AN ABSTRACT OF THE THESIS OF

Derek M. F. Gourley for the degree of Master of Science in Sustainable Forest Management presented on July 18, 2016.

Title: Impact of Climate and Disturbance on the Formation of Earlywood and Latewood in Douglas-fir at the Salal Fields Study Site.

Abstract approved:

____

Douglas A. Maguire

Wood density is controlled to a large extent by the relative widths of earlywood and latewood in the stem, but the mechanisms controlling these amounts are poorly understood in coastal Douglas-fir. To understand the role of climatic factors, one hundred and thirty-six increment cores were collected and measured from the Salal Fields study site located in Western Oregon. Increment cores were collected from the four following heights on 38 Douglas-fir trees representing differing social positions: 1.37, 2.44, 4.88, and 7.01 m. A master chronology was constructed using the median earlywood and latewood time series for all of the increment cores collected. Statistical models indicated that earlywood growth was impacted most by temperature, while latewood growth was impacted most by the amount of summer precipitation. The site experienced disturbance events, which impacted earlywood growth in 1980 and latewood growth in 1983. The majority of variation in the master chronologies of both earlywood and latewood for this site can be explained by changes in climate and the presence of disturbance events.

Impact of Climate and Disturbance on the Formation of Earlywood and Latewood in Douglas-fir at the Salal Fields Study Site.

by
Derek M. F. Gourley

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented July 18, 2016
Commencement June 2017

Master of Science thesis of Derek M. F. Gourley presented on July 18, 2016

APPROVED:

Major Professor, representing Sustainable Forest Management

Head of the Department of Forest Engineering, Resources and Management

Dean of the Graduate School

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.

Derek M. F. Gourley, Author

ACKNOWLEDGEMENTS

The author expresses sincere appreciation to Dr. Doug Maguire, Dr. Henry Lee, Mark Gourley, Starker Forests Inc., and the numerous other graduate students who have helped me along the way.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

Impact of Climate and Disturbance on the Formation of Earlywood and Latewood in Douglas-fir at the Salal Fields Study Site

Chapter 1

Introduction

Introduction

Many if not most forest landowners have an interest in the quality of wood produced at rotation age, particularly if they depend on timber revenues to provide their only or major source of income, or even just to their pay property taxes. The potential to increase wood value and associated revenue for landowners, and the opportunity for mills to increase value recovered from logs, are two major motivations for understanding the factors that influence the relative growth rates of earlywood and latewood. During periods characterized by a high supply of timber and a low demand, log buyers are able to be more selective about the logs they purchase. Some may even put a premium on timber that comes from sites that have historically been shown to produce higher quality wood. The result for landowners who have the sites or the silvicultural technology to produce high-quality timber is that they not only are able to successfully sell timber during a flooded market, but can also receive a premium for their higher quality wood.

Earlywood and latewood width largely determine wood density, particularly with regard to the relative proportion of earlywood and latewood produced in the growth rings. Wood density is an integrative variable that correlates strongly with the bending and breaking strength of wood, so reflects the potential value of end products that can be manufactured from wood by the time it reaches rotation age. Improving the predictive ability of growth models with regard to earlywood width, latewood width, and overall wood density can provide managers with another tool to improve the quality of wood they can grow. In the effort to enhance our understanding of controls on earlywood and latewood proportions, a retrospective study was conducted with the goal of better understanding the causative link between climatic variables and wood quality.

In chapter 2, one-hundred and thirty-six increment cores were taken from four different stem heights at the Salal Fields Fertilization study to test growth responses within the annual ring level as a function of monthly climate. Statistical analyses of the time series represented by annual earlywood growth and annual latewood growth were conducted separately because the anatomical properties and wood densities of each are very different. Sampling at a single site minimized the influence of geographic variation in site, genetics, and climate factors and facilitated focus on the effects of annual fluctuations in climate and disturbance events on earlywood and latewood formation. The goal was to better understand the controlling variables on earlywood and latewood width from pith to bark and from tree tip to tree base by applying dendrochronological techniques. The use of dendrochronology models allowed detection of weather and disturbance-related changes in earlywood or latewood widths to be assessed without the noise of age related trends. This approach was based on regarding site quality as a function of monthly climate and its implications for soil water and nutrient availability. Understanding the functional relationships between past climate and earlywood and latewood formation could also be helpful in better predicting what we can expect in the future, and the limited extent to which we can influence earlywood and latewood formation through silvicultural manipulations.

Chapter 2

Impact of Climate and Disturbance on the Formation of Earlywood and Latewood in Douglas-fir at the Salal Fields Study Site

Abstract

Wood density is controlled to a large extent by the relative widths of earlywood and latewood in the stem, but the mechanisms controlling these amounts are poorly understood in coastal Douglas-fir. To understand the role of climatic factors, one hundred and thirty-six increment cores were collected and measured from the Salal Fields study site located in Western Oregon. Increment cores were collected from the four following heights on 38 Douglas-fir trees representing differing social positions: 1.37, 2.44, 4.88, and 7.01 m. A master chronology was constructed using the median earlywood and latewood time series for all of the increment cores collected. Statistical models indicated that earlywood growth was impacted most by temperature, while latewood growth was impacted most by the amount of summer precipitation. The site experienced disturbance events, which impacted earlywood growth in 1980 and latewood growth in 1983. The majority of variation in the master chronologies of both earlywood and latewood for this site can be explained by changes in climate and the presence of disturbance events.

Introduction

A combination of factors, including cambial age, genetics, climate, geology, and nutrients are all known to impact several important wood properties such as average density, ring width, and the proportion of earlywood and latewood (Jozsa et al. 1989). Earlywood, produced in the beginning of the growing season, is characterized by large cells with thin walls, resulting in low earlywood density. In contrast, latewood accrues towards the end of the growing season and is characterized by small cells with thick walls, and therefore has a higher density (Jozsa et al. 1989). Controlling mechanisms on wood properties generally fall into one of two groups, i.e., mechanisms subject to managerial manipulation, and environmental mechanisms that cannot be controlled. As examples of the latter, climate and geology are unlikely to be manipulated directly in a forest management setting. In contrast, managers can influence cambial age at time of harvest, genetic source, and nutrient availability and, hence their effects on within-stem variation of wood properties. Silvicultural treatments and regimes can therefore potentially alter certain features of wood quality at the end of a rotation to influence the quality of corresponding wood products that should provide a more favorable return on investment. Climatic effects determine the background variation in wood properties that can be further influenced to varying degrees by management, so it is important to understand the impacts of climate variables to facilitate isolation of the type and magnitude of silvicultural effects. In addition, understanding the influence of climatic variables could help to predict response of similar sites to future climate trends.

Models constructed by Franceschini et al. (2013) to show temporal trends in *Picea abies* growth rings showed that water availability controlled the formation of both earlywood and latewood, while temperature was responsible for the formation of latewood. A study of Douglas-fir (*Pseudotsuga menziesii*) by Filipescu et al. (2014) demonstrated spatial differences in the wood properties trees that are also most likely attributable to regional variation in climatic influences. As a result, the authors emphasized the importance of local research within specific silvicultural field trials as a way of limiting the noise introduced by differences in climate and geology among replications or among different studies. This local focus would allow the effects of silvicultural treatments to be quantified more clearly.

Objective Statement

The objectives of this research were to: 1) model the influence of site variables, such as climate and implied soil water availability, on earlywood and latewood width; 2) identify through the resulting model the key site (primarily climatic) variables that control the majority of variation in earlywood and latewood width.

Methods

Study Site

The Salal Fields study site is located in Western Oregon, near the town of Summit at the eastern edge of the Oregon Coast Range (44°40'21.458"N, 123°41'15.9396"W). The site was initially established in 1975 using Douglas-fir from a nearby natural seed source. Starting in 2003, Starker Forests Inc. decided to use the 28-year-old stand to study the potential growth impacts of applying a site-specific blend of nutrients. Four 0.101-hectare plots were installed in 2003 and the initial fertilization began in 2004. Nutrients were applied every year through 2014. The year of application and amount of each nutrient applied is shown in Table 1. The experimental design included two control plots and two treatment plots. In addition to the initial nutrient application in 2004, the treatment plots also received intensive vegetation control to remove any understory vegetation, in particular salal (*Gaultheria shallon*).

The stand selected for this study was regenerated using local natural seed sources, thereby eliminating any potential influence of genetic tree improvement on the earlywood or latewood widths. Because this area was also impacted to varying degrees by Swiss Needle Cast (*Phaeocryptopus gaeumannii*), a disease known to impact the relative proportions of earlywood and latewood, restricting the study to one site and one corresponding level of Swiss needle cast intensity reduced the potential complications of accounting for site-to-site variation in these influences.

During the years of 1980 to 2014, the Salal Fields study site received an average 165 centimeters of precipitation each year. Temperatures for the site from 1980 to 2014 ranged from an average daily low of -8°C in the winter to an average daily a high of 36°C in the summer with a yearly average temperature of 10°C. The general terrain is flat and the site is located near a local hilltop. In 2003 the four plots ranged from a basal area of 7.44 m^2/ha (32.42 ft^2/ac) to 8.98 m^2/ha (39.12 ft^2/ac). Tree density ranged from 348 to 435 trees per ha (141 to 176 trees per acre) for the four plots. Additional information about the conditions in each of the plots in 2003 can be found in Table 2. Given that the site was planted using local natural seed sources and was precommercially thinned, the four plots would be expected to have a slightly different tree density and basal area in 2003. The potential effects of these differences in stand conditions on earlywood and latewood widths therefore need to be accounted for in the models.

An interesting challenge with this site was the presence of Swiss-needle cast (*Phaeocryptopus gaeumannii*). This pathogen has infected many of the Douglas fir trees in each of the four plots. This pathogen is known to potentially reduce the growth of both earlywood and latewood, and to have a stronger effect on reducing earlywood growth (Johnson et al. 2003). Despite the equal disease pressure most likely present at this one site, trees appeared to be differentially tolerant of Swiss-needle cast, as has been observed in progeny tests (Temel et al. 2004). Intensity of Swiss-needle cast infection was assessed by visual estimation of foliage retention (number of annual cohorts) to account for level of Swiss-needle cast infection in the wood ring analyses.

Weather Data

The weather data used in this study came from three sources. The first source was the PRISM Climate Group Data Explorer (PRISM. 2016). Climate data on a monthly resolution were gathered from PRISM by entering the longitude and latitude of the Salal Fields study site and selecting the "interpolate grid cell values" option. The site-specific PRISM estimates included monthly precipitation, minimum temperature, mean temperature, maximum temperature, and mean dewpoint temperature, each downloaded as a monthly time series from 1895 to 2014 using from the following link on June 2, 2016:(*http://www.prism.oregonstate.edu/explorer/*).

The second source of weather data was a weather station at a nearby study site just one air mile away and representing the "Nortons" replication of a regional Douglas-fir provenance trial administered by Dr. Connie Harrington, with weather monitoring managed by Dr. Dave Thornton, both of the USDA Forest Service. The Nortons weather database provided an opportunity to compare and calibrate the PRISM weather data for minimum temperature, mean temperature, maximum temperature, and precipitation, given that it was not part of the existing PRISM weather station network. The weather station had been online since December 2008 and has 88 months of weather data for validation of the PRISM interpolations for that site. A PRISM weather monthly time series corresponding to the same 88-month period for the latitude and longitude of the weather station was downloaded and compared to the data collected on site.

Dr. Henry Lee at the Environmental Protection Agency provided the final source of climate data for this study, the Palmer Drought Severity Index (PDSI) data, which was downloaded from the NOAA's National Centers for Environmental Information website (*http://www.ncdc.noaa.gov*). PDSI provides an index that can be used to determine the relative wetness and dryness of a given year. A higher PDSI (1 or greater), generally indicates a wet year and a lower PDSI indicates a drier year (-1 or lower). While there can be some time lag in response of growth to the PDSI index for a given year, the index is useful as a relative measure of climatic extremes and therefore as an explanation for unusual growth trends.

The PRISM weather data validated very well with the weather station data from the Nortons study site. Figures 1 and 2 show that PRISM tends to be slightly conservative for minimum and maximum temperature over the 88 month of available data. Figures 3 and 4 show that the PRISM data for average temperature and precipitation matched up with the local weather station data almost exactly. The PRISM data were concluded to match up very well with the local weather station and required only minor adjustments to calibrate predictions to Nortons. Calibration of the PRISM weather variables to the local weather station was achieved by calculating the differences between averages over the 88 months available at Nortons. An assumption was made that the difference in weather data that occurred over the 88 months used for validation remained constant for the entire period between 1980 and 2014. A second assumption was that the correction factor for the provenance trial weather station was the same as would be computed for the Salal Fields study site if weather data were available for the latter. The possible error in weather variable estimates for Salal Fields is unknown, but inferred to be trivial. The calibration factors determined from the 88 months at the provenance trials were therefore applied to the entire PRISM monthly time series downloaded for the Salal Fields site from 1980 to 2014.

Another potentially useful weather variable, dewpoint deficit (dpd), could be calculated from the available weather variables. The dewpoint deficit is an indication of the atmospheric moisture stress that the site is experiencing. The mean dewpoint temperature was subtracted from the mean temperature in order to calculate the dpd. This was done to generate a variable that would be comparable to vapor pressure deficit. In addition, moisture stress from the current year could conceivably impact growth in the following year. To account for any potential lags in moisture stress effects, two more variables were calculated for each year, i.e., the previous year's dewpoint deficit and the previous year's PDSI.

Tree Data

Given that the silvicultural trials at this site represented a long-term study, destructive sampling by felling trees was not possible. Scaffolding was set up to obtain increment cores from different heights on the stem. Due to the difficulty of starting a ½ inch increment Haglof borer from the erected scaffolding, the borer was attached to an electric impact drill to collect the cores higher up on the stem. The use of a drill also made it possible to get ½ inch cores without compromising the integrity of the cores, because without the electric drill the outer rings were easily lost. A total of 136 increment cores were collected from 38 trees at stem heights of 1.37, 2.44, 4.88, and 7.01 m (4.5 ft, 8 ft, 16 ft, and 23 ft, respectively). Each increment core was taken from the north facing side of the tree if possible. In some cases the exact height of the cores had to be adjusted slightly for branch whorl swell and other stem defects. In the case that a slight adjustment in height was needed to avoid stem defect, it was often minor and the increment core was only taken a few cm from the planned location. After all of the increment cores were collected, the cores were slowly air dried for several months. This drying time was used to prevent any major warp or distortion that could result from quick drying in an oven or climate chamber, and that could negatively impact the accuracy of the annual ring widths, earlywood widths, and latewood widths.

Preparing the Data

Once the tree cores had sufficiently dried, they were taken to the Environmental Protection Agency lab in Corvallis, Oregon, for preparation and measurement. The cores were first sanded using 120-grit sandpaper and were then sanded again with 220-grit sandpaper. Sanding clarified the earlywood and the latewood zones and thereby facilitated more accurate measurements. Wood cores were measured with an Epson Expression 10000XL flatbed scanner and WinDENDRO Density software. This equipment has been paired and calibrated to allow wood samples to be measured with an accuracy of better than 0.01 mm.

Following the completion of the earlywood and latewood measurements, the COFECHA software package developed by Richard L. Holmes at the University of Arizona Tree Ring Laboratory was used to ensure there were no missing rings (Holmes. 1983). Cross-validation of cores was achieved by comparing total ring widths from WinDENDRO. A mean chronology was built by selecting six cores, each of which had the largest and most distinct rings. This process was repeated for each of the four plots. After the best six cores for a plot were cross validated, the remaining cores were added one at a time into the core list in COFECHA in order to validate each added core against the mean chronology created from the six best cores. Cross-validation involves computing the correlation coefficient between the ring widths of two cores or a core and a chronology. A correlation of 0.5 or greater is generally desired when cross-validating. In the Salal Fields cores, a series of small rings in some of the cores prevented achievement of the desired correlation of 0.5. Given that Swiss Needle Cast has been present in the stand, and that no rings were missing, the acceptable correlation coefficient was dropped to 0.2. The acceptable correlation of 0.2 was used as long as the peaks and troughs for the core matched up with the mean chronology throughout the entire time series.

Creating the Master Chronologies

After cross-validation was completed, age-related trends from each of the individual earlywood and the latewood time series had to be removed so that the residual climatic signals could be analyzed. To accomplish this, each individual time series of earlywood and latewood was transformed using the common logarithm. After the logarithmic transformation, a spline curve was fit to each of the time series. A spline curve using parameters set at "50% frequency at a wavelength of 32 years" was used to individually fit each of the earlywood and latewood time series (Grissino-Mayer. 2001). The parameters selected for the spline curve were selected to match the default parameters for cross-validation in COFECHA; however, the user has the option to change these default parameters (Holmes. 1983). Setting parameters at "50% frequency at a wavelength of 32 years" has been shown to provide the best results when applied to data sets from several different regions and is generally considered a safe option (Grissino-Mayer. 2001). A spline curve with these parameters removes systematic and predictable growth trends that occur over time while at the same time preserving higher frequency climate signals (Grissino-Mayer. 2001). The values from the spline curves fitted to a given time series were then subtracted from each of the measured values in that series in order to remove the age related trends over time, essentially leaving the time series of residuals from the fitted curves.

To determine the general impacts of climate on earlywood and latewood at Salal Fields, i.e., without any influence of the nutrient application or the social position of the trees, two-master chronologies were created. The first master chronology consisted of the median detrended earlywood time series selected from all of the increment cores, resulting in a single time series of median values selected independently for each of the years from 1980 to 2014. This was done to eliminate any stem height or plot influence, with the hope of using the median to select a core that is the most representative of climate for the site. This same process was used to make the second master chronology for the detrended latewood time series at the site. The end result was a master chronology for earlywood and a master chronology for latewood that represented the Salal Fields study site from 1980 to 2014.

Modeling the Chronologies

To model the chronologies, the following methods described and implemented by Lee et al. (2016) were used. First a cross correlation analysis between the monthly climate variables and each of the chronologies was conducted to determine which climate variables correlated well with the earlywood and the latewood master chronologies. Second an auto-regressive moving average (ARMA) model was used for the variance-covariance structure, allowing simultaneous testing of climate and disturbance effects on this site. Models were fitted by maximum likelihood in the R statistical software (R Core Team. 2015). Earlywood and the latewood models were fitted with the GLS function in the NLME package in R (Pinheiro et al. 2016). To handle the presence of autocorrelation in the time series of earlywood and latewood, numerous models were fitted assuming different autoregressive covariance structures and compared by AIC and other related statistics. The best autoregressive structures were determined separately for the earlywood model and for the latewood model.

For the latewood model a new earlywood variable was calculated in order to remove the autocorrelation present in the earlywood time series. This new earlywood variable was calculated by subtracting the mean response function as specified in the earlywood model from the observed earlywood widths. This allowed for the newly created earlywood variable to be included in the latewood model in order to create a seasonal time series. Adding the new earlywood predictor variable to the latewood model acts as a check to help verify that the model form of the earlywood was correct. In the latewood model, the new earlywood variable had a positive coefficient, which is expected, since current year earlywood growth is expected to have a positive impact on the latewood growth for the same year.

In order to account for the impact of disturbance events in the model, a pulse intervention technique was implemented. If a there was a reduction in growth that fell outside the range in growth typically observed by climate trends for the entire time series, the year was classified as a possible disturbance year. In the model an indicator variable was added specifically for each possible disturbance year and was tested for significance. Disturbance years were examined individually for the both the earlywood and latewood master chronologies.

Results

Earlywood Model

The final model for earlywood width was as follows:

[1] $\mathrm{Log}_{10}(EW) = \beta_{10} + \beta_{11} * \text{last\_year\_dpd} + \beta_{12} * \text{winter\_tmax} + \beta_{13} * \text{summer\_tmax} + \beta_{14} * \text{d1980} + \varepsilon_1$

where, EW was the observed width of earlywood (nearest 0.01 mm) after removing the age related trend using spline curves, last_year_dpd was the mean of the previous year's June, July, August, September, October, November, and December monthly dewpoint deficits for June through December (°C), winter_tmax was the mean of November and December maximum temperatures from last year and maximum temperatures for January and February in the current year (°C), summer_tmax was the mean June and July maximum temperature (°C), D1980 was the pulse intervention indicator for the disturbance detected in 1980 (1 for 1980; 0 for all other years), β_{10}-β_{14} were parameters estimated from the data, and ε_1 was the error term with a specified second order autoregressive variance-covariance structure.

The previous year dewpoint deficit, winter maximum temperature, and summer maximum temperature were the only statistically significant variables selected as biologically reasonable for inclusion in the earlywood model. Precipitation and any variables that indicate current year moisture conditions failed to enter the model in a form that made biological sense. The growth of earlywood was inferred to be insensitive to water at this site, but rather was influenced almost entirely by temperature. As winter temperature increased, growth of earlywood in the subsequent growing season increased. In contrast, as summer temperature increased, growth of earlywood decreased. The positive coefficient of winter temperature potentially indicated that warmer winter temperatures reflected an earlier start to the growing season, resulting in an increase in total earlywood width. In contrast, the negative coefficient for summer temperature potentially indicated that as summer temperature increased, the site began to experience earlier water limitation and earlier start of moisture stress, hence a shorter growing season.

Besides the impact of temperature in the earlywood model, there was a single and very significant disturbance event that occurred early in the history of the site. In 1980, a disturbance event reduced earlywood growth by 46%, after accounting for the impacts of climate. This reduction in earlywood growth is outside the typical 25% to 30% range in growth reduction that would occur from normal fluctuations in climate. The three variables in the earlywood model accounted for 80% of the variation in the growth of earlywood within the Salal Fields study site.

Latewood Model

The final model for latewood width was as follows:

$$[2] \quad \text{Log}_{10}(\text{LW}) = \beta_{20} + \beta_{21} * \text{earlywood} + \beta_{22} * \text{summer\_ppt} + \beta_{23} * \text{summer\_tmean} + \beta_{24} * \text{d1983} + \varepsilon_2$$

where LW was the observed width of latewood (nearest 0.01 mm) after removing the age related trend using spline curves, earlywood was the observed earlywood width (nearest 0.01 mm) in the same year after subtracting out the mean response function (parameter estimates from equation [1]), summer_ppt was the mean June, July, August, September, and October precipitation for June through October (cm), summer_tmean was the mean of July through September mean temperature (°C), D1983 was the pulse intervention indicator for the disturbance detected in 1983 (1 for 1983; 0 for all other years), β_{20}-β_{24} were parameters to be estimated from the data, and ε_2 was the error term with a specified second order autoregressive variance-covariance structure.

The explanatory variables representing the earlywood of the same year, summer precipitation, and mean summer temperature were the only statistically significant variables that made biological sense for inclusion in the latewood model. In contrast to the earlywood model, precipitation was statistically significant, so apparently latewood growth on this site was impacted by both temperature and water. The parameter estimate for summer precipitation was positive indicating that any additional water available during the summer in the form of precipitation increased latewood growth. This is one indication that the site experienced water limitation towards the end of the growing season. In addition, the parameter estimate for mean summer temperature was negative, indicating that an increase in mean summer temperature reduced the growth of latewood. The parameter estimates for both of these variables appear to indicate that the site experienced a water limitation and high moisture stress during the summer months.

In addition to the impact of summer precipitation and summer temperature, there was one important disturbance event that had a statistically significant impact on the growth of latewood at the site. In 1983 there was a disturbance event that reduced latewood growth. Surprisingly, 1980 was not a significant disturbance year for latewood, even though it was a disturbance year for earlywood. Conversely, 1983 was not a disturbance year for the earlywood. Apparently, earlywood and latewood responded differently to detected disturbance events, despite the expectation that a detectable disturbance would impact both the earlywood and the latewood in that year. The disturbance in 1983 reduced total growth by 15%. The three variables in the latewood model accounted for 50% of the variation in the growth of latewood at Salal Fields.

Discussion

Testing the impacts of climate and disturbance at Salal Fields led to several interesting conclusions. First, application of a statistical technique that accounted for the impacts of climate and disturbance event simultaneously was essential to explaining the variation in earlywood and latewood width. As is the case with most field studies, it was important to simultaneously account for multiple environmental variables that may impose very different patterns on annual growth. For example, in order to accurately assess the relatively pure impact of a disturbance event, it was necessary to first account for the impact of climate and then assess the marginal effect of the disturbance. Reductions in growth were statistically significant and the negative impact of a disturbance event was severe when compared to the multiple years of disturbance free growth throughout each of the time series. Furthermore the presence of disturbance events impacted the growth of earlywood and latewood during different years. On this site earlywood was impacted in 1980, while latewood was impacted in 1983. This difference in the years of disturbance impacts indicates the need of modeling the earlywood and latewood separately.

The exact cause of the disturbance events that this site experienced can only be speculated about, but it is possible that Swiss-needle cast could have been the disturbance agent. To attribute the cause of disturbance events on this site to Swiss needle cast, simultaneous earlywood width, latewood width, and needle retention measurements would need to be collected in the future. The resolution of the detrending procedure relative to sustained growth impacts of the current Swiss needle cast epidemic must also be considered. Early in an epidemic, disturbance events might be detectable in a given year, but later in the epidemic, longer-term trends would be evident, but would also be at risk of being lost by the detrending process. Regardless, a better understanding of the cause of disturbances and their impacts could help managers to better separate disturbances that are not related to climate or silviculture in the future.

The second significant conclusion from this study was that the impact of climate varied between the beginning of the growing season and the end of the growing season as indicated by the earlywood and the latewood growth at Salal Fields. In the beginning of the growing season, temperature was the dominating factor. Water limitation was not significant in the earlywood model, probably due to the fact that this type of site has most likely recharged its water reserves from the plentiful fall and winter precipitation. Winter temperature controls the start of the growing season, so it made sense that this variable was not only statistically significant, but positive in its effect. Earlywood growth would be greater in any year when the growing season was able to start sooner as a result of warmer winter temperatures. In contrast, warmer summer temperatures negatively impacted latewood growth, a physiologically logical response to implied evapotranspiration demands and water limitations. As the growing season reached the summer months, the need for water would increase as soil water availability declines. Both the earlywood and the latewood models reflect relative water availability. For latewood, summer precipitation was statistically significant, but Precipitation was not statistically significant in the earlywood model, most likely because water is not limiting during the early months of the growing season.

The two models developed in this study provide insight into the background effects of climate on the variation in wood properties related to earlywood and latewood growth and anatomy. The models also suggest the possible influence that future climatic trends could have on this and similar sites. The ability to understand and isolate the variation in earlywood and latewood width in response to climate provides forest researchers with greater statistical power to test and quantify the separate influence of Silvicultural treatments on earlywood and latewood widths, and also provides managers with perspective on the degree to which they can control or manipulate earlywood and latewood width.

Acknowledgements

I thank Mark Gourley and Starker Forests Inc. for allowing me to take increment cores from this long-term silvicultural research site. In addition, Starker Forests provided all of the necessary equipment in order to complete this study, including scaffolding, a crew to help with core collection, and shop space to prepare the cores for measurement. All of this help and resources made it possible to collect the data for this study in a non-destructive manner and allowed for the successful completion of this project.

I also acknowledge the help, guidance, and equipment provided to me by Henry Lee at the Environmental Protection Agency in Corvallis, Oregon. Henry was generous enough to provide me with a flatbed scanner as well as access to the WinDENDRO Density software. Henry's guidance and training with the COFECHA cross dating dendrochronology software and the WinDENDRO software helped ensure that measurements met conventional dendrochronology standards for quality. Henry also spent countless hours explaining the methodology behind his modeling approach; his guidance on dendrochronological modeling procedures was invaluable.

Finally, I acknowledge the USDI Bureau of Land Management for providing the funding for this study through Agreement No. L14AC00134 under the umbrella of the Pacific Northwest CESU Cooperative and Joint Venture Agreement No. BLM-OR952-1101.

Figure 1.

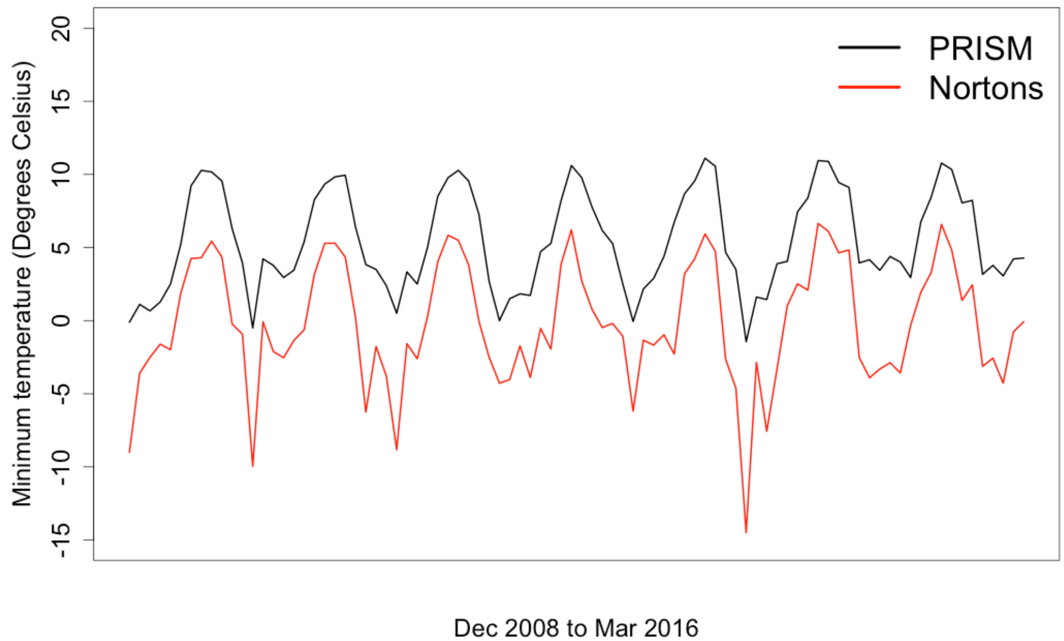
PRISM
Nortons
Minimum temperature (Degrees Celsius)
20
15
10
5
0
-5
-10
-15
Dec 2008 to Mar 2016

Figure 2.

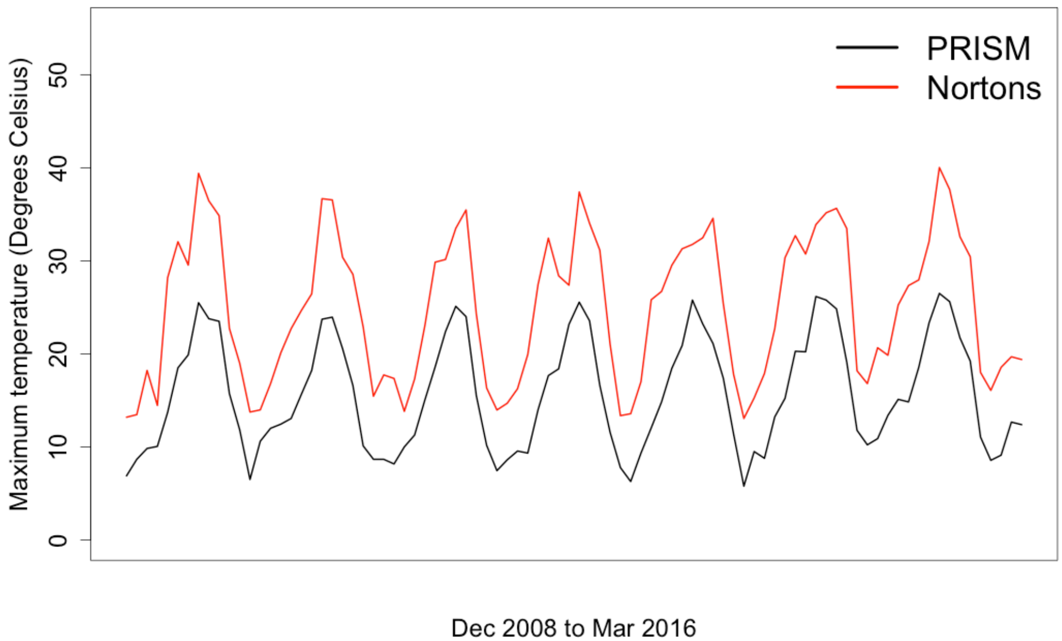
PRISM
Nortons
Maximum temperature (Degrees Celsius)
0
10
20
30
40
50
Dec 2008 to Mar 2016

Figure 3.

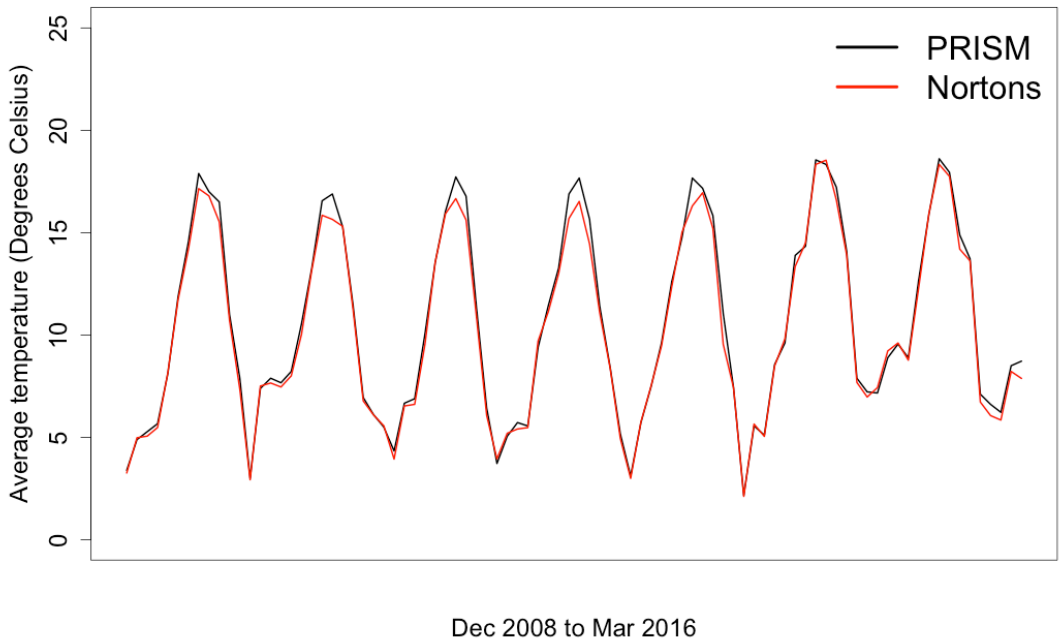
PRISM
Nortons
Average temperature (Degrees Celsius)
0
5
10
15
20
25
Dec 2008 to Mar 2016

Figure 4.

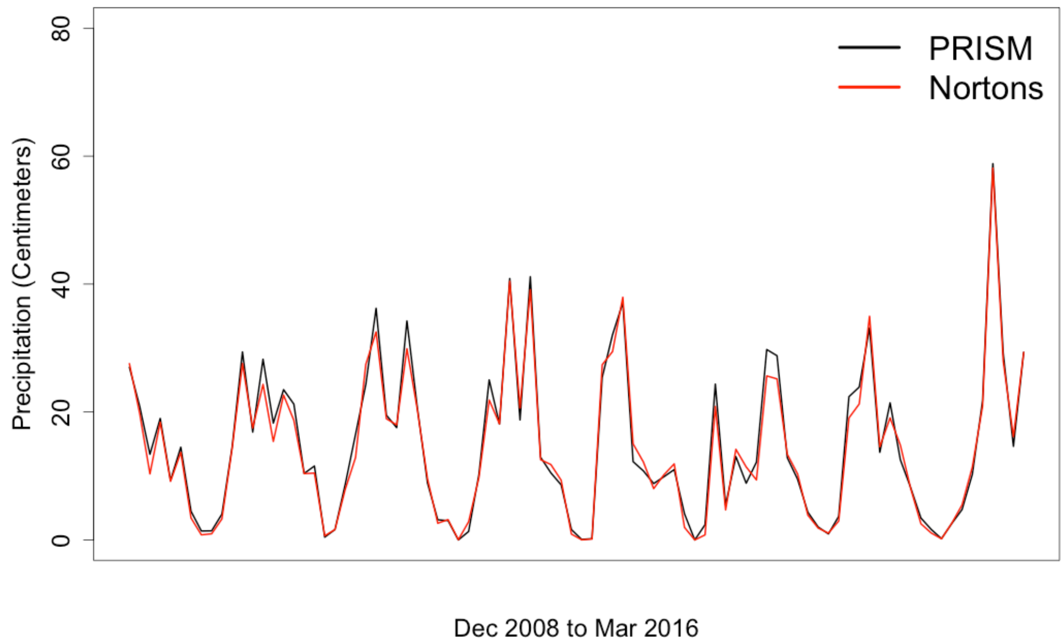
PRISM
Nortons
Precipitation (Centimeters)
0
20
40
60
80
Dec 2008 to Mar 2016

Table 1.

Material	Amount by date (kg/ha)				
	2004	2005	2007	Jan, 2013	Jun, 2013
Sulfur 90	101	0	0	0	0
Calcium Carbonate	1438	1922	0	0	0
Doloprill	1828	2710	0	0	0
Potassium Sulfate	188	0	0	0	0
Copper Sulfate 23%	22	11	0	0	28
Zinc Sulfate 36%	28	0	0	0	0
Boron 14.3%	11	6	0	0	0
Florida Iron	0	0	1120	0	0
Soft Rock Phosphate	0	0	560	0	0
Mosaic Phosphorus (12-40-10-1)	0	0	0	0.454 kg/Tree	0

Table 2.

Plot #	**Basal Area (m^2/ha)**	**Trees per ha**	**Average height (m)**
2 (Treatment)	8.98	435	24.77
4 (Control)	7.46	356	23.84
9 (Control)	8.51	348	23.85
10 (Treatment)	7.44	375	23.22

Table 3.

	Min	Mean	Max
PDSI	-4.21	-0.13	4.48
Precipitation (cm)	0.00	5.40	25.32
Minimum Temperature (°C)	17.05	31.63	43.55
Mean Temperature (°C)	33.79	50.95	65.59
Maximum Temperature (°C)	50.02	77.76	97.92
Mean Dewpoint Temperature (°C)	27.00	42.57	54.80
Dewpoint Deficit (°C)	2.99	8.37	15.99

Table 4.

Parameter	Estimate	Std.Error	T-value	P-value
B_{10}	0.3752978	0.09065063	4.140046	0.0003
B_{11}	0.0170806	0.00475843	3.589538	0.0012
B_{12}	0.0103408	0.00257938	4.009023	0.0004
B_{13}	-0.0112650	0.00181000	-6.223771	<0.00001
B_{14}	-0.2669732	0.01669440	-15.991783	<0.00001

Table 5.

Parameter	Estimate	Std.Error	T-value	P-value
B_{20}	0.2702619	0.08973990	3.011614	0.0052
B_{21}	0.3508792	0.08245505	4.255400	0.0002
B_{22}	0.0053315	0.00155793	3.422174	0.0018
B_{23}	-0.0149323	0.00525768	-2.840087	0.0080
B_{24}	-0.0703692	0.02044462	-3.441944	0.0017

Literature Cited

Filipescu, C. N., Lowell, E. C., Koppenaal, R., and Mitchell, A. K. 2013. Modeling regional and climatic variation of wood density and ring width in intensively managed Douglas-fir. Canadian Journal of Forest Research, 44(3), 220-229.

Franceschini, T., Longuetaud, F., Bontemps, J. D. et al. 2013. Effect of ring width, cambial age, and climatic variables on the within-ring wood density profile of Norway spruce Picea abies (L.) Karst. Trees, 27(4), 913-925.

Grissino-Mayer, Henri. D. 2001. Evaluating Crossdating Accuracy: A Manual And Tutorial For The Computer Program COFECHA. Tree-Ring Research, Vol. 57(2), 205-221.

Holmes, Richard L. 1983. Computer-Assisted Quality Control in Tree-Ring Dating and Measurement. Tree-Ring Bulletin. 43, 69-78.

Johnson, G.R., B.L. Gartner, D. Maguire, and A. Kanaskie. 2003. Influence of Bravo fungicide applications on wood density and moisture content of Swiss needle cast affected Douglas-fir trees. Forest Ecology and Management 186:339-348.

Jozsa, L.A., Richards, J. and Johnson, S.G. 1989. Second Growth Douglas-fir: Its Management and Conversion for Value, Part II: Characterizing the Resource, Chapter 1: Relative density. Wood Science Department, Forintek Canada Corp.

Lee, H. E., Wickham, C., Beedlow, P., et al. 2016. A time series modeling approach for application in dendrochronology to examine the growth-climate relations and forest disturbance history. Submitted to Environmental and Ecological Statistics.

Pinheiro J, Bates D, DebRoy S, Sarkar D and R Core Team (2016). _nlme: Linear and Nonlinear Mixed Effects Models_. R package version 3.1-128, <URL: http://CRAN.R-project.org/package=nlme>.

PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 2 June 2016.

R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Temel, F., G.R Johnson, and J.K. Stone. 2004. The relationship between Swiss needle cast symptom severity and level of *Phaeocryptopus gaeumannii* colonization in coastal Douglas-fir (*Psuedotsuga menziesii* var. *menziesii*). Forest Pathology 34:383-394.

Impact of Climate and Disturbance on the Formation of Earlywood and Latewood in Douglas-fir at the Salal Fields Study Site

Chapter 4

Conclusion

Conclusion

In this thesis, models were developed from data collected at the Salal Fields Fertilization study to understand the impact of climate and disturbance on earlywood and latewood widths.

In chapter 2, several key climate variables were identified as the primary controls on the growth of earlywood and latewood. The dewpoint deficit from the previous year had a positive impact on the growth of earlywood, as did maximum winter temperature. The variable that limited earlywood growth was conversely, higher maximum summer temperatures reduced earlywood growth. Warmer winter temperatures presumably indicated an earlier start to the growing season, resulting in an increase in the amount of earlywood if the date of transition to latewood remained constant. In contrast, as the maximum temperature in summer months increased, the Salal Fields site started to experience water stress and earlywood growth was reduced.

Latewood growth increased in response to greater summer precipitation but was reduced as maximum summer temperature increased. The model for latewood also showed that growth was reduced towards the end of the growing season as the amount of available water decreased. In the beginning of the growing season when earlywood is formed, the amount of winter and spring precipitation had no impact on the amount of earlywood, indicating that during these months there is sufficient available water. As the end of the growing season approached, the amount of available water had decreased to a point where it was the major limiting factor influencing tree growth.

The models constructed to study the influence of climate also simultaneously accounted for disturbance years, defined as years with unusually high or low growth. Earlywood and the latewood widths at the Salal Fields Fertilization study experienced separate disturbance events. A disturbance event in earlwood occurred during 1980, reducing growth by 46%. A disturbance event in latewood occurred during 1983, reducing latewood growth by 15%. Despite the expectation of close synchronization, earlywood and latewood experienced a reduction in growth during different years.