Estimating Silvicultural Treatment Response Utilizing a Six Meter Height-Intercept Approach

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Authorization to Submit Thesis

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Abstract

Managed forests are subjected to a wide variety of silvicultural treatments. These treatments or the lack thereof can influence the height growth of young stands. There is no standard approach to evaluating or quantifying the differences between silvicultural treatments. This is especially true with regard to forest models.

We utilized a two-point height intercept method at 6 meters as an approach to quantify the treatment response of site preparation and planted versus naturally regenerated on ponderosa pine (*Pinus ponderosa*) and western larch (*Larix occidentalis*) within the Inland Northwest, USA. Sampling was performed utilizing a balanced orthogonal matrix to ensure that samples were collected across a range of climatic and environmental conditions present in the study area. Three geospatially derived variables: Mean Annual Precipitation (MAP), Soil Depth to Restrictive Layer (SDEP), and Annual Growing Season Days (GDAY) greater than 10 degrees Celsius were used to develop the sample matrix. Stand histories were researched to obtain accurate site preparation and planting records.

A site-treatment linear regression model was developed for each species after performing step wise model reduction techniques from a larger full multiple regression model. Adjusted R^2 for the western larch model was 0.4029, while the adjusted R^2 for ponderosa pine was 0.6052. The addition of site preparation treatment before planting did not increase the growth rates of planted western larch. There was a significant increase in growth rates between planted and naturally regenerated western larch and ponderosa pine ($p<.001$). A two-point height intercept method at 6 meters can be used to quantify and differentiate the silvicultural treatment response in height growth for young stands taller than 6 meters, particularly in non-pioneer species.

Acknowledgments

First, I would like to thank my employer, Inland Empire Paper Company for supplying me with the time and financial resources necessary to accomplish this task. I would also like to thank my major professor Dr. Mark Kimsey and my advisors Dr. Dan Opalach, Dr. Andrew Nelson, and Dr. Ann Abbott. These people provided me thoughtful input and direction for my project, statistical analyses, and suggested course work. Next, I would like to thank timber faller Sean Hammond for doing all the hard and dangerous work. Finally, I would like to thank Dr. Jim Arney and the Forest Biometrics Research Institute for providing financial assistance for my course work, assisting me with my project, and most importantly furthering my knowledge of forest biometrics.

Dedication

This thesis is dedicated to Charlie. You are the best friend that I could have ever asked for.

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Statement of Contribution

I declare that the research and writing of this Thesis is my own original work that I performed as a student at The University of Idaho. This paper is co-authored by Mark Kimsey. Mark reviewed several drafts of this Thesis, helped with project design, and provided guidance on statistical analysis. Ann Abbot provided input on statistical analysis. Dan Opalach provided input and guidance on project design and statistical analysis. I performed all the research, data collecting, data editing, and statistical analysis.

Estimating Silvicultural Treatment Response Utilizing a Six Meter Height-Intercept Approach

Introduction

Managed forests across the Inland Northwest are subjected to a wide variety of silvicultural treatments. These treatments range from even-aged silvicultural systems such as seed tree, shelterwood, and clearcut to uneven-aged silvicultural systems such as individual tree selection and group selection systems. Within the even-aged silvicultural systems, many organizations employ intensive forest management, which can often consist of one or more site preparation treatments, planting of stocktypes with genetically improved seed, and post-planting competition removal treatments. These more intensive management practices are often employed to shorten rotation lengths, or increase planting survival (Creighton et al., 1987).

Young stand height growth is influenced by a wide variety of factors. These factors range from what silvicultural regeneration system was employed at timber harvest, site preparation treatments prior to planting, and the size of nursery stocktype at outplanting (Ledermann and Stage 2001). In particular, regeneration harvests such as clearcutting, seed tree, and shelterwood systems have been shown to increase seedling height growth as canopy gap size increased, and overstory basal area decreased (Coates 2000; Lam and Maguire 2011; DeLong et al. 2005). In fact, DeLong et al. (2005), found that western larch in clearcuts were more than twice the height of western larch found in heavy retention treatments.

Site preparation treatments can also influence planted seedling height growth and survival (Creighton et al., 1987; Bennett et al., 2003). In the Pacific and Inland Northwest, USA, vegetation management is commonly used to increase planted seedling survival, height, and volume growth. In a metadata review by Wagner et al. (2006), they conclude that vegetation management leads to increased yields. Furthermore, Wagner et al. (2006) highlights the positive role vegetation management has on increased stand volume for several species including Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), and others. In the Inland Northwest, Cherico et al. (2020) found increased height and diameter gains of western white pine and Douglas-fir compared to the control over a 34-year measurement period. Similarly, Rose et al. (2006) found that vegetation management increased both individual tree volume and volume per hectare in excess of 300% at a Coastal Douglas-fir plantation.

The effect of silvicultural treatments on young stand height growth has implications for site productivity estimation. The traditional approach to estimating site index typically involves determining the age of suitable site trees via an increment core at 1.4 meters and determining their total height, which is then compared against a conifer species published site curve. Furthermore, this one-point method is often used to calibrate growth and yield and models. Error may be introduced into these growth and yield and models, if the silvicultural treatment effect on young stand height growth is ignored.

For decades, land managers and foresters alike have been using the traditional one-point method of breast height age site index (BHASI) as a measure of classifying forest productivity (Cochran 1979; Monserud 1984). The traditional BHASI methodology while simple and efficient has its drawbacks. For one, suitable site trees must be present. Finding suitable site trees is often a problem due to the age of the stand, or due to past management practices (Milner, 1987; Vopicka, 2007; Tomé et al., 2006). Second, these published site curves ignore the influence of early silviculture on height growth (Arney et al., 2009). Finally, traditional BHASI ignores the need of land managers and forest modelers to have flexible site curves that can not only be calibrated to silvicultural treatments but more importantly can be calibrated to regional environmental and climatic trends such as annual precipitation or soils.

The limitation of traditional BHASI with regards to younger stands was identified decades ago (Wakeley and Marrero 1958). In their paper, Wakeley and Marrero (1958) identified several shortcomings of traditional BHASI in younger southern pine plantations stands, including the difficulty of measuring tree height in tightly spaced stands, the adverse role of insects and animal damage on young tree heights, and the effect of measurement error when indexing age on young versus older trees.

Early attempts at quantifying forest productivity in younger stands include a two-point method called the "Five Year Intercept" (Wakeley and Marrero 1958). They defined the Five-Year Intercept as the "five-year period during the first year of which the tree attaints breast height." This period was selected as it was relatively easy and efficient to measure regardless of tree age, and a 5-year period provides a smoothing function for annual weather variation (Wakeley and Marrero, 1958).

More recent attempts of using growth intercept models to quantify forest productivity include work performed by Nigh (2011) and Arias-Rodil et. al. (2015). Nigh (2011) utilized growth intercept models for species without distinct annual growth whorls, by sectioning trees at predetermined intervals based on the estimated site index of the plot. Arias-Rodil et al (2015), tested a 4, 5, 6, and 7-year growth intercept model above diameter at breast height concluding that a 7-year growth intercept model was the most accurate at predicting site index.

In order to evaluate the effectiveness of different silvicultural treatments, there needs to be a reliable method to predict young stand height growth in a growth and yield model. This method must be robust, capable to detect differences in young stand height growth between naturally and artificially regenerated stands by species and by silvicultural treatment type. The need for such a robust model was identified by Westfall et al. (2004) as most growth and yield models were predicting growth after canopy closure in southern pine plantations.

In this paper, we utilized a two-point height intercept method to evaluate young stand height growth of natural and artificially regenerated stands following varying silvicultural treatments. The objectives of this study were to 1) determine whether a two-point height intercept method can discriminate early stand height growth between different conifer species and silvicultural treatments and 2) evaluate the role of climate, soil, and landform on young stand height growth.

Methods and Materials

Study Area

The study area covered 47,435 ha of forest land across six counties in eastern Washington and northern Idaho, USA (Fig. 1.1). Elevation ranged from 400 m along the Columbia River to 1575 m along the upper slopes of Mica Peak in Spokane County. Mean annual precipitation ranged from 43 to 119 cm (Oregon State University, 2012). Soil textures reflected loamy fine alluvial sand along the Columbia River to fine-textured silt loam volcanic soils in higher elevations of the study area. Soil depths ranged from 36 to 150 cm (Natural Resource Conservation Service, 2017).

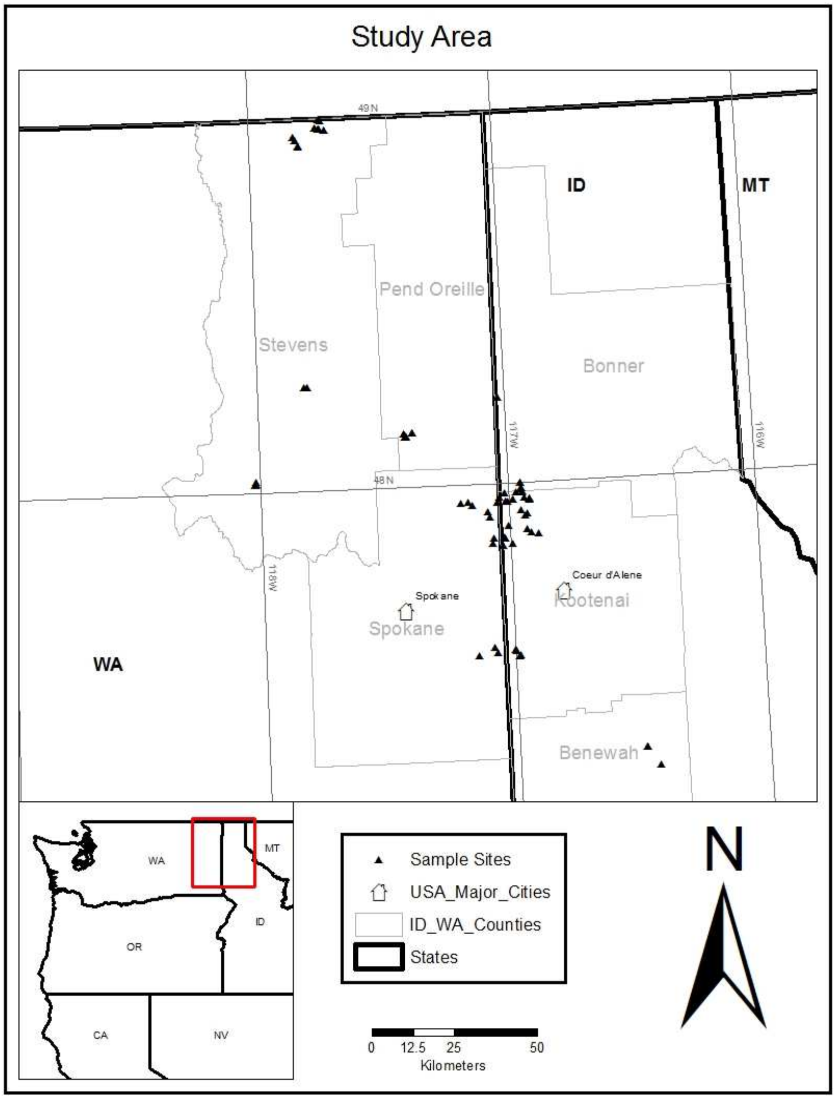

Figure 1.1. Study Location performed on lands owned by Inland Empire Paper Company in northern Idaho and eastern Washington, USA. Triangles represent sample locations of 103 western larch and 87 ponderosa pine.

Study Area Stratification

The study area was stratified for field sampling into 27 unique strata using three variables (Hemmingway and Kimsey, 2020; Arney, 2015). These variables included mean annual precipitation (MAP), annual growing season days greater than 10 degrees Celsius (GDAY), and soil depth to restrictive layer (SDEP) (Fig. 1.2). These variables were selected as they are highly correlated to site quality and forest productivity within this region (Hemingway and Kimsey, 2020) and have been used in a prior forest productivity calibration study on Inland Empire Paper Company's ownership. These variables were classified into three groups each, creating a low, medium, and high for each variable, for a total of 27 unique strata. The medium level of MAP and GDAY was identified as the mean ± one half the standard deviation. All values below the medium level were placed in the low level, while all values above the medium level were placed in the high level. SDEP classes were created in similar manner except the medium level was identified as mean ± one standard deviation. SDEP classes were created in this manner due to the unbalanced nature of the soils data classifying most of the soils in the study area as deep, well drained soils.

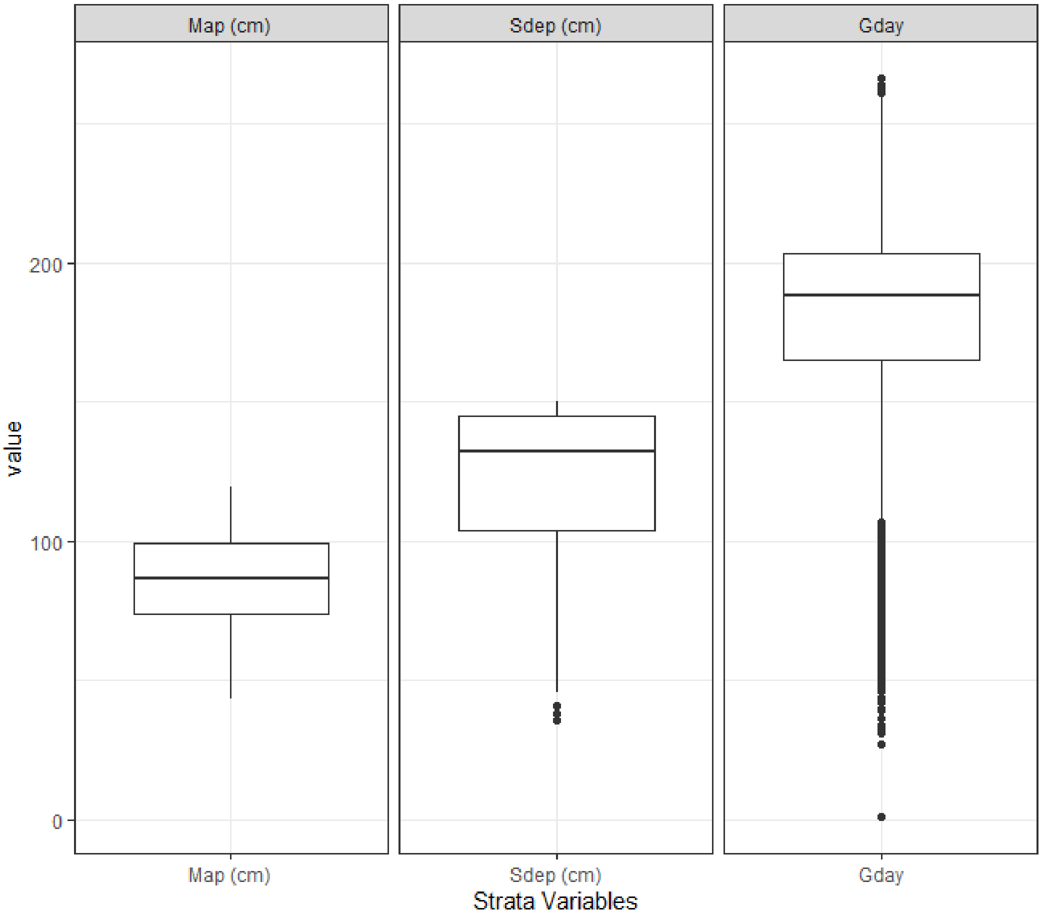

Figure 1.2. Boxplot illustrating the distribution and variability of MAP, SDEP, and GDAY.

This balanced, orthogonal matrix ensured that field sampling was distributed across the entire range of environmental and climatic conditions present in the study area (Table 1.1). A more in-depth review on variable selection, computation and application across the landscape as a site selection grid can be found in Hemingway and Kimsey (2020).

Table 1.1. Range of site conditions present in the study area.

Site Condition Variables	Minimum	Maximum	Mean	Standard Deviation
Elevation (m)	398.7	1,572.8	946.7	183.3
Mean Annual Precipitation (cm)	43.18	119.38	85.69	16.5
Growing Season Days Greater than 10°C	1	266	182.8	28.3
Soil Depth to Restrictive Layer (cm)	35.56	149.86	121.55	26.3

Site Selection

In order to investigate the influence of early silviculture and tree planting on height growth, it was necessary to have a detailed and documented history of stand origination. For this study, we were provided detailed historical silvicultural stand records (1953-2019) from Inland Empire Paper Company (IEP). Detailed information included species planted, nursery source, stocktype, planting contractor, weather, and first-year survival. In addition to planting information, IEP provided records regarding silvicultural treatments such as mechanical site preparation, broadcast burning, and herbicide application.

Upon investigation of this database, we found that IEP predominately planted four conifer species, which ranked in their planting abundance were 1) ponderosa pine (*Pinus ponderosa*), 2) western larch (*Larix occidentalis*), 3) western white pine *(Pinus monticola*), and 4) Douglas-fir (*Psuedotsuga menziesii* var. *glauca*). Furthermore, we discovered that herbicide application was the predominant site preparation treatment. Broadcast burning and mechanical site preparation treatments were performed on an "as needed" basis on a much smaller percentage of IEP's ownership. Thus, for this study, we decided to focus our sampling efforts on the difference between naturally and artificially regenerated ponderosa pine and western larch, and the site preparation treatment effect of herbicide application.

Stand locations for sampling early ponderosa pine and western larch tree height growth were identified using the balanced, orthogonal matrix site grid. It should be noted that the confounding geographical dispersion of IEP ownership across the region and the available stands for this study did not allow us to capture all 27 site strata. For western larch, we sampled 16 strata, and for ponderosa pine, we sampled 15 strata. Despite field access limitations and an inability to capture all site strata across the study region, we felt confident that we did capture the range of site characteristics that define tree growth at our various study locations (Tables 1.2 and 1.3).

Table 1.2. Range of site conditions for western larch sample tree locations.

Site Condition Variables	Minimum	Maximum	Mean	Standard Deviation
Elevation (m)	462.99	1,403.91	977.49	207.25
Mean Annual Precipitation (cm)	53.34	111.76	86.89	17.99
Growing Season Days Greater than 10 C	57.00	231.00	170.37	38.79
Soil Rooting Depth (cm)	60.96	149.86	123.99	26.67

Table 1.3. Range of site conditions for ponderosa pine sample tree locations.

Site Condition Variables	Minimum	Maximum	Mean	Standard Deviation
Elevation (m)	421.54	1,182.32	898.77	183.86
Mean Annual Precipitation (cm)	53.34	111.76	80.05	19.37
Growing Season Days Greater than 10 C	140.00	231.00	194.45	21.01
Soil Rooting Depth (cm)	40.64	149.86	109.79	29.90

We identified two to three trees per strata for sampling in order to obtain a strata average for each species early height growth. Sample trees were selected no further than 50 m apart, and in stands where only one stratum was present. At each location, two to three trees were felled, total tree height measured, and ring counts obtained at 0.3 m and 6 m. Annual rings were counted in the field with the help of an orbit sander, standard 2X magnifying glass, and a 40X jeweler's lens. This will be referred to as the 6-meter height intercept method (6MHI) with units expressed as meters of height growth per decade. Sampled trees were in the dominant or codominant crown class and free of defect.

Data Analysis

Multiple linear regression was used to evaluate site preparation, regeneration method, and site covariates on 6MHI for ponderosa pine and western larch. All statistical analyses were performed using the “lm” function in R version 4.0.1 (R Core, 2020). Normality was assessed utilizing a series of scatter plots and the “gvlma” package (Pena & Slate, 2019). Assumptions of normality were generally met, so no transformations were needed. The full model for each species was:

$$6MHI = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_1 x_2 + \sum_{i=1}^{k} \beta_i x_i x_j + \varepsilon \qquad \textbf{(Eq. 1)}$$

where 6MHI is a species 6-meter height intercept growth rate expressed in meters per decade and x_1= site preparation treatment, x_2= regeneration treatment, x_3 = elevation, x_4 = MAP, x_5= SDEP, x_6= GDAY, x_7 = site preparation treatment * regeneration treatment, and $x_i x_j$ are model interaction terms. For x_1, site preparation is 1 if chemically treated, 0 if none, for x_2, regeneration treatment is 1 if artificially planted, 0 if naturally regenerated. Elevation, MAP, GDAY, and SDEP are site covariates. We then employed the R “leaps” package to reduce the full model for each species to three variables representing treatment and biologically relevant site characteristics (Lumley et al, 2020). The reduced model with the highest adjusted R^2 was selected for each species to define 6MHI as a function of silvicultural treatment and site.

Results

Observed 6MHI Growth Rates by Treatment

Field measured 6MHI for western larch ranged from 3.21 – 11.46 m per decade with a mean of 6.96 m per decade growth (Table 1.4). 6MHI for naturally regenerated western larch ranged from 3.21 – 7.85 m per decade with a mean of 5.12 m per decade growth. The 6MHI for plant only western larch ranged from 5.79 – 11.07 m per decade with a mean of 8.02 m per decade growth; whereas, plant with an herbicide site preparation treatment ranged from 4.81 – 11.46 m per decade with a mean of 7.09 m per decade.

Table 1.4. Summary of six meter per decade height growth rates for western larch (n equals number of felled trees in each treatment and one standard deviation is represented under the observed 6MHI mean).

Silvicultural Treatment	Mean	Minimum	Maximum
All (n = 103)	6.96 (1.78)	3.21	11.46
Natural (n = 25)	5.12 (1.42)	3.21	7.85
Plant Only (n = 39)	8.02 (1.34)	5.79	11.07
Plant + Site Preparation (n = 39)	7.09 (1.43)	4.81	11.46

6MHI for ponderosa pine ranged from 2.18 – 7.62 m per decade with a mean of 4.94 m per decade growth (Table 1.5). The 6MHI for naturally regenerated ponderosa pine ranged from 2.18 – 4.69 m per decade with a mean of 3.34 m per decade growth; whereas, 6MHI for plant only plus herbicide site preparation treatment ranged from 3.41 – 7.62 m per decade with a mean of 5.30 m. All sites planted to ponderosa pine by IEP included an herbicide site preparation treatment, thus we could not compare between plant only with and without a site preparation treatment.

Table 1.5. Summary of six meter per decade height growth rates for ponderosa pine (n equals number of felled trees in each treatment and one standard deviation is represented under the observed 6MHI mean).

Silvicultural Treatment	Mean	Minimum	Maximum
All (n = 87)	4.94 (1.10)	2.18	7.62
Natural (n = 16)	3.34 (0.67)	2.18	4.69
Plant + Site Preparation (n = 71)	5.30 (0.82)	3.41	7.62

Across both species, planted vs. natural regeneration method was the primary differentiation in 6MHI, regardless of site strata (climate, soils) (Fig. 1.3). The fastest growing naturally regenerated western larch had a growth rate of 7.85 meters per decade (commonly ranging between 3-6 meters per decade); whereas, 30 planted western larch showed a growth rate exceeding 8.0 meters per decade. The influence of regeneration method on height growth is more significant with ponderosa pine. Only one naturally regenerated ponderosa pine had a 6MHI growth rate greater than 4.0 meters decade; whereas, 68 of 71 planted ponderosa pine showed 6MHI growth rates greater than 4.0 meters decade.

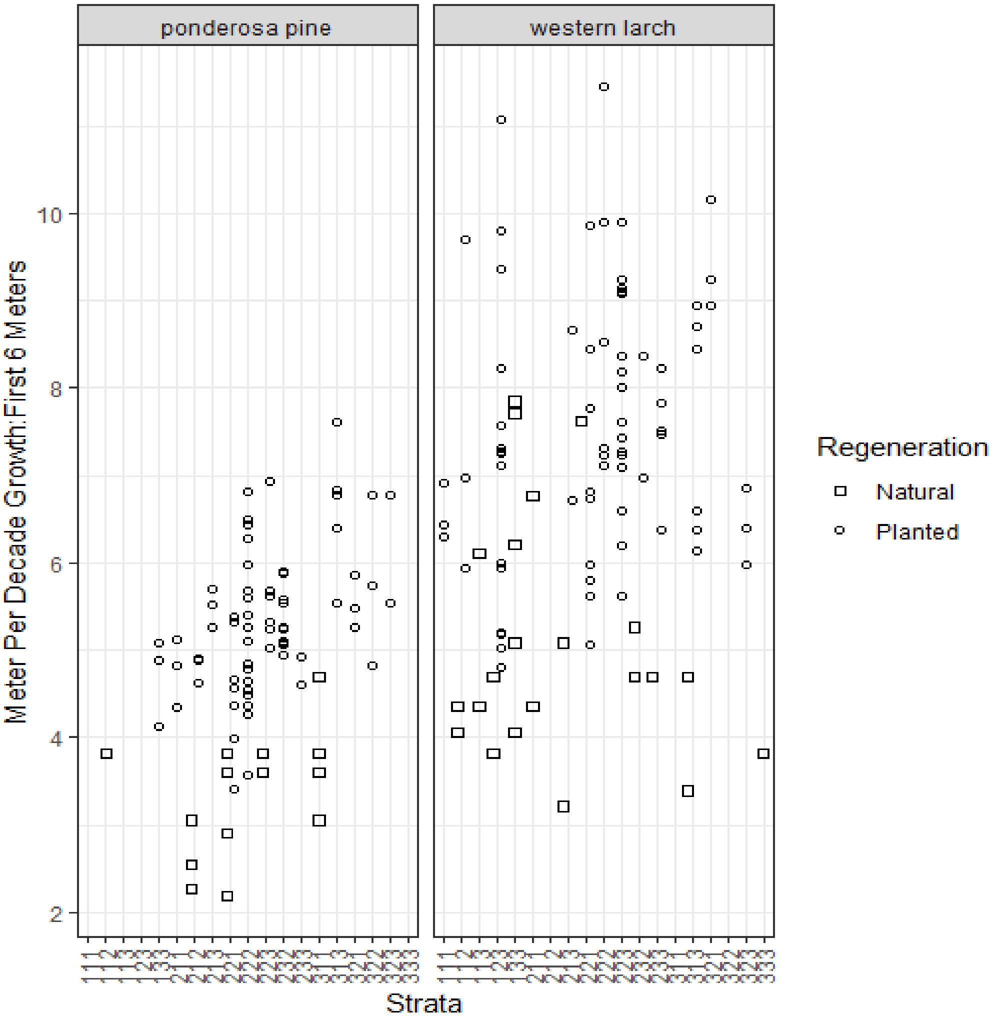

Figure 1.3. 6MHI growth rates of ponderosa pine and western larch by regeneration treatment type and strata. The first number in the strata is GDAY, the second number is MAP, and the third number is SDEP.

Effect of Site on 6MHI

Strata variables and elevation showed differential effects on 6MHI growth rates for western larch and ponderosa pine (Fig. 1.4). For western larch, 6MHI growth rates were positively correlated with MAP (r = 0.236) and GDAY (r = 0.089). Elevation had a slight positive correlation (r = 0.040) on 6MHI growth rates. SDEP had negative correlation (r = -0.182) on 6MHI values. As depth to restrictive layer increased (SDEP), 6MHI values decreased. However, MAP was the only covariate that was statistically significant (p<0.1). For ponderosa pine, SDEP, GDAY, and MAP were all positively correlated with 6MHI growth rates. SDEP had the highest correlation (r = 0.415) with respect to overall 6MHI values, followed by GDAY (r = 0.248), and MAP (r = 0.154). Elevation had a slight negative correlation (r = -0.178) with 6MHI growth rates.

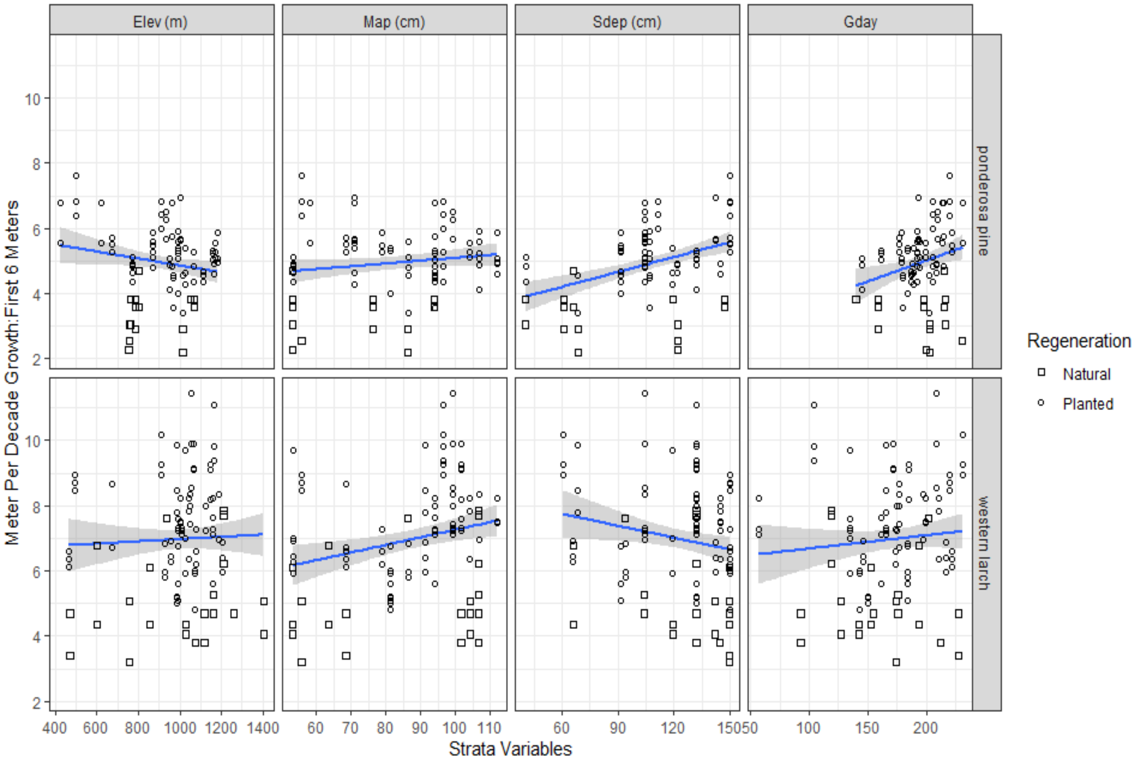

Figure 1.4. Influence of elevation and strata variables on 6MHI growth rates for western larch and ponderosa pine with 90% confidence intervals (grey shading).

Multiple Regression Model Development - Western Larch

All covariates and treatment variables were analyzed using Eq. 1 with one notable exception. We removed SDEP from the full regression model due to an inadequate sampling of the lower values of SDEP and meters per decade growth rates. Unbalanced SDEP sampling created unreasonable growth response patterns. The reduced model for western larch was:

$$6MHI = 3.07 + 0.79\,SP + 2.79\,REGEN + 0.01\,MAP$$ **(Eq. 2)**

where 6MHI is a species 6-meter height intercept growth rate expressed in meters per decade. For site preparation, SP = 1 if chemically treated, 0 if none, for regeneration treatment REGEN is 1 if artificially planted, 0 if naturally regenerated. We obtained an adjusted R^2 value of 0.4195 for the full multiple regression model for western larch (Eq.1). The reduced model (Eq. 2) resulted in an adjusted R^2 value of

0.4029 (Table 1.6). Furthermore, all three variables in (Eq.2) had a positive effect on 6MHI values. Site preparation treatment = “none” (SP = 0) was statically significant (*p* = 0.0159), regeneration treatment = “planted” (REGEN = 1) was statistically significant (*p*<.001), and MAP was statistically significant (*p* = 0.0616).

Table 1.6. Western larch reduced multiple linear regression model.

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	3.07162	0.72132	4.258	4.69E-05
MAP	0.01478	0.00782	1.891	0.0616
SitePreparationUntreated	0.78762	0.32088	2.455	0.0159
RegenerationPlanted	2.78576	0.35791	7.783	6.97E-12
Residual standard error: 1.376 on 99 degrees of freedom				
Multiple R-squared: 0.4205, Adjusted R-squared: 0.4029				
F-statistic: 23.94 on 3 and 99 DF, p-value: 9.823e-12				

Multiple Regression Model Development - Ponderosa Pine

Similar to western larch, all covariates and treatment variables were analyzed using Eq. 1. SDEP was included for ponderosa pine due to balanced sampling of SDEP across the range of observed 6MHI values. Upon model reduction, the reduced model for ponderosa pine was:

$$6MHI = 2.78 + 1.66\ REGEN + (-1.60E - 07\ Elev * MAP * SDEP) + 1.25E - 06\ (MAP * SDEP * GDAY) \qquad \textbf{(Eq. 3)}$$

where 6MHI is a species 6-meter height intercept growth rate expressed in meters per decade. For regeneration treatment, REGEN is 1 if artificially planted, 0 if naturally regenerated. We obtained an adjusted R^2 value of 0.7707 for the full multiple regression model for ponderosa pine (Eq.1). The reduced model (Eq. 3) resulted in an adjusted R^2 value of 0.6052 (Table 1.7). Regeneration treatment = “planted” $(= 1)$ had a positive treatment effect on 6MHI growth rates and was statistically significant (*p*<.001). The three-way interaction of elevation, MAP, and SDEP had a negative effect on 6MHI values and was statistically significant (*p*<.001). Finally, the three-way interaction of MAP, SDEP, and GDAY had a positive effect on 6MHI values and was statistically significant (*p*<.001).

Table 1.7. Ponderosa pine reduced multiple linear regression model.

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	2.78E+00	2.41E-01	11.533	< 2e-16
RegenerationPlanted	1.66E+00	2.16E-01	7.683	2.77E-11
Elev:MAP:SDEP	-1.60E-07	3.24E-08	-4.936	4.06E-06
MAP:SDEP:GDAY	1.25E-06	2.35E-07	5.329	8.33E-07
Residual standard error: 0.69 on 83 degrees of freedom				
Multiple R-squared: 0.619, Adjusted R-squared: 0.6052				
F-statistic: 44.94 on 3 and 83 DF, p-value: < 2.2e-16				

Discussion

Results indicate a two-point height intercept method at 6 meters has the potential to be a useful tool in determining and classifying young stand height growth by species and silvicultural treatments as modified by site characteristics. The two-point height intercept method was better at distinguishing the regeneration treatment response for ponderosa pine than that of western larch. The addition of site preparation treatment before planting did not improve height growth for western larch. As a retrospective analysis it is possible that our “plant only” sites for western larch did not need a site preparation treatment due to a low amount of vegetation competition. Available records did not contain vegetation communities present, nor their abundance. In addition, particular herbicides have been shown to have a negative impact on western larch seedling growth rates and root development (Kimsey and Shaw, 2019; Robertson & Davis, 2012). Regeneration treatment, site preparation treatment, elevation, MAP, GDAY, and SDEP all proved to be important variables in developing a multiple linear regression model. Different variables and different interactions of these variables were statistically significant for ponderosa pine and western larch.

Regeneration treatment was present in the reduced models for western larch and ponderosa pine. Planted seedlings for both western larch and ponderosa pine grew faster than naturally regenerated seedlings, as observed in other early stand establishment studies (Aleksandrowicz-Trzcińska et al., 2017; Holgén & Hånell, 2000; Robert & Lindgren, 2006). This is not surprising due the nature in which naturally generated seedlings often must compete with vegetation and other trees for critical resources such as water and sunlight (Harrington et al., 2013). Furthermore, planted seedlings were planted following a regeneration harvest, which reduces or eliminates the overstory competition from neighboring trees and reduces vegetation competition temporarily from timber harvest activity.

Increasing levels of MAP lead to an increase in 6MHI growth rates. Chen and Nelson (2020) found similar results in western larch seedlings in Northern Idaho. The importance of MAP is to be expected given the Mediterranean climate and droughty summers that are often present in the Inland Northwest. One would expect that warmer, wetter sites would produce higher 6MHI growth rates, while cooler or warmer, but drier site types would result in lower 6 MHI growth rates.

The influence of SDEP on ponderosa pine 6MHI growth rates may be explained due it's well-known rooting habit of establishing a deep tap root (Klinka, et al., 2000). Higher growth rates for ponderosa pine were generally found on sites with deeper well drained soils, and longer growing seasons, which tend to be found at lower elevations.

The combination of a longer growing season with higher precipitation values is expected to result in an increase of 6MHI growth rates for ponderosa pine. Furthermore, it would also be expected that areas with a longer growing season are generally found at lower elevations. Conversely, areas with shorter growing season days, would generally be expected to be in areas of high elevations resulting in lower 6 MHI growth rates.

In summary, the three-way interactions observed in the ponderosa pine model reflect the complexity of site growth factors observed across its regional growing range. A simple substitution of elevation for growing days in the three-way interaction changed the model coefficient from positive to negative. In addition to the general trends observed above, this substitution effect suggests that topographic position would play a large role on ponderosa pine growth as elevation increases. At lower elevations, northerly aspects may outperform southerly aspects (i.e., lower evapotranspiration); whereas, the relationship would reverse due to cooler growing seasons at higher elevations (Kimsey et. al. 2019).

Other studies investigating the role of various climate and topographic variables on site index for different species, found similar results. Eckhart et al., (2019), found that summer precipitation, soil water holding capacity, and summer mean temperature were all important variables in explaining the variance in Douglas-fir site index. Brown and Lowenstein (1978) found that site index was negatively correlated with elevation, mostly related to cooler (i.e., shorter) growing seasons. We did not use elevation as a strata variable because of study limitations, but due to its importance as a covariate in our regression models, we would suggest that elevation be used in future sampling designs (Hemingway and Kimsey, 2020).

The reference point of 6 meters was also predetermined before any samples were collected. The height of 6 meters was chosen because this is the preferred reference height that is used by the Forest Biometrics Research Institute (FBRI) (Arney et al., 2009). We did not investigate other reference heights, the relationship of a lower reference height to the chosen 6-meter height, or the relationship of higher reference height to the chosen 6-meter height. It is possible that a different reference point may be appropriate for different regions in the USA, different species based on a given species growth form, or the regional growth trends of a given species within its natural range (Chen et al., 2010).

Conclusion

Traditional one-point BHASI methods of defining forest site productivity ignore the influence that silviculture has on stand height. The 6MHI method in combination with a balanced orthogonal sampling matrix is effective in discriminating the silvicultural and site effects in young stand development. This method can allow for better calibration of young stand height growth and silvicultural treatment effects in forest growth and yield models. This is especially true for the FBRI Forest Projection and Planning Software (FPS), which utilizes similar methodology and climatic variables.

Future research in the 6HMI method should look at alternative sampling approaches, such as high density lidar to sample the heights of all trees in a stand or lowering the reference height to answer silvicultural treatment effects in a more rapid fashion. Other areas of improvement would involve the development of higher resolution soil and climatic geospatial models and datasets to further refine the balanced orthogonal sampling matrix design.

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