative to a lower RH day. However, this increase in magnitude and duration of contraction on higher RH days could also be occurring because the tree is more likely to keep its stomata open to transpire because it does not have as high of a risk of water loss due to the shallower concentration gradient causing a slower transpiration rate (Pallardy 2008). One of the most surprising findings regarding the contraction phase was that the PIPO_Con treatment group had a positive correlation with magnitude of contraction and mean air temperature and solar radiation whereas the PIPO_RD1.2 treatment group had a negative relationship with those environmental variables. This means that the control treatment group contracted more on those hotter and sunnier days than the RD1.2 treatment group. This difference between the control and RD1.2 treatment groups for the ponderosa pine species is an early indication that the extended radial release treatments are beneficial for higher tree productivity. This will be explored more once the stem radial increment correlations are discussed.

The duration of expansion for PIPO_Con was positively correlated to mean solar radiation and mean air temperature but negatively correlated to mean RH. Liu et al. (2017) had a similar finding regarding air temperatures in which they found a positive correlation between stem expansion and maximum air temperature during the dry summer stage defined for their study. Though this finding is similar, it was for maximum air temperature and magnitude of expansion instead of mean air temperature and duration of expansion. However, they are comparable since duration and magnitude of expansion were positively correlated for the PIPO_Con group (Fig. 3). Liu et al. (2017) attributed this positive correlation to the fact that air temperature was controlling the stem contraction during the daytime. Therefore, when the stem contracted more during the daytime with increased temperatures, the stem also expanded more during the evening and overnight to try to replenish the lost water from the stem contraction phase (Liu et al.

2017).

The lack of significant correlations between the stem radial increment phase of PIPO and the environmental variables is likely due to the fact that stem radial increment is not very common during the dry summers in Mediterranean climates; this lack of significant correlations with the increment phase also occurred in Vieira et al. (2013). The significant negative correlation of duration and magnitude of radial increment to mean solar radiation and mean air temperature, though not found in either the Vieira et al. (2013) or the Liu et al. (2017) studies, can likely be explained by the increasingly dry conditions created on those days from the high temperatures drying out the soil (Vieira et al. 2013). Even though contraction is limited on those days as explained by Vieira et al. (2013), the decreased soil moisture created by the high temperatures in a climate already known for its dry summers would create a microclimate that is not conducive to gains in stem radial increment.

It is important to note that the magnitude of radial increment of the PILA_RD1.2 treatment group was positively correlated to mean solar radiation. This means that the PILA_RD1.2 group increased radial increment on sunnier days. This finding, along with the previous finding that the PILA_RD1.2 treatment group contracted less on warmer and sunnier days suggests that the PILA_RD1.2 treatment group was less negatively affected by increasing temperatures and solar radiation and that it may even benefit from warmer and sunnier days. This may shed light on the extended radial release RD1.2 treatment being the most effective at releasing these legacy sugar pine trees to improve growth and vigor since trees in this treatment category seemed to be less negatively affected by increasing temperatures and higher solar radiation. A thinning study done by Magruder et al. (2013) found that a moderate thinning intensity (21 m^2/ha) may be best for increasing productivity and climatic resiliency of the remaining trees for a red pine plantation in Michigan. Since the work reported here did not categorize specific thinning intensities and rather categorized radial release sizes, it is hard to make an accurate comparison between the two. However, the diameter based radial release using the RD1.2 treatment may help to apply extended radial release treatments that increase available resources for remaining trees compared to unthinned stands or the standard thinning radius of 9.1 m used by the USDA Forest Service (Hood et al. 2018). Furthermore, Hood et al. (2018) found that a radial thinning radius of 9.1 m around legacy ponderosa and Jeffrey pines in the Lassen National Forest, California was not sufficient to result in increased growth (Basal area increment, BAI), but it did help to lessen growth decline. Lessening growth decline and a heterogenous canopy structure may then bring about other benefits such as increased drought tolerance and a reduction in wildfire severity and bark beetle attack risk (Hood et al. 2018). In addition, Hood et al. (2018) suggests a thinning radius larger than 9.1 m may be sufficient to increase BAI. Therefore, the larger thinning radius that would be applied using the extended thinning radius RD1.2 treatment may be sufficient to increase growth and vigor of the remaining legacy trees—especially for sugar pines. The results from this study indicate that the PILA_RD1.2 contracted less on warmer, sunnier days and put on more radial increment on sunnier days appears to support that claim.

Conclusions

The findings from this study highlight the important role that mean solar radiation, air temperature, and relative humidity play in stem variations of sugar and ponderosa pines from the Sierra Nevada region. One of the more significant findings from a management perspective highlights both positive and negative correlations between magnitude of contraction and mean solar radiation and air temperature. The positive correlation with those variables was found for the control treatment group; suggesting control group (greater stand density) tended to contract more on those warmer days. The negative correlation with contraction and mean solar radiation and air temperature was found for the RD1.2 treatment group where trees tended to contract less on those warmer days. This suggests that the extended radial thinning treatments likely provided more resources for the residual trees. When considering the magnitude of stem radial increment, however, the only significant positive correlation with mean solar radiation or air temperatures was found with the PILA_RD1.2 treatment group and mean solar radiation. The contraction phase seems to be more likely due to increased moisture levels in RD1.2 treatments causing the trees to more readily replenish water in their stems and therefore contract less. Since they contract less on those hotter and sunnier days, they are likely to put on stem radial increment under those conditions.

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