Estimating site susceptibility to Scotch broom dominance in young Douglas-fir plantations for control prioritization in western Washington, USA

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Forestry

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August 18th, 2023
Blacksburg Virginia

Keywords: Site index, LiDAR, early-term site index, competition, Pseudotsuga menziesii, SSURGO, textural class, particle size, phosphorous, carbon, nitrogen, elevation, slope

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ABSTRACT

Douglas-fir (*Pseudotsuga menziesii (*Mirb.) Franco var. *menziesii)*, a keystone species in western Washington, faces threats on plantations across this region from the invasive species Scotch broom (*Cytisus scoparius* (L.) Link), whose invasions on recently established stands can lead to mortality of Douglas-fir through overtopping. The susceptibility of sites to Scotch broom achieving dominance over Douglas-fir has been demonstrated as highly site dependent, however the site conditions that cause this have not yet been identified. Scotch broom has a demonstrated average maximum height of 3m, thus, after Douglas-fir exceeds this height, its risk of being overtopped is significantly reduced. This thesis strives to identify sites that were at the greatest risk Douglas-fir being overtopped by Scotch broom by first, identifying what factors improved growth of Douglas-fir during the period when they are at the greatest risk, and second, identifying factors that led to Douglas-fir outcompeting Scotch broom on sites they cohabitated.

In Chapter 1, we utilized LiDAR scans, Soil Survey Geographic Database characteristics, and management histories to identify conditions that improved growth for Douglas-fir in ages 3-8. Individual tree detection was used to measure Douglas-fir heights, and a correction algorithm for LiDAR measured young Douglas-fir heights was established from field validation data. We identified that young Douglas-fir had improved growth on sites with lower elevation, flatter slopes, and finer textured soils. The factors identified were then transformed into four potential site index models based on mean stand elevation class, Mean stand elevation class and clay class, textural class and slope class, and textural class and Mean stand elevation class.

In Chapter 2, we used paired field plots to examine Douglas-fir and Scotch broom competition on 19 sites across western Washington. Each site had 2 plots with only Douglas-fir and 2 plots with Douglas-fir and Scotch broom. Elevation, soil texture, and soil nutrient composition for carbon, nitrogen and available phosphorous were examined for influence on height and growth rate of both species. We identified that Scotch broom presence was negatively related to Douglas-fir height growth and that sites with either higher percentages of silt, lower concentrations of phosphorous, or higher percentages of Carbon were more likely to have growth patterns close to or exceeding Scotch broom.

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GENERAL AUDIENCE ABSTRACT

Douglas-fir (*Pseudotsuga menziesii (*Mirb.) Franco var. *menziesii)* is a valuable timber species across western Washington that is commonly grown in plantations. In western Washington when Douglas-fir are planted on a site they often face competition from the invasive shrub Scotch broom (*Cytisus scoparius* (L.) Link). When Scotch broom invasions occur on a recently planted Douglas-fir stands, they can cause death of the trees if Scotch broom plants grow taller than the young Douglas-fir and obstruct their access to light, a process called overtopping. The risk of Douglas-fir being overtopped has been shown to be dependent on location, however what causes a location to be at risk of overtopping is yet unknown. Scotch broom has a demonstrated average maximum height of 3m, thus, after Douglas-fir exceeds this height, its risk of being overtopped is significantly reduced. This study aims to identify sites that were at the greatest risk Douglas-fir being overtopped by Scotch broom by first, identifying what sites generate the best Douglas-fir growth when they are young and at risk of being overtopped, and second, identifying site characteristics led to Scotch broom growing faster than Douglas-fir on sites they both occur on.

To identify sites that produced greater young Douglas-fir height growth we used publicly available soil data from the Soil Survey Geographic Database and company management histories to predict tree heights measured through aerial laser scanning (LiDAR). We found that sites with soil textures that had higher percentages of smaller particles, were on lower elevations, and had gentler hillslopes could all produce greater Douglas-fir height growth.

When attempting to identify what causes Douglas-fir to be at risk of being overtopped by Scotch broom we used plots with and without Scotch broom on a variety of field sites. This allowed us to not only identify which characteristics of sites where Douglas-fir was being outgrown by Scotch broom, but also identify if Scotch broom was changing how Douglas-fir grew. We found that reductions in Douglas-fir growth were related to Scotch broom being present and that increases in soil silt percentages, decreases in soil phosphorus concentrations, and increases in soil carbon percentages were related to Douglas-fir having height growth closer to or exceeding that of scotch broom.

This thesis is dedicated to my partner Tayler and my family, without whose sacrifices and support I would not be here today.

ACKNOWLEDGEMENTS

I would like to Acknowledge Funding from the United States Forest Service's Forest Health Protection: Special Technology Development Program.

I would like to thank my advisor Dr. David Carter for offering me this opportunity and helping me to not only complete this thesis but develop my vision and plan for my career going forward. He has sat through countless failed metaphors and abstract figure designs drawn in the air with incredible patience.

Additionally, I would like to thank Dr. Robert Slesak for the time he took to help in the planning of this project, hosting me at the Olympia Forest Sciences Lab, and offering support and advice throughout my degree.

Thank you to my committee members, Dr. Brian Strahm and Dr. Valerie Thomas, for their assistance in planning my degree program and project.

I would like to express my deepest appreciates to the Olympia Forest Sciences Laboratory team, especially Leslie Brodie and James Dollins, who visited countless sites in search of ideal locations for this study, performed a massive lift in completing the field work for this study, and offered me guidance and assistance throughout my time at the lab.

Thank you to additional collaborators Trevor Host, Dr. Mark Corrao, Dr. Michael Premer, Bruce Ripley for their assistance in making this project possible.

Finally thank you to everyone in the forestry department who made it such a welcoming place. The staff, faculty, and graduate students have all formed an incredible community I am feel fortunate to have been a part of.

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1.1 Abstract

Site index values, a measure of the average height of a dominant or codominant tree at a given base age, are a commonly used measure of site quality for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii)* and other timber species across the globe. These indices are frequently used for deciding how to manage stands; however, my examinations indicate that they often fail to accurately predict growth patterns while trees are young (3-8 years). This timespan when site index values incur weakened accuracy is coincident with a time period that contains a significant portion of management decisions. We aimed to develop a new site index for young Douglas-fir by leveraging industry collected LiDAR scans for 161 stands between 3-8 years old in conjunction with Soil Survey Geographic Database information to identify site qualities that are associated with more productive young Douglas-fir sites. We utilized individual-tree detection algorithms to measure tree heights and developed a linear model for correcting heights in young Douglas-fir stands. My findings indicate that Douglas-fir growth tended to be greater on sites that were lower in elevation, flatter, and had finer textured soils. We propose a site index for young Douglas-fir based on elevation and soil textural classes.

1.2 Introduction

Forest productivity is closely tied to site characteristics (Carmean, 1975; Splechtna 2001). Measures of site quality are essential for informing management decisions, especially in deciding where to deploy intensive management (Carmean, 1975; Carmean, 1996). The most commonly utilized measure of site quality is site index which is based on the relationship

between tree age and height (Skovsgraad & Vanclay, 2008). Assessing forests through this dendrocentric approach is efficient for forestry purposes as an index based on height is closely tied to volume production and relatively independent of factors such as spacing when trees are planted within the normal range of plantation densities (Lanner, 1985; Skovsgraad & Vanclay, 2008). The simplicity of these dendrocentric approaches offer an advantage for modeling mature forests, but may not accurately function for more complex and erratic stages of growth.

Early silvicultural intervention in young forests can result in significant growth and survival benefits over the rotation (Wagner et al., 2006). Despite this, most site index curves do not provide site index values in stands younger than five years old, nor do regional indices exist which could be used to evaluate early stand development based on site characteristics. This is partially due to the potential of non-site factors causing erratic growth patterns in early stand development. Moreover, in many cases, young growth patterns have been shown to fail to accurately predict later growth patterns, suggesting that factors influencing early-term growth differ from those impacting later-term growth (Brown and Stires, 1981; Carmean et al., 2006). These challenges have led researchers to seek out other methods for predicting site quality in young stands than traditional site index (Carmean, 1975).

Previous research has largely avoided developing site quality metrics for young stands due to their perceived low predictability. LiDAR technologies, however, may present new opportunities to develop site indices for young stands. LiDAR enables the measurement of large areas of trees with relatively high height accuracy (Gatziolis, 2007). Studies have already begun using LiDAR in combination with management data to develop site indices on a regional scale (Gopalakrishnan et al., 2019), and inform management decisions in young stands (Watt et al., 2013). The

expansion of LiDAR's use to young stands is partly due to individual-tree detection (ITD) algorithms. ITD algorithms provide much more accurate measurements of young trees with heights between 1 and 5 m than traditional canopy height model approaches (Rodriguez-Puerta et al., 2021). Abilities to accurately measure the heights of entire stands presents a new opportunity for capturing the regional variability of young stand growth.

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) is a globally important timber species in temperate zones. It is heavily managed across its native range of North America and is managed as an exotic in Europe, South America, Australia, and New Zealand (Hermann & Lavender, 1999). This widespread utilization has resulted in a wealth of research being produced on site quality metrics for Douglas-fir across its planted range. Studies that have examined young growth in Douglas-fir stands have mostly focused on the early stem exclusion stage of stand development, i.e. shortly after the crowns have escaped the threat of being overtopped by competing vegetation (Stoate & Crossin, 1959; Curt et al., 2001). This provides a challenge for managers. There is no existing guide to inform management decisions and characterize a stand's developmental progress during arguably the most important stage of stand development. Silvicultural interventions made during this period, such as whether to control competing vegetation, can have long-term effects on the development of the stand (Mickael et al., 2007; Harrington & Schoenholtz, 2010).

Douglas-fir site quality has been linked to a variety of different factors in the Pacific Northwest with factors such as increased water-stress, elevation, gravel content, and soil compaction all leading to lower-quality sites (Carmean, 1954). In young Douglas-fir stands, water stress has proven to be one of the dominant factors in determining early growth patterns (Gonzalez-

Benecke & Dinger, 2018). This study demonstrated that a 0.01 cm^3cm^{-3} decrease in soil water content during mid-august, the typical peak of the dry season, will lead to a growth decrease between 5.6% and 7.75% in Douglas-fir seedlings, leading August soil water content to be a strong predictor of site quality for young Douglas-fir (Gonzalez-Benecke & Dinger, 2018). The importance of water stress makes competition control extremely important for young Douglas-fir, and even more so on sites with high susceptibility to drought stress (Gonzalez-Benecke & Dinger, 2018; Devine & Harrington, 2006). Variables such as soil texture, including single textural factors like percent sand, have been shown to be strong predictors of soil moisture at the small (<100m^2) and intermediate (1-100km) spatial scales (Dong & Oschner, 2018). These studies have shown that the finer textured the soil, the greater the soil moisture retention can be expected to be at a given site (Rawls et al., 1991). In addition, factors such as slope and geomorphic positions have been shown to have strong impacts on soil fertility and subsequent forest growth due to moisture and nutrient accumulations (Schloten et al. 2017). The effects of geomorphic position have been shown to be greatest in the top 50 cm of soil (Schloten et al., 2017) which is the depth of soil that contains the largest volume of roots for planted Douglas-fir seedlings up until age 10 (Sundstrom & Keane 1999). Soil temperature regimes can also significantly alter a seedling's ability to uptake water with colder temperature regimes resulting in lower water uptake (Lopushinsky & Kaufmann, 1984). In the pacific northwest Douglas-fir on colder high elevation sites typically also face negative impacts from reduced growing season due to later snowmelts. The exhibited importance of soil moisture on Douglas-fir growth results in a suite of variables that all potentially influence Douglas-fir growth due to their modification of a site's soil moisture.

I examined site-level factors relating to soil and geomorphic position that may be responsible for differing patterns of young growth among Douglas-fir stands between the ages of 3-8 years old at the time of scanning. My objectives were to (1) assess the association of site variables with young Douglas-fir height growth using management histories and LiDAR coverage in combination with SSURGO (Soil Survey Geographic Database) data in western Washington, USA (n=161 sites); and (2) to develop an early-term (age 3-8) site index for Douglas-fir plantations. We hypothesized that (*i*) coarse-textured soils would have less Douglas-fir height growth than that measured on fine-textured soils; (*ii*) Douglas-fir height growth would decrease with increasing elevation, and (*iii*) that fine-textured, low-elevation sites would have the greatest young-stand site index of all elevation and soil texture combinations tested.

1.3 Materials and Methods

1.3.1 Study Area

161 Douglas-fir plantations used in this study were selected based on (1) availability of industrial LiDAR coverage, (2) requisite age ranges of 3-8 years old, (3) geographic distribution within the state of Washington, (4) similar management histories, and (5) greater than 5 ha area to minimize edge effects of mature trees. Stands were located primarily in the Willapa Hills and southern Cascades descending into the Puget lowlands (Figure 1.1).

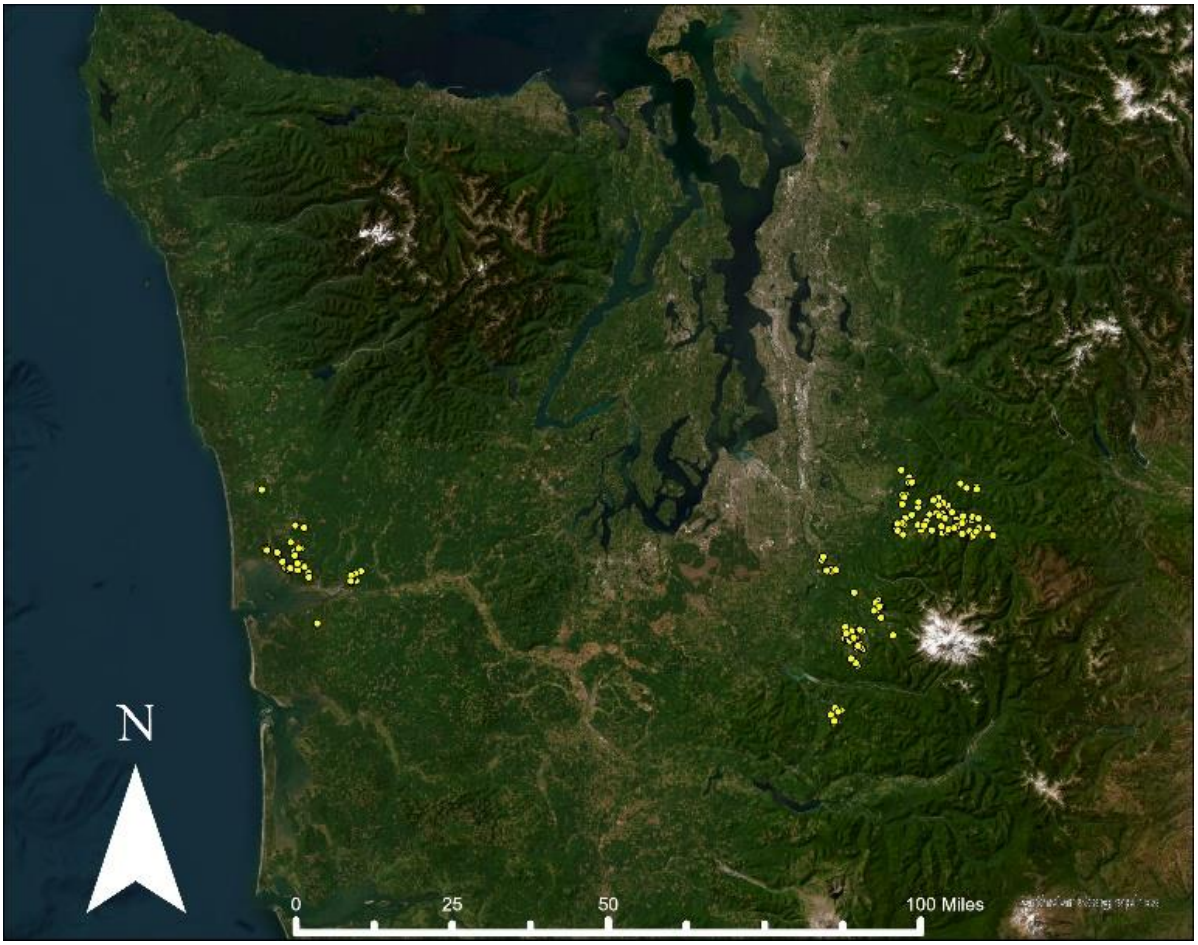

Figure 1.1. Young stands (yellow dots)(ages 3-8) across western Washington, USA, with industrial LiDAR coverage (18-20 pulses per m^2) used in this study (n=161).

For each site, SSURGO data were extracted through the ESRI ArcGIS.com SSURGO downloader. Every site was attributed the characteristics of the soil unit that covered the greatest proportion of the stand. Sites in large part occurred on only one soil map unit or if two units were present it was a minor inclusion of less than 20%, this is likely due to many stand boundaries being developed utilizing soil maps provided by SSURGO. Sites occurred on four soil orders, Alfisols, Andisols, Spodosols, and Ultisols, and five soil map unit textural classes, clay loam, silt loam, loam, loamy sand, sandy loam, over a range of elevations from 15-1,319 m (Table 1.1).

Table 1.1. LiDAR-data summary of the mean and standard deviation for elevation (meters above sea level), age, and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) height growth rates for each of the major soil order and texture characteristics from Soil Survey Geographic Database (SSURGO). (+/- indicates standard error).

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Order	Textural Class	N	Elevation (m)		Age (Years)		Growth rate ($cm \cdot yr^{-1}$)	
			Mean	+/-	Mean	+/-	Mean	+/-
Alfisols		3	601.9	164.3	3.8	0.6	55.6	5.6
	Clay Loam	1	789.3	-	3.5	-	55.7	-
	Sandy Loam	1	533.8	-	3.5	-	61.1	-
	Silt Loam	1	482.6	-	4.5	-	49.9	-
Andisols		79	408.0	339.3	4.8	1.3	60.1	12.9
	Loam	24	655.8	161.8	4.6	1.2	54.4	7.4
	Loamy Sand	1	777.5	-	4.5	-	38.9	-
	Sandy Loam	5	489.3	314.8	4.5	1.0	52.4	7.3
	Silt Loam	49	270.8	335.9	4.8	1.3	64.1	13.8
Inceptisols		19	619.9	231.1	4.9	1.0	51.8	7.6
	Loam	15	576.4	229.4	4.9	1.0	51.6	7.4
	Silt Loam	4	783.1	173.1	5.0	1.3	52.5	9.4
Spodosols		60	838.5	200.3	5.4	1.0	51.3	11.4
	Loam	3	1,116.5	191.5	5.8	0.6	41.1	10.9
	Loamy Sand	27	945.3	159.2	5.4	1.0	47.7	10.6
	Sandy Loam	30	714.5	147.9	5.3	0.9	55.5	10.7

For each numeric SSUGRO variable used, such as sand, silt, clay, and slope percents, the representative value was used. SSURGO particle size variables, (sand, silt, and clay) were converted into 0-30cm and 30-60cm increments for each map unit using a weighted average of the horizon values based on their depths. SSURGO categorical variables of texture major, texture minor, and taxonomic order were also extracted for each map unit.

1.3.2 LiDAR Data and Height Validation

Two separate aerial LiDAR acquisitions were utilized in this analysis: one from 2020 and one from 2021. The 2020 scan was performed using a Riegl VQ-1560i attached to a Cessna Caravan

208B at an average altitude of 1,464m flying at an average speed of 145 knots. Lastools (Isenburg, 2014) was used to merge LiDAR tiles that could be clipped down to stand size. The R package LidR (R Core Team, 2022) was then used to clip tiles into stand areas using stand shapefiles provided by industry partners. Digital terrain models for each stand were created using the Rasterize Terrain tool to create a 1m triangulated irregular network of each stand. These digital terrain models were then used to normalize each stand using the normalize_height tool.

In the spring of 2022, 27 field sites were selected to generate a height validation dataset. The sites were relatively representative of all age classes and soil characteristics (Table 1.2). At each site, two, 5m radius plots were installed on areas characteristic of the two extremes of stand growing conditions. Usually, this presented itself as one upslope and one downslope location per site. At each plot, the heights of each Douglas-fir were collected with a height pole measuring to the nearest half centimeter. Plot centers were recorded with a Javad Triumph-2 GNSS with sub-meter accuracy.

Table 1.2. Field data summary of the validation sites elevation (meters above sea level), age, and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) height growth rates for each of the major soil order and texture characteristics from Soil Survey Geographic Database SSURGO (+/- indicates standard error).

Order	Texture	N	Elevation (m)		Age (Years)		Growth rate ($cm \cdot yr^{-1}$)	
			Mean	+/-	Mean	+/-	Mean	+/-
Andisols		20	**413.3**	**359.7**	**4.7**	**1.1**	**55.8**	**12.1**
	Loam	5	805.6	97.1	4.7	0.8	48.5	4.5
	Loamy Sand	1	799.5	-	6.5	-	59.3	-
	Sandy Loam	1	231.3	-	5.5	-	66.6	-
	Silt Loam	13	246.7	305.6	4.5	1.2	57.6	13.6
Inceptisols		4	**740.6**	**223.3**	**5.0**	**1.2**	**55.1**	**14.4**
	Loam	3	682.3	231.2	4.8	1.4	60.7	11.7
	Silt Loam	1	915.6	-	5.5	-	38.1	-
Spodosols		4	**718.5**	**234.1**	**5.7**	**0.9**	**60.7**	**12.2**
	Loamy Sand	4	718.5	234.1	5.7	0.9	60.7	12.2

LiDAR height validation was then performed using the R lidR package (Roussell & Auty, 2023) and plot-level data. GPS-coordinate plot centers were buffered by 5m to create a polygon plot shapefile. These plots were clipped from the normalized point clouds using the clip_roi tool. An ITD algorithm, "locatetrees", was used to detect trees using a local maximum filter with a height minimum of 0.5m and an adjustable window size defined by the function $f = \{x * 0.1 + 3\}$. The local maximum window size function was derived through parameter testing to minimize mean square error of height for each plot while ensuring tree counts always matched field values. Individual tree heights for each plot were output to lists where they were used to generate plot height averages. These plot averages were subsequently utilized with field plot averages to create a correction factor for LiDAR heights using simple linear regression.

In order to create stand-level averages of height for all stands, the ITD algorithm and LiDAR correction factors established during the validation process were used on all stands. Stand-level

tree lists of heights were generated using the Locate_trees ITD. Tree heights occurring greater than two standard deviations of the mean were removed to eliminate retained mature trees and buffer regions in the stand. This trimmed tree list was then related to field heights in a simple linear regression which produced an equation to correct the height underestimation bias from the LiDAR dataset. Stands were then averaged to generate a stand-level mean height. Mean heights were then turned into growth rates using stand establishment dates provided by industry partners.

1.3.3 Analysis

In order to examine the individual effects of soil texture, elevation, soil order, and slope on Douglas-fir growth, linear mixed effects models and analysis of covariance (ANCOVAs) were used to identify variables that were associated with Douglas-fir growth ($cm \cdot yr^{-1}$) and Douglas-fir height (cm). For both response variables, age was used as a covariate while stand ownership was used as a random effect. Age was included in growth rate models in order to account for the trend that in these age ranges growth rates tend to be increasing still, as such it may be expected that a lower growth rate will occur in younger trees regardless of site quality differences between them and older trees. All linear mixed effects models were performed using LMER from the R package LME4 (Bates et al. 2016).

When developing models for predicting Douglas-fir growth and height from all identified predictors, a stepwise regression was performed using the Step function from the R package Stats(R Core Team 2023) to identify models that minimized the Akaike Information Criterion (AIC). Variables were eliminated using bidirectional elimination in the initial function where the

step function evaluated variable importance through performing both a forward and backward regression. From here, the model was placed into an LMER object with stand ownership as a random effect and variables were systematically removed by significance, with the least significant p-value being removed each time until only significant variables remained. Once a model with only significant predictors remained, collinearity was checked for using a variance inflation factor (VIF). If collinearity concerns were found, represented by a VIF value greater than 5, the least significant predictor with a VIF value of concern was eliminated until only all remaining predictor variables had VIF values less than 5. Final models were evaluated for performance based on marginal and conditional R^2 values extracted using r.squaredGLMM from the MuMIn package (Bartoń, 2023). The alpha value for all tests was set at $p \leq 0.05$.

Site index curve models were examined using regression approaches to further analyze variables that had shown significant interactions with age when predicting height in ANCOVA analyses. Continuous variables were converted to categorical where necessary for regression analyses. Texture and elevation variables were divided based on tertiles to establish high, medium and low levels. Slope percent, which has larger gaps between jumps in values and clusters around certain values due to map units being assigned a semi-categorical slope percent, was also split into three groups, however groups were selected for similar values to avoid illogical groupings created by tertiles.

1.4 Results

1.4.1 LiDAR Correction

LiDAR predicted heights from the locate_trees function underpredicted field heights for the validation plots by approximately 20% (Figure 1.2). Regressing field height with LiDAR height provided a correction with a high R^2 value of 0.91. The correction equation was 48 + 1.2*LiDAR height.

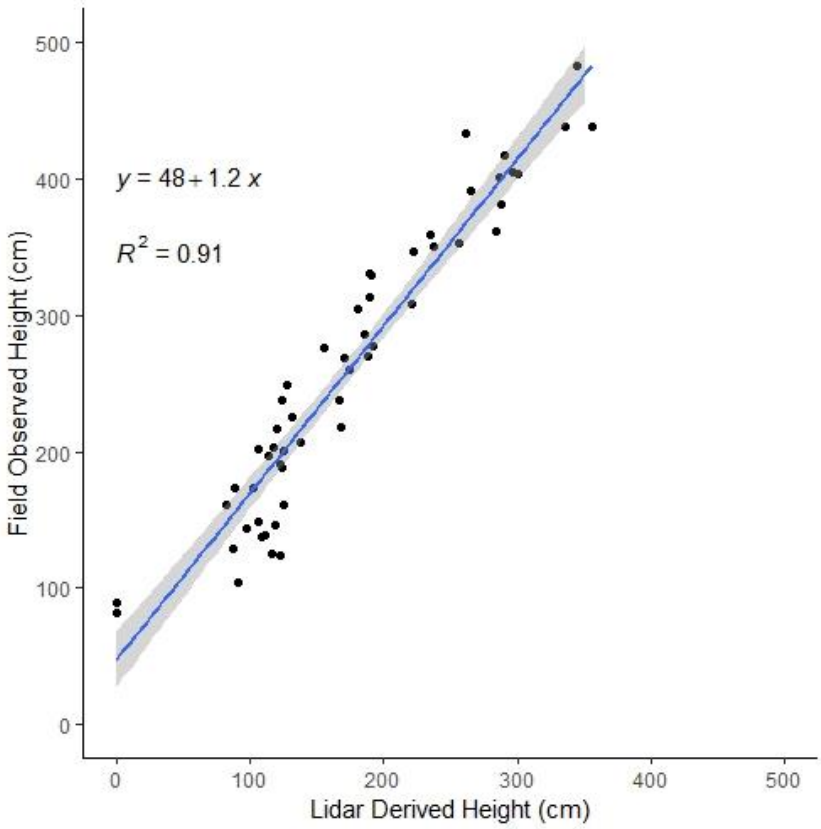


Figure 1.2. Comparison of LiDAR-derived *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* height measurements and field height measurements for 56 validation plots across 28 sites in western Washington. Linear model y=48+1.2x represents the equation to correct LiDAR-derived heights to resemble field-measured heights.

1.4.2 Soil Variable's Impact on Growth Rate

Major textural classes showed significant interactions with age to predict height Douglas-fir height growth (F = 18.0, p <0.01). Douglas-fir total height growth accumulation in years 3-8 was greater in fine-textured soils, such as silt-loams and loams, than coarse texture soils, such as sandy loams and loamy sands (Figure 1.3). Douglas-fir growing on silt loams (β_1 = 85.6±7.6 cm·yr^{-1}) demonstrated more rapid growth patterns from year to year than other textures, such as loams (β_1 = 47.0±5.9 cm·yr^{-1}), sandy loams (β_1 = 42.8±9.2 cm·yr^{-1}), and loamy sands (β_1 = 20.4±8.5 cm·yr^{-1}), which tended to grow at slower rates.

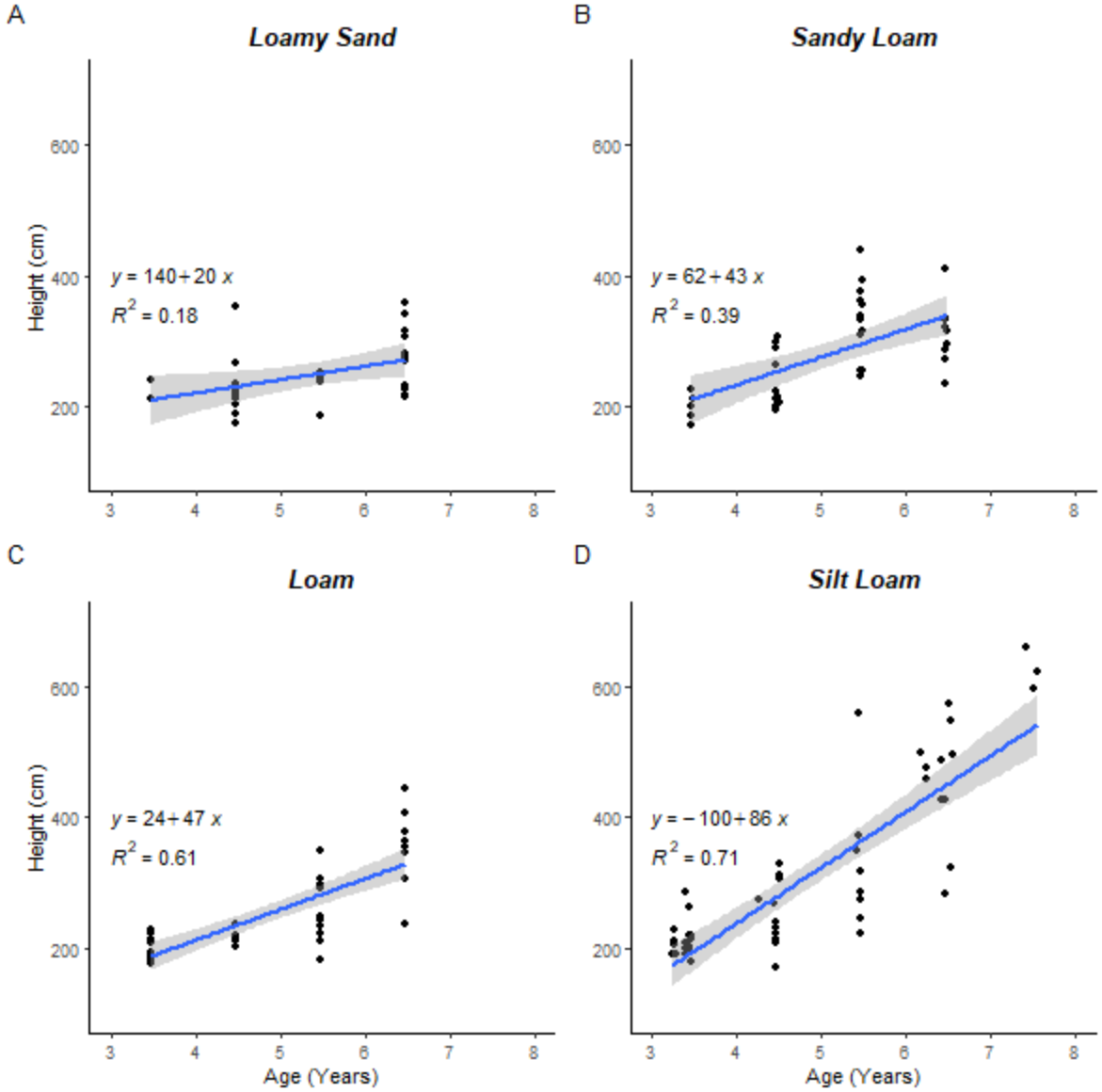


Figure 1.3. Douglas-fir LiDAR corrected heights plotted by age for Soil Survey Geographic Database major textural classes in western Washington, USA.

This pattern reemerged when examining the relationship between Douglas-fir growth rate and changes in texture fractions. Increases in percent silt or clay in both 0-30cm and 30-60cm depths resulted in increases in Douglas-fir growth rate while increases in percent sand at both depths resulted in decreases (Figure 1.4). Particle size variables did not yield any significant

predictors for Douglas-fir growth rates, they did however all yield significant interactions with age to predict Douglas-fir height (Table 1.3).

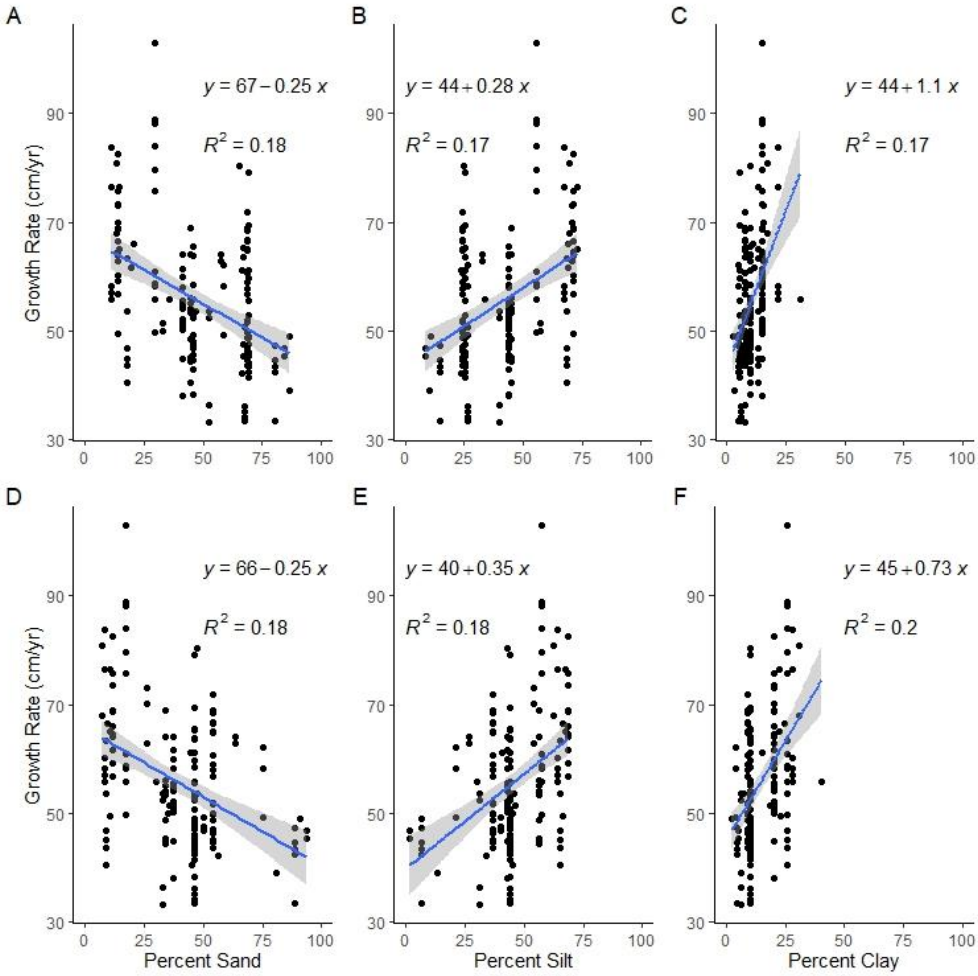


Figure 1.4. Relationship between 3-8 year old *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* height growth rates, based on LiDAR measured heights, with Soil Survey Geographic Database particle size fractions of sand (panels A&D), silt (panels B&E), and clay (panels C&F) for depths 0-30cm (panels A-C) and 30-60cm (panels D-F). All slope coefficients were significant (p <0.01).

Table 1.3 Analysis of variance results for *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* growth predictor variables including those extracted from the Soil Survey Geographic Database and average stand elevation (m) extracted from LiDAR scans. Growth rate models show results for model that included age as a covariate, Height models show results for interaction between variable and age.

Variable	Growth Rate ($cm \cdot yr^{-1}$)		Height (cm)	
	Test Statistic	*p*	*F*	*p*
% Sand 0-30cm	t = 0.49	0.49	39.09	<0.01
% Sand 30-60cm	t = 0.63	0.43	31.67	<0.01
% Silt 0-30cm	t = 0.05	0.82	35.79	<0.01
% Silt 30-60cm	t = 1.58	0.21	31.86	<0.01
% Clay 0-30cm	t = 2.37	0.13	45.53	<0.01
% Clay 30-60cm	t = 3.03	0.08	40.02	<0.01
Elevation (m)	t = 78.49	<0.01	92.84	<0.01
% Slope	t = 0.17	0.68	15.85	<0.01
Texture Minor	*F* = 5.55	0.16	8.08	<0.01
Texture Major	*F* = 2.35	0.06	18.03	<0.01
Taxonomic Order	*F* = 0.49	0.69	11.57	<0.01

SSURGO taxonomic orders also displayed strong relationships with Douglas-fir height growth when crossed with age (Figure 1.5; $F = 11.6$, $p < 0.01$). Those grown on Andic soils tended to have greater height for a given age than other soil orders (Figure 1.5) and were approximately 50 cm greater in height by age five than the next closest soil order's height.

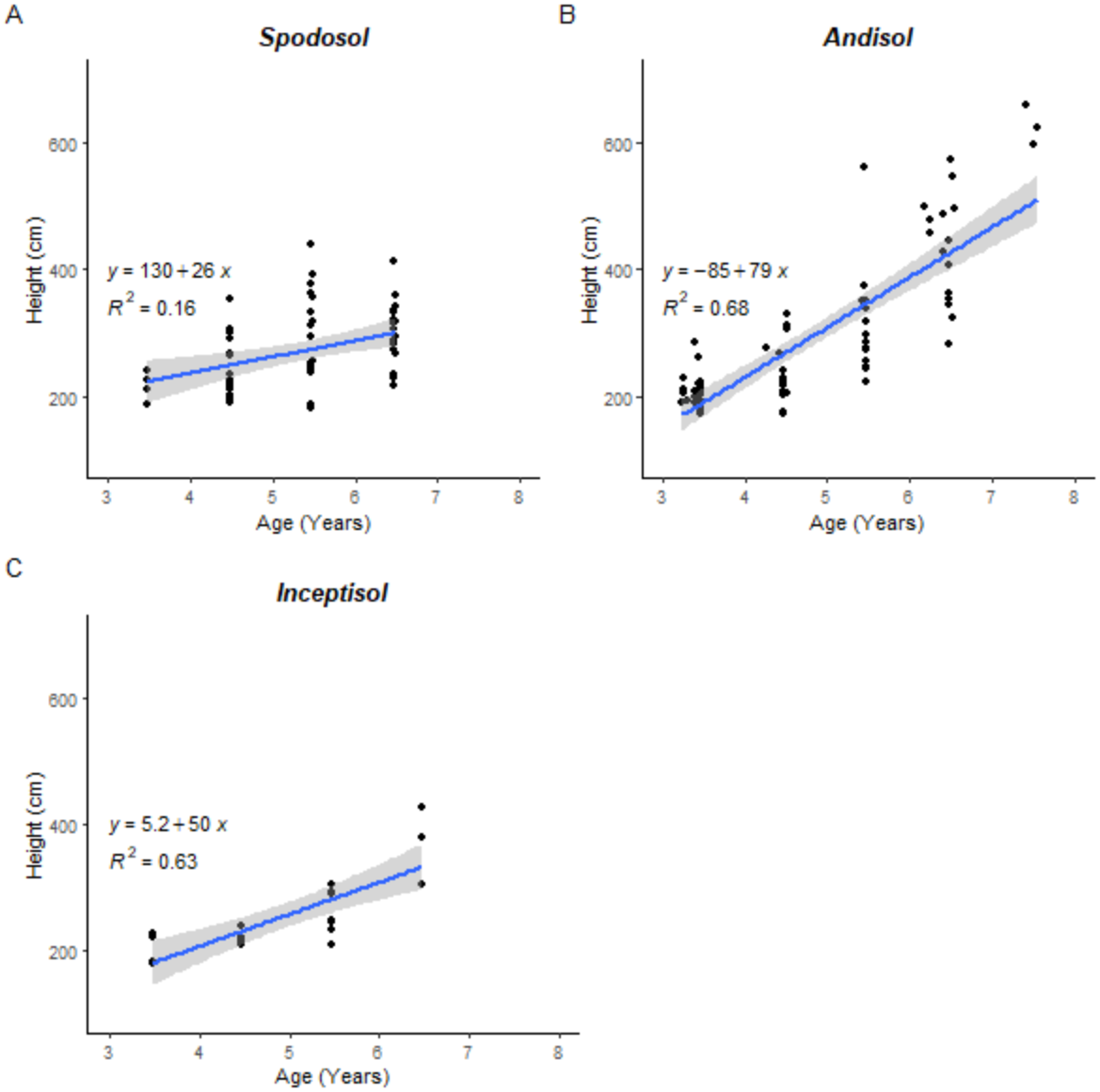


Figure 1.5. *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* LiDAR corrected heights plotted by age for soil orders.

1.4.3 Effect of Site Variables on Height Growth

Mean stand elevation had the highest r^2 (0.42) of any single variable predicting Douglas-fir growth rates. Growth rates decreased with increasing elevations (Figure 1.6.; β_1 = -

0.023±0.003; $p < 0.01$) and elevation provided the strongest individual relationship with height (marginal R^2= 0.78).

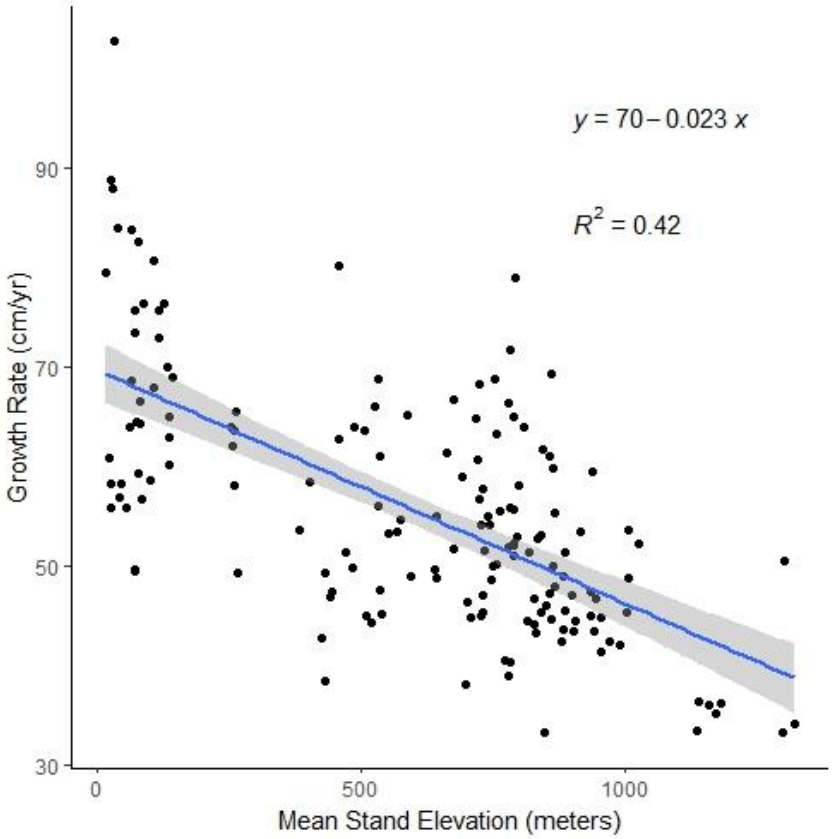


Figure 1.6. Relationship between western Washington *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* stand-level growth rate in years 3-8 derived using LiDAR heights and planting dates.

Site index base age 50 (β_1 = 0.19±0.06; p <0.01) and growth rate for the corresponding stands are significantly related, however it explains a small portion of the variation (R^2= 0.046) (Figure 1.7). Elevation (β_1 = -0.023±0.003; $p < 0.01$) explained a greater portion of the variation (R^2=0.42) than site index base age 50 predicting young stand growth rates.

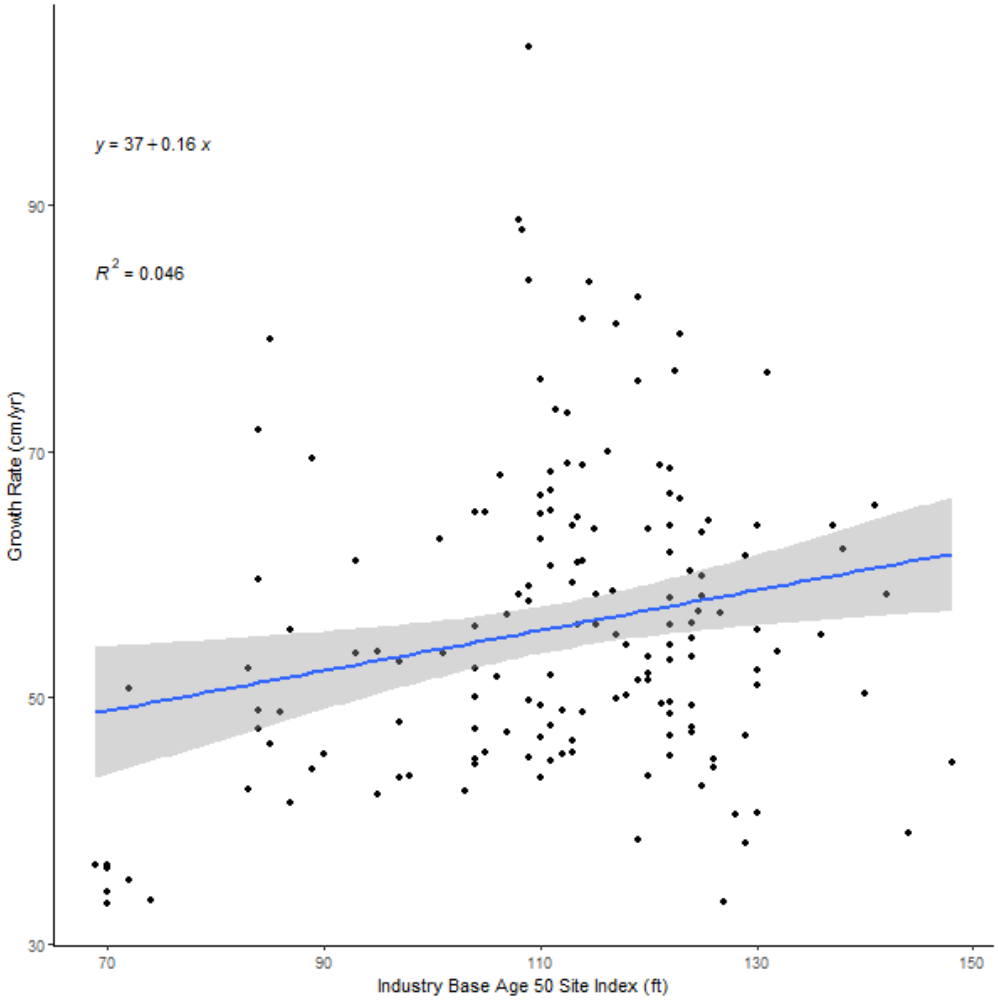


Figure 1.7. Industry base age 50 site index values for each site compared with current stand growth rate age 3-8.

1.4.4 Douglas-fir Growth Models

Mean stand elevation and average map unit slope composed the strongest model for growth rate (marginal R^2 = 0.44) after variables had been removed for collinearity (Table 1.4). The Mean Stand elevation and Age (marginal R^2 = 0.42, AIC = 1197.9) relationship demonstrated above performed closely to the mean stand elevation and slope model proposed here however the lower AIC value and a slightly greater marginal R^2 seen in Table 1.4 resulted in it being the selected model. (Mean stand elevation has a negatively relationship with growth rate in the

model (β_1 = -0.03±0.003; t-value= -9.6; p<0.01) while average SSURGO map unit slope was positively relationship with growth rate (β_1 = 0.14±0.05; t-value = 2.9; p<0.01). The models for height performed only marginally better with the inclusion of average map unit slope (marginal R^2=0.70) than they did with only average stand elevation in the model (marginal R^2=0.69)(Table 1.4). The models each provided greater R^2 values when shifting from predicting height growth rate to predicting height and including age as a predictor variable (Table 1.4).

Table 1.4. Models for *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* height growth rate (cm yr^{-1}) and height (cm) based on Site and Soil Survey Geographic Database based predictors; average stand elevation (m), average map unit slope (%), Clay 30-60cm (%), age (years) where +/- represent the direction of the relationship.

Response Variable	Model	AIC	Marginal R^2	Conditional R^2
Height Growth Rate (cm yr^{-1})	-Average Stand Elevation + Average Mapunit Slope	1195.2	0.437	0.445
Height Growth Rate (cm yr^{-1})	- Average Stand Elevation	1197.6	0.405	0.417
Height (cm)	-Average Stand Elevation + Average Mapunit Slope + Percent Clay 30-60cm +Age	1740.5	0.707	0.707
Height (cm)	- Average Stand Elevation + Age	1743.2	0.686	0.687

1.4.5 Early Term Site Index

When elevation classes formed by tertiles are used to compare heights over corresponding ages a pattern of separation after age 4 is shown (Figure 1.8). While Douglas-fir younger than 4 years old have very similar heights, they separate after age 4, as low elevation sites (β_1 = 78.6 cm·yr^{-1}) outpace the medium (β_1 = 47.1 cm·yr^{-1}) and high elevation sites (β_1 = 24.8 cm·yr^{-1}).

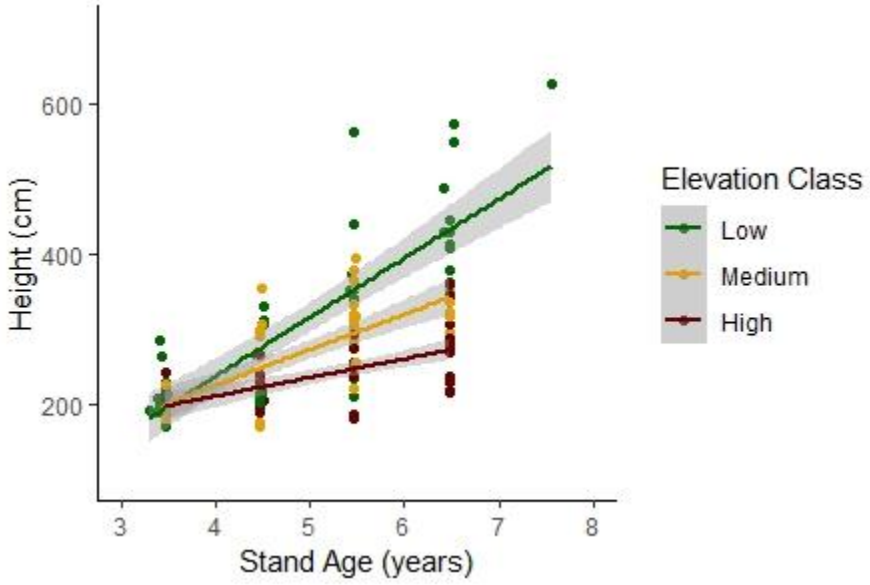


Figure 1.8. Linear models predicting average *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* stand height in western Washington plantations based on stand age and elevation class where low = (elevation < 492.13m), medium = (492.1m<elevation<789.3m)), and high = (789.3m<elevation).

A significant three-way interaction exists between elevation classes, age, and the percentage of clay at the 0-30cm depth(F = 3.54, p = 0.03). Within clay classes growth rates regularly increased with increasing elevation class across all categories (Figure 1.9).

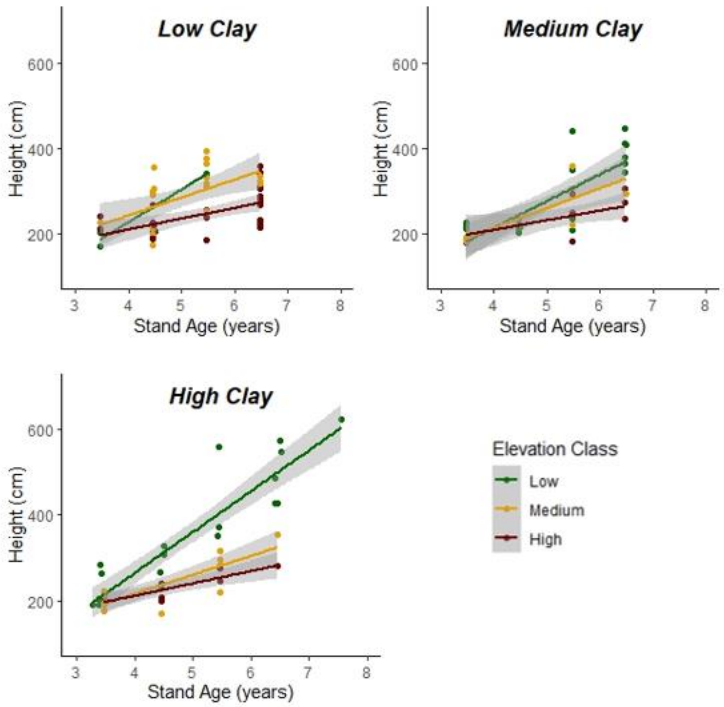


Figure 1.9. Linear models predicting average *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* stand height in western Washington plantations on low (<7.3%), medium (7.3%-10%), and high (>10%) clay soils across ages 3-8. Elevation classes were low = (elevation < 492.13m), medium = (492.1m<elevation<789.3m), and high = (789.3m<elevation).

A significant interaction existed between Slope percents of stand soil map units, textural classes, and age when predicting height (F = 2.93, p = 0.04). Slope classes showed little effect on loamy sands with the steep (β_1 = 21.0±12.2) and moderate (β_1 = 20.9±11.2) slopes exhibiting similar growth patterns. However, in silt loam soils, there is a distinct pattern of increasing growth with decreasing slope (steep β_1 = 45.8±15.1; moderate β_1 = 82.0±10.1; little β_1 = 103.2±18.5).

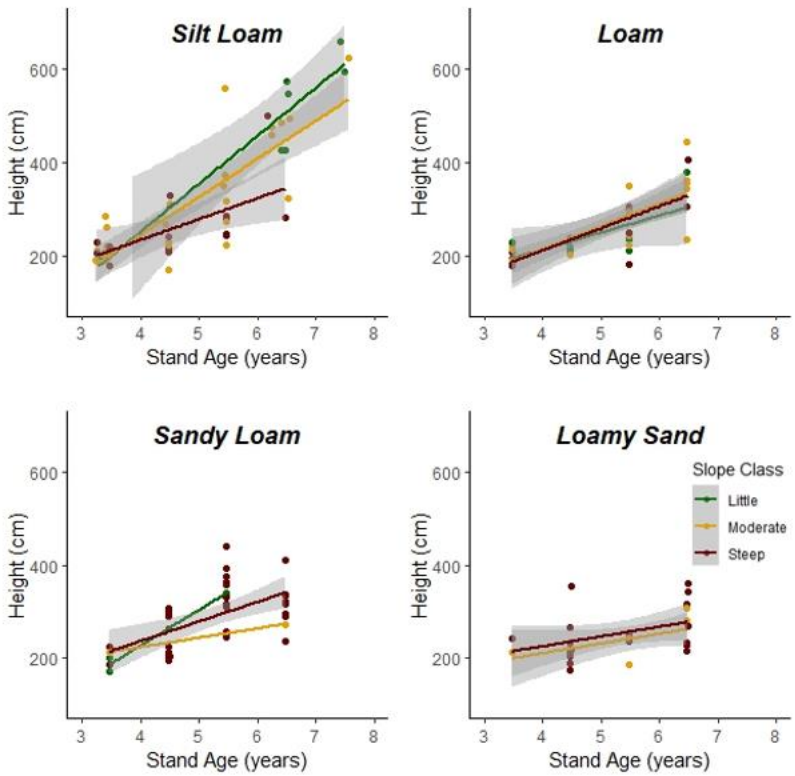


Figure 1.10. Linear models predicting average *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* stand height in western Washington plantations on varying soil textures. Slope classes were designated as little (<11%), moderate (11%-47%), and steep (>47%).

Soil texture class and age ($F = 18.0$, $p < 0.01$) and elevation and age ($F = 92.8$, $p < 0.01$) had significant two-way interactions when predicting Douglas-fir height. Though no significant three-way interaction existed among these two factors and age.

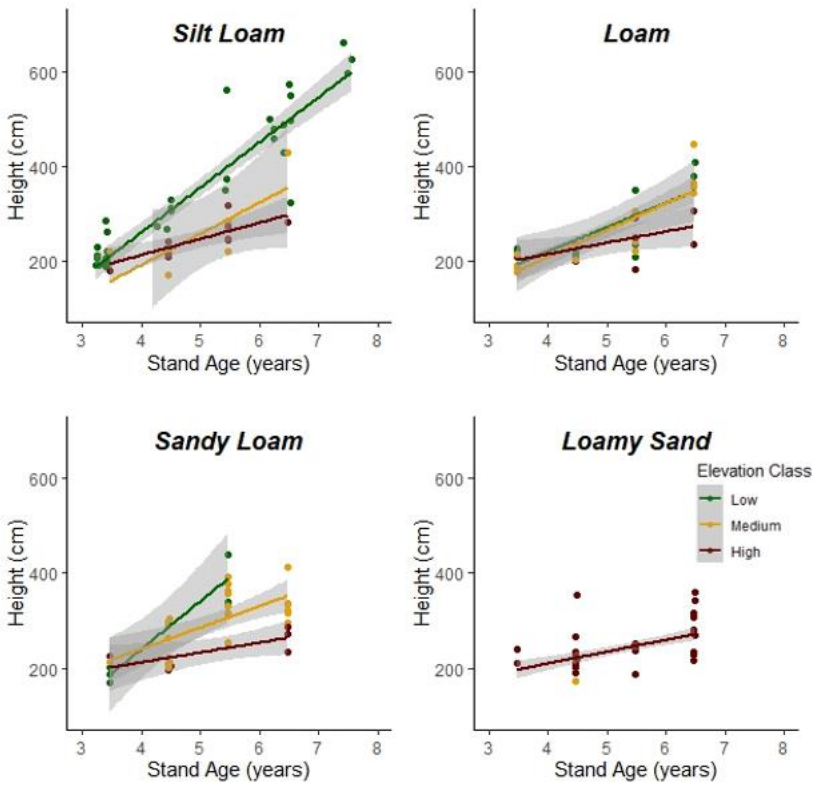


Figure 1.11. Linear models predicting average *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* stand height in western Washington plantations on varying soil textures based on stand age and elevation class where elevation classes where designated as low = (elevation < 492.13m), medium = (492.1m<elevation<789.3m), and high = (789.3m<elevation).

In silt loams and sandy loams, Douglas-fir in low-elevation sites (β_1 = 94.9±6.3; β_1 = 101.5±19.5, respectively) tended to outpace the growth found on corresponding medium- (β_1 = 65.7±28.1; β_1 = 44.9±11.4, respectively) and high-elevation sites (β_1 = 34.0±8.9; β_1 = 20.8±8.7, respectively) (Table 1.5). Loam soils showed more similar growth patterns between their low (β_1 = 51.2±14.6) and medium-elevation sites (β_1 = 56.5±6.6) however these both still rapidly outpaced their corresponding high elevation site (β_1 = 23.8±10.4).

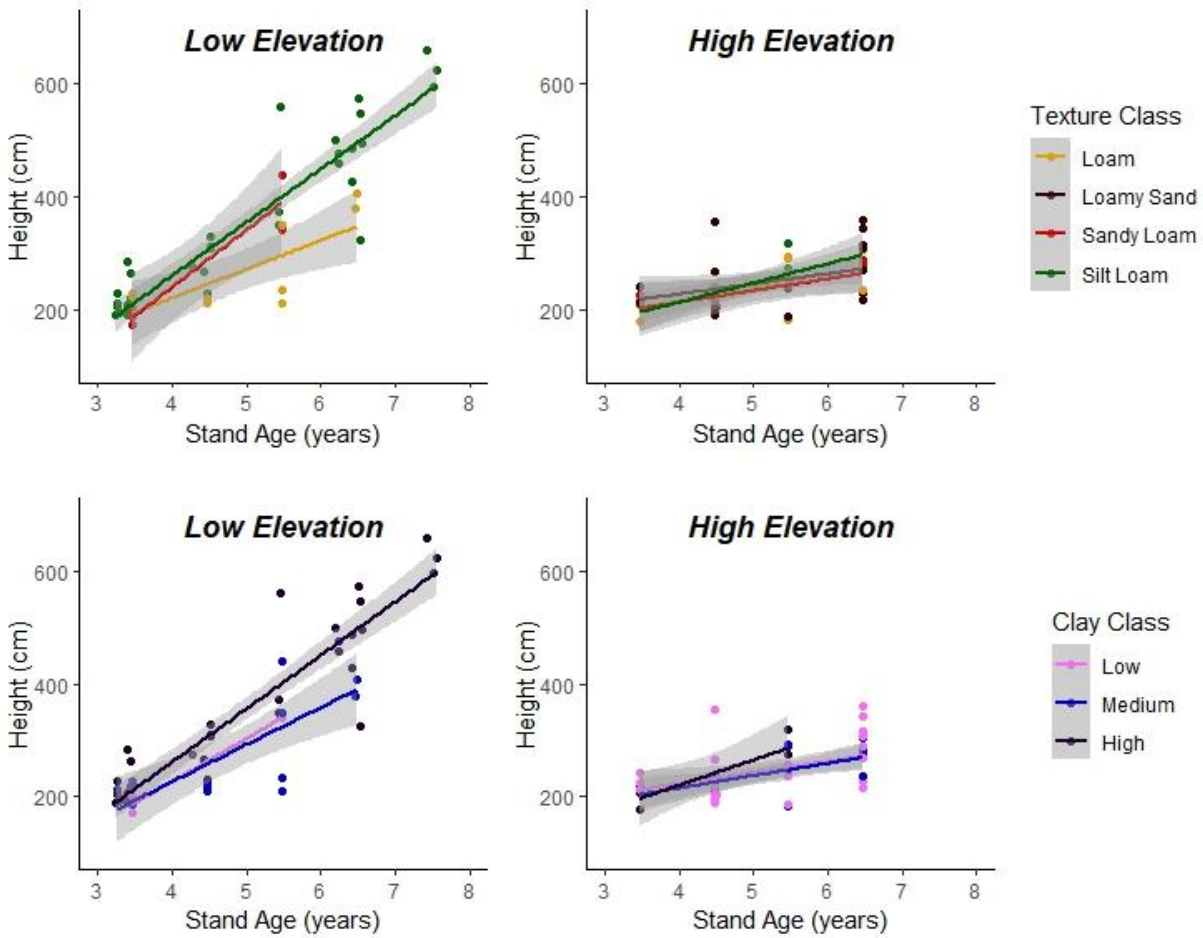
Table 1.5. Models and fit values for elevation and soil texture based young *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* site index curves predicting height (cm) at a given age(years) where low = (elevation < 492.1m), medium = (492.1m<elevation<789.3m)), and high = (789.3m<Elevation).

Texture	Elevation Class	Model	R^2	n
Silt Loam	Low	Height ~ -120+95*Age	0.86	38
	Medium	Height ~ -71+56*Age	0.58	6
	High	Height ~ 76+34*Age	0.64	10
Loam	Low	Height ~ 16+51*Age	0.58	11
	Medium	Height ~ -17+56*Age	0.8	20
	High	Height ~76+34*Age	0.37	11
Sandy Loam	Low	Height ~ -170+100*Age	0.9	5
	Medium	Height ~ 61+45*Age	0.42	24
	High	Height ~130+21*Age	0.53	7
Loamy Sand	High	Height ~ 140+20*Age	0.18	26

Differences in elevation appear to change the importance of texture in predicting Douglas-fir height (Figure 1.12). At low elevations soil textural class has significant interactions with age (F= 3.9, p = 0.03) to predict Douglas fir height however in high elevations no significant interaction existed (F = 0.4, p = 0.78). At Low elevations clay concentrations form similar patterns to those shown in the soil textural classes with high clay contents mirroring the growth patterns of silt loams and sandy loams while low and medium clay contents mirror loam growth patterns. The clay classes create slightly more differentiation at the high elevation classes than the textural classes. However, both the models show far less variation in growth pattern than their low elevation analogues. The high clay class sites models increase from the low clay sites (β_1 = 20.0±7.6) to the medium (β_1 = 22.1±7.0) and eventually the high site (β_1 = 44.9±14.23) which features a growth pattern almost twice as rapid as other classes. In the textural classes

the spread at high elevation is much smaller with Silt loams being the high end of the range (β_1 = 34.0±8.9) and loamy sands the low end (β_1 = 18.0±8.9).

Figure 1.12. Linear models predicting average *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* stand height in western Washington plantations on varying soil textures and clay classes based on low (elevation < 492.13m) and high (789.3m<elevation) elevations and stand age (years).



Discussion

Models in this study indicate that elevation serves as a primary predictor of Douglas-fir height and growth rates while factors such as soil texture and slope provide differentiation within areas of similar elevation. Patterns of decreasing growth with increasing elevations occurred similarly

across a range of clay percent classes, while soil textural classes only provided significant impacts to growth at certain elevations. Finer textured soils and lower elevations were associated with greater growth rates within the western Washington region. Elevation and major textural classes both provided useful relationships for the development of an early term site index.

My expectation of increasing growth rates with increasing fine soil fractions appeared to be met. My results were very similar to growth rate patterns of young Douglas-fir from Carter et al., (2022), where increasing sand resulted in decreasing growth rates, increasing silt percent resulted in an increase of growth rate, and increasing clay percent resulted in an even greater increase in growth rate than silt. These results were consistent with the results of the major textural classes where classes that shifted towards the silt and clay end of the texture spectrum exhibited greater growth rates than those with higher sand proportions. As in Carter et al., 2022 the results here likely indicate an influence of soil water content as the finer textured soils, especially silt loams, that have the higher concentrations of silt particles which hold the greatest volume of plant available water.

Elevation was one of the strongest predictors across all models in this study, appearing in every model and having significance as a main effect for both height and growth rate. Our study exhibited a persistent decreasing pattern in growth with increasing elevations from 15-1300 m across a range of soil textures. This is congruous with the site quality findings for Douglas-fir by Carmean (1954) who described a decreasing site index across a gradient of elevations from 0-1500 m. This response is likely due to the difference in the start of growing season between the low and high elevations. Growing seasons begin earlier at low elevation than at high elevations

allowing lower elevation trees to take advantage of this longer season and produce greater growth (Carmean 1954). In addition, slope was an important factor that produced contrasting relationships between the regression models and the growth rate models. We see that in a model including elevation the influence of slope becomes positive while a simple regression approach demonstrates that increasing slope reduces growth rate. This may indicate that there are some potential positives of steeper slopes within certain elevations that could be created through sheltering effects or beneficial hill aspects.

I hypothesized that fine-textured, low-elevation sites would provide the highest site quality. The data indicated there to be a pattern such as this at the extremes; however, this trend was not consistent across all texture and elevations classes. Within textures, elevation classes occasionally produced unexpected patterns. For example, in loam soils, medium elevation sites had Douglas-fir heights which eventually exceeded those of low elevations due to higher growth rates. While these results align with my expectations and previous studies (i.e., McArdle 1930; Carmean 1954), my study showed that growth rates of young stands are poorly predicted by site index base age 50 values. Existing site indexes for Douglas-fir in this region are usually calibrated to either low elevation sites (King 1966; Bruce 1981) or to high elevations (Curtis & Reukama, 1971; Monserud 1984). Comparisons made between these site indexes have shown that there is little overlap in site qualities covered with most of the high elevation site indexes having height predictions at age 50 well below any measured in low site index studies (Monserud 1985). It is possible that these young trees exhibit extreme sensitivity to elevation, relative to their mature counterparts. It may be this sensitivity and coverage of a broad range of elevations

in my dataset that resulted in a poor relationship between early stand growth rate and base age 50 site index values.

Several different metrics displayed in this study provide promise for describing early term site index. Elevation throughout this study has been demonstrated as one of the dominant factors determining early term growth. While it can serve as a valuable site index tool in isolation the inclusion of soil texture variables such as clay and major textural classes has been demonstrated to improve elevation's ability to capture the variability on the landscape. Additionally, slope has been shown to improve models with both textural variables and elevation in predicting Douglas-fir growth. When attempting to scale up these relationships to map early-term site index across the region, the relationships of soil textural classes and elevation may provide the best approach. Although Soil particle size fractions such as clay provide some of the strongest relationships with elevation, they require processing to transform the data into the depth-based factors utilized in this study. Without transformation these data are horizon-based and difficult to compare from site to site. With this in mind, major map unit textural classes may provide a streamlined way to include the impacts of texture on elevation-based site indices and provide easy to use management information for the region.

Conclusion

In western Washington and nearby neighboring areas with similar climates from the cascades to the coast, for plantations occurring on elevations between 15-1319m in cascades, elevation and soil texture appear to be dominant factors in determining site quality in young Douglas-fir (ages 3-8). My data suggests young Douglas-fir grow better on sites with lower elevation and fine-textured soils. This study demonstrated the use of LiDAR and individual tree detection

algorithms for the measurement of young trees and the potential to capture regional variability that was previously sample-size prohibitive using traditional field methods. The method outlined in this study shows promise for being applied to other systems to develop site indices for ages existing site quality metrics fail to describe. The importance of having site quality metrics for this age range is demonstrated by the poor estimation of site quality for young trees using existing site index values.

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Chapter 2: Relating Soil Properties to Douglas-fir and Scotch Broom Growth

2.1 Abstract

Scotch broom is a pervasive threat to invade Douglas-fir plantations across western Washington. Douglas-fir's risk of being overtopped by Scotch broom has been shown to be highly site dependent, however the factors which determine what sites are most at risk are currently unknown. We aimed to identify soil characteristics relating to nutrient or water availability associated with Douglas-fir outcompeting Scotch broom in terms of height growth. Paired field plots were established to measure Douglas-fir independently, and in the presence of Scotch broom at each site. Soil samples and vegetation height measurements were collected to model which site characteristics led to Scotch broom outcompeting Douglas-fir. My study identified that Scotch broom presence was negatively related to Douglas-fir height growth and altering Douglas-fir's relationships with the resources that support it. Higher percentages of silt, carbon, or phosphorus were identified as factors that were related to improving Douglas-fir growth when growing on sites with Scotch broom. These factors may identify sites that allow Douglas-fir height growth to emulate or exceed the height growth of Scotch broom reducing its risk of being overtopped.

2.2 Introduction

Invasive species are one of the greatest causes of biodiversity loss (Mainka & Howard 2010). The effects of these invasions are expected to be exacerbated by climate change as the tolerance of invasive species to a wide range of conditions makes them more likely to succeed than native species (Hellman et al., 2008). With the ever-increasing threat these invasive

species pose to native ecosystems, there is a growing need for tools that facilitate efficient invasive species management (Lennox et al., 2015).

In the Pacific Northwest (PNW) of the United States, Scotch broom (*Cytisus scoparius* (L.) Link) is one of the most prevalent invasive plants in forests, with significant risk to native vegetation and reforestation efforts (Oneto et al., 2010). Scotch broom is native to Mediterranean climates making it well-adapted to the climate in the western PNW (Williams 1981). Since Scotch broom's introduction to the PNW in the 1850s, it has rapidly expanded its range in response to frequent forest disturbances such as fire and harvesting (Prasad 2000; Oneto et al., 2010). Scotch broom is an adept invader utilizing a suite of traits to out-compete native vegetation, including biological N fixation, high seed production, seed banking, photosynthetic stems with reduced leaf coverage during drought, and rapid growth following germination (Wheeler et al., 1979; Bossard & Rejmanek, 1992; Bossard & Rejmanek, 1994; Fogarety and Facelli 1999; Matias et al., 2012). Today, Scotch broom is one of the costliest forest plant invaders to control in the region (Bossard 1990; Alexander & D'Antonio 2003; Mefford et al. 2017).

In western Washington state, Scotch broom has caused significant financial impacts for the state and its timber industry (Mefford et al. 2017). This is due to Scotch broom's competitive effect on the state's keystone timber species Douglas-fir (*Pseudotsuga menziesii (*Mirb.) Franco var. *menziesii*) (Harrington and Schoenholtz 2010; Watts 2017). Scotch broom and Douglas-fir compete for dominance early in stand development which can result in significant losses as tree seedlings that are overtopped by shrubs have high mortality rates (Balandier et al. 2006). High site quality has been shown to increase the likelihood of

competitive success for Douglas-fir against Scotch broom, with its risk of overtopping being reduced (Harrington et al., 2018). Carter et al. (2022) demonstrated that Scotch broom height growth tends to asymptote around 3m and Douglas-fir reaching the 3m threshold height before Scotch broom diminishes the risk of being overtopped. This makes identifying factors that lead to more rapid Douglas-fir growth early in stand development before they reach this 3m threshold a key for identifying site susceptibility to Scotch broom dominance.

Scotch broom capitalizes on a variety of efficient water-use strategies to gain a competitive advantage over Douglas-fir seedlings (Carter et al. 2019a; Carter et al. 2021). Scotch broom utilizes drought-deciduous properties to limit drought damage during dry periods (Watt et al. 2003; Carter et al. 2019a). In dry periods, Scotch broom limits water usage while maintaining growth by limiting evapotranspiration through a combination of lower stomatal conductance and drought deciduousness in combination with photosynthetic stems (Matias et al., 2012). In periods of relative resource abundance, Scotch broom utilizes rapid growth, especially in comparatively early and late seasons, leveraging high evapotranspiration and extensive deep rooting to preempt use of water resources (Allen and Allen 1981; Fogarety and Facelli 1999; Boldrin 2017, Carter et al. 2018). It is possible that these water use advantages, in combination with a climate that favors these strategies contribute to Scotch broom gaining an advantage over less-adapted competitors on more drought-affected sites.

The improved water-use efficiency of Scotch broom provides it with a competitive advantage over Douglas-fir, but this competitive advantage may be mediated by site conditions. Carter et al., (2022) have demonstrated that on high-quality sites with fine-textured soils and, subsequently, greater soil water content, Douglas-fir tends to outcompete Scotch broom.

Conversely, Scotch broom appeared to be relatively unaffected by changes in soil water availability. This could, in part, be due to Douglas-fir's tendency to see stunted root growth in drought conditions, further exacerbating the inability to outcompete the extensive root systems of Scotch broom (Smit and Driessche, 1992). Douglas-fir's more conservative water use strategy leads it to not only use but acquire less soil water than its Scotch broom competitors (Carter et al. 2019a). These results show that factors like water stress may be a dominant mechanism determining competitive outcomes between Douglas-fir and Scotch broom.

Several metrics exist to analyze site soil water conditions based on soil properties and topography. Site soil water retention has been modeled to correspond strongly with soil texture (Rawls et al. 2003; Warren et al. 2004). Using digital elevation models (DEMs) to measure runoff likelihoods can also allow you to make estimations of relative soil moisture through indices such as topographic wetness index (Schmidt & Persson 2003) and downslope index (Hjerdt et al. 2004). Through variables such as these, one could attempt to characterize how likely a site is to be water limited throughout the year, inducing water stress in species like Douglas-fir and Scotch broom.

In addition to factors relating to water stress, increased nutrient availability has also been linked to increased Douglas-fir growth (Carter et al., 2019a). Douglas-fir growth increases with increases in nitrogen (N), phosphorous (P), and carbon (C) (Littke et al., 2007; Mainwaring et al., 2014; Slesak et al., 2016). Scotch broom has been shown to be less responsive to increasing concentrations of nutrients as their growth rates can be relatively unaffected by resource limitations (Carter et al., 2019a). However, Scotch broom presence has been attributed to P depletion over time on some sites (Slesak et al., 2016), indicating that Scotch

broom's phosphorus requirements for N fixation may lead to sites with higher P:N ratios benefitting Scotch broom growth (Carter et al., 2022). The intersection of these two species' potential nutrient limitations may lead to the differential site susceptibility to Scotch broom dominance.

Nutrient pools may be altered in the presence of Scotch broom as studies have shown that uptake of nutrients, such as P, has been reduced in the presence of other N-fixing woody plants, like red alder (*Alnus rubra*) (Cole and Newton, 1986). This ability of N fixers to transform their competitor's ability to access nutrients may be one reason studies have shown Scotch broom grows better on sites that have had previous Scotch broom invasions (Fogarty and Facelli 1999; Weidenhamer and Callaway 2010). Studies have suggested that these legacy impacts on soil chemical properties may be lasting (Slesak et al. 2016) and that removing Scotch broom may only create an even less favorable, further altered soil environment for native vegetation (Slesak et al. 2022).

The demonstrated impact of Scotch broom on soil nutrient properties has led some to hypothesize that Scotch broom itself could cause positive fertilization effects for Douglas-fir growth by increasing total C, N, and P due to its ability to biologically fix N (Helgerson, 1984; Haubensak et al. 2004). These hypotheses suggest the increased biomass created as a result of N fixation is then introduced to the soil when Scotch broom plants shed their leaves during the summer, thus increasing soil C and N, and potentially altering microorganism activity and ion adsorption and releasing P in the form of phosphate (Fogarety and Facelli 1999). This potentially positive influence on nutrient pools and native plant growth has largely been disproven due to any nutrient benefits being negated by proximity competition effects from

Scotch broom (Slesak et al. 2016; Littke et al. 2020). Some studies have measured positive increases in C, N, and P nutrients from invasions (Fogarety and Facelli 1999), while others have found that plant-available N (NO_3-) has increased in invaded areas but not total N (Littke et al. 2020). Slesak et al. (2016; 2022) found that these effects appear to be associated with site quality, as low-quality sites see no increase in total C or N, while on high quality sites accumulation of C and N in the soil occurs. They hypothesized that this was a result of Scotch broom retaining nutrients in systems that were more nutrient limited. Likewise, decreases in P have occurred in the presence of Scotch broom and more specifically the fraction of P that is believed to be extractable by plants (Slesak et al., 2016). It is thus hypothesized that P limitations could also be attributed to the relative success of Scotch broom over Douglas-fir as these effects have been seen in the greatest magnitude on lower quality sites where Scotch broom sees more competitive success (Slesak et al., 2016). If the potential of Scotch broom to alter nutrient pools is site-dependent, interactions between Scotch broom presence and soil nutrients on Douglas-fir growth may elucidate the drivers of competitive success in this relationship.

I aimed to identify the site-level factors that are associated with Douglas-fir growth rates, and subsequently the potential to outcompete Scotch broom. By examining the growth of Douglas-fir in the presence and absence of Scotch broom, we aimed to find the factors affecting Douglas-fir growth that may be altered by Scotch broom and differentially influence growth among the two species. We hypothesized that (*i*) Douglas-fir growth rates would increase as soils became increasingly fine-textured due to factors relating to water retention. (*ii*) we hypothesized that Scotch broom growth would be dependent on available P, due to the

high P requirements of N fixation. (*iii*) We hypothesized indicators of site-level soil moisture, such as fine soil texture and increasing topographic wetness index, would be associated with increased Douglas-fir growth rates. (*iv*) In cases where Nitrogen content was correlated with Scotch-broom growth rate we hypothesized that it was due to fertilization effects from nitrogen fixation.

2.3 Materials and Methods

Site Characterization

This study occurred on 19 Douglas fir plantations between ages of 2-7 years that currently had Scotch broom invasions (Table 2.1). Sites were located in Washington state, west of the coastal range in the Willapa hills, Puget Lowland, and Southern Cascade regions. All sites were clear-cut before re-planting Douglas-fir. Sites were chosen to reflect the regional variety of soil types where Scotch broom and Douglas-fir co-occur. Only sites with Douglas-fir two to seven years of age were considered to capture the most pivotal years in this competitive relationship.

GPS coordinates and DEM's were utilized to extract additional plot metrics. Plot centers and a 3m DEM from the Washington Department of Natural Resources were used to derive an elevation from each point by extracting values to points from the DEM raster. Plots were also evaluated for hydrologic conditions using ArcGIS and R. Topographic wetness index and downslope index were derived using the 3m DEM from the Washington DNR using the R package Whitebox (Wu & Brown, 2022). ArcGIS was then used to extract values to points from topographic wetness index and downslope index rasters.

Table 2.1. Characteristics of the 19 *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* plantation field sites in western Washington organized by soil series. (TWI-topographic wetness index; DWI-downslope wetness index; C-Carbon; N-Nitrogen; P-Phosphorous)

Soil Series	Alderwood	Barneston	Calawah	Dystric Xerothents	Everett	Lebar	Melbourne	Mopang	Nordby	Shelton	Willaby	Zenker
Climate												
Mean Prec. (mm)	115.2	107.8	214.7	122.7	136.7	215.8	138.8	214.9	242.8	126.3	242.8	207.0
Mean Temp. (°C)	10.1	9.9	10.0	9.8	10.1	9.9	9.8	9.9	9.8	10.0	9.8	10.1
Sites												
Douglas-fir Ages (years)	2-4	3-4	2-4	4	2-6	3	4	4	3	2-7	3	5
Mean Elevation (m)	90.4	156.6	78.5	130.0	166.3	60.3	50.5	64.0	74.0	138.0	79.3	70.0
Mean DSI[a]	0.3	0.1	0.1	0.1	0.1	0.2	0.0	0.1	0.1	0.1	0.1	0.1
Mean TWI[a]	4.9	5.1	4.2	5.0	7.4	5.2	6.0	5.8	6.8	6.4	5.9	6.2
Soil Properties												
0-30cm Depth												
Sand/Silt/Clay(%)[b]	70/24/5	67/30/3	75/21/4	69/28/3	70/26/4	76/21/4	58/39/3	71/24/5	68/30/2	64/29/7	69/28/2	78/19/4
C (%)[c]	5.0	6.1	6.9	3.0	3.6	7.4	3.4	5.5	6.7	3.8	5.8	6.9
N (%)[c]	0.2	0.3	0.3	0.1	0.1	0.3	0.2	0.2	0.4	0.1	0.3	0.3
P ($mg \cdot kg^{-1}$)[d]	2.5	7.5	2.3	14.9	20.2	2.2	12.2	1.0	4.8	13.9	3.3	1.7
30-60cm Depth												
Sand/Silt/Clay(%)[b]	73/21/6	64/30/5	69/23/8	73/24/3	70/23/7	67/26/7	52/44/4	66/25/9	67/32/1	66/27/7	71/28/1	72/22/6
C (%)[c]	2.8	3.7	3.8	2.0	1.4	3.8	1.8	3.0	3.1	1.9	5.6	4.4
N (%)[c]	0.1	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.3	0.2
P ($mg \cdot kg^{-1}$)[d]	1.6	3.4	0.8	13.0	12.8	0.5	3.9	0.6	1.8	7.3	3.2	0.9

Notes:
[a]Calculated using USGS DEM and R package Whitebox
[b]Mean measured sand, silt, clay of plots occurring on this series measured with hydrometer method
[c]Mean total carbon and nitrogen measured through combustion
[d]Mean available P extracted with Mehlich 3

Plot Measurements

At each site, four 5m-radius circular plots were installed. Two plots were placed in areas with Scotch broom (CYSC) and Douglas-Fir (PSME; plots which contained both species are referred to as PSME/CYSC) and two other plots were placed in areas where Douglas-fir was growing in the absence of Scotch broom (plots which contained only Douglas-fir are referred to as PSME-only). The plot locations had to contain representative samples of Douglas-fir and Scotch broom in size and frequency .

At each of the four plots located at each site, three soil bucket auger samples were taken 1.83m from plot center and at 120˚ intervals from each other, starting at magnetic north. The three soil cores were combined into composites of 0-30cm depths and 30-60cm depths per site. Every tree within a plot was measured for height (cm) with a height pole and stem diameter (mm) at 15cm above the plant's root collar using calipers. At PSME/CYSC plots, Scotch broom heights were also collected using a height pole. Scotch broom diameters were collected at the base of the tallest stem. The bottom section of the stem was also removed for use in aging the Scotch broom plant. These cross-sections were later sanded with progressively fine-grained sandpaper until rings could be counted for age estimates. Ages and Scotch broom heights were then used to create average plot level Scotch broom growth rates. GPS coordinates were collected for all plot centers.

Lab Analyses

Soil was first air-dried to remove excess moisture. Soil composites were ground with mortar and pestle to break up aggregates and then sifted through a 2mm sieve to remove rocks

and large organic material. Each plot's 0-30cm and 30-60cm soil composite were evaluated for soil texture using a PSA hydrometer analysis (Gee & Bauder 1986). Soil total C and N were evaluated using an *Elementar Vario Max CNS.* Soil available P was extracted using a Mehlich 3 extraction (Mehlich 1984) and analyzed using inductively coupled plasma spectroscopy with a *Spectro Analytical Instruments ARCOS-III MultiView*. Soil available P testing results in estimations of what plant available P truly is as we try to mimic extraction processes that fit soil properties specific to a region. While other extractions like Bray P1 are often used through the pacific northwest our selection of Mehlich 3 is due to its use in comparable studies on Douglas-fir Scotch broom competition like Slesak et al., (2016) and Carter et al., (2022) allowing us to contextualize our results.

Statistical Analyses

A bidirectional stepwise regression model was used to quantify the effect of soil texture, nutrients (N, P, and C), topographic wetness index, downslope index, and Scotch broom presence on the growth rates of Douglas-fir in R (R Core Team, 2023). The step function was used to identify initial variable choices for the mixed effect model performed using LMER, by identifying variables that minimized model AIC through running forward and backward stepwise models. The output of the step function was subsequently adjusted by removing variables from the output until all remaining variables were listed as significant predictors ($P<0.1$). The least significant variables based on p-value were removed from the model output of the step first until no insignificant variables remained. Final models were checked for collinearity using VIF, if variables had a VIF value greater than 5 the variable with the highest VIF was removed and models were rerun until no variables with collinearity concerns remained.

Additionally, this same technique was used for predicting the growth rate of Scotch broom using the same site aforementioned variables characterizing soil texture, nutrients, topographic wetness index, and downslope index. For both models, site, which refers to the management-unit plots were located in, was used as a random effect. Other stepwise regressions used plot average height (cm) of Douglas-fir or Scotch broom as a response variable and developed models based on the same variables identified for each species above in the growth rate models, in addition to age. Where post hoc analyses for models were performed, the emmeans package (Lenth 2023) was used to perform Tukey tests using the Kenward-Rogers approximation for degrees of freedom. In addition, paired t-tests were used to check for potential effects of Scotch broom on nutrients where strong significant relationships between Scotch broom presence and the variable existed. The alpha value for all tests was set at $p \leq 0.1$ due to the inherently high variability demonstrated by our sites. Comparisons between regression models for Douglas-fir and Scotch broom growth rate and height models were performed to identify intersections of plot characteristics where Douglas-fir may outpace Scotch broom growth. Significant predictors for Douglas fir or Scotch broom were used in these regression comparisons.

2.4 Results

When examining the main effects of various plot-level variables on Douglas-fir growth, Scotch broom presence was shown to be a significant predictor of Douglas-fir growth rates (F = 3.35 p = 0.02), reducing growth rates by -2.99 ±9.89cm·yr^{-1}. It was also a significant predictor of total Douglas-fir height (cm) (F = 4.78, p = 0.03) reducing total height by -9.91± 38.71cm on average. Other variables such as available soil phosphorus concentration 30-60cm (mg/kg) (β_1 =

-0.5±0.28, p = 0.02) also influenced Douglas-fir growth rate (cm·yr^{-1}) (Table 2.2). Likewise, available soil phosphorus concentration 30-60cm (mg/kg) (β_1 = -2.38±1.01, p = 0.04) and topographic wetness index (β_1 = -1.83±0.98, p = 0.06) were both negatively associated with Douglas-fir height overall (Table 2.2).

Table 2.2. Main effects and interaction effects with plot characteristics and *Cytisus scoparius* (L.) Link (CYSC) presence predicting *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* (PSME) growth rate (cm yr^{-1}) and height (cm) collected over 19 field plots located in western Washington on Douglas-fir plantations. Significant predictors are in bold font. TWI and DWI represent topographic wetness index and downslope wetness index, respectively.

Variable	Depth (cm)	PSME Growth Rate (cm yr^{-1})				PSME Height (cm)			
		Main Effect		CYSC Interaction		Main effect		CYSC Interaction	
		T-Value	P-value	F-Value	P-value	T-Value	P-value	F-Value	P-value
Sand (%)	0-30	0.09	0.93	1.83	0.18	0.32	0.75	2.01	0.16
	30-60	-0.86	0.39	1.64	0.21	-0.661	0.51	1.80	0.19
Silt (%)	0-30	-0.18	0.70	3.06	***0.09***	-0.58	0.56	3.35	***0.07***
	30-60	1.01	0.32	2.65	0.11	0.83	0.41	3.04	***0.09***
Clay (%)	0-30	0.61	0.55	0.26	0.62	0.40	0.69	0.20	0.66
	30-60	0.06	0.95	0.12	0.73	-0.08	0.94	0.08	0.77
Nitrogen (%)	0-30	1.03	0.31	<0.01	0.97	1.03	0.31	<0.01	0.98
	30-60	0.48	0.63	0.21	0.65	0.44	0.66	0.20	0.65
Carbon (%)	0-30	1.15	0.25	0.02	0.88	1.17	0.25	0.03	0.87
	30-60	0.69	0.49	0.28	0.60	0.69	0.49	0.28	0.60
Phosphorus	0-30	-1.37	0.18	3.04	0.09	-1.10	0.28	2.56	0.12
(mg/kg)	30-60	-2.35	***0.02***	0.51	0.48	-2.09	***0.04***	0.50	0.48
CYSC Presence	--	*F*= 5.35	***0.02***	--	--	*F*= 4.78	***0.03***	--	--
Elevation (m)	--	-0.23	0.82	0.22	0.64	-0.44	0.66	0.28	0.60
TWI	--	1.89	0.06	0.01	0.91	-1.94	***0.06***	<0.01	0.96
DSI	--	0.65	0.52	0.50	0.50	0.86	0.39	0.41	0.53

Several soil resources showed significant interactions with Scotch broom presence when predicting Douglas-fir growth rate and height. Primary among these was silt percentage which had significant interactions at 0-30cm (F = 3.35, p=0.07) depth predicting Douglas fir-height and growth rate (F = 3.06, p = 0.09). At 30-60cm depth silt had significant interactions with Scotch broom presence predicting height (F = 3.04, p = 0.09) (Table 2.1). The relationships with silt,

however, were relatively weak with both the presence and absence of Scotch broom producing linear relationships with silt with R^2 values less than 0.1 when predicting Douglas-fir growth rate (Figure 2.1). The Douglas-fir growth rates both in the presence of and absence of Scotch broom were below the average Scotch broom growth rate until low percentages of silt were reached. Similar patterns are shown when examining the effects of 0-30cm depth silt fractions Douglas-fir height where plots without Scotch broom present perform better than those with Scotch broom at higher percentages of silt.

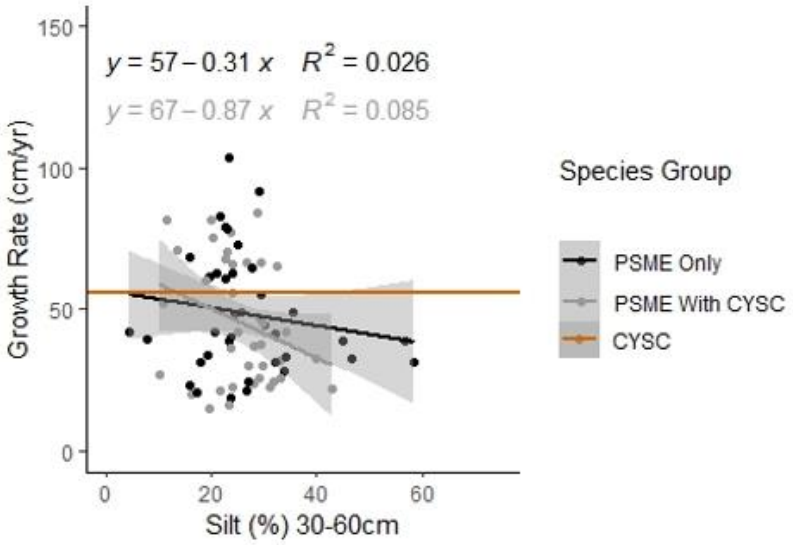

Figure 2.1. Comparison of *Cytisus scoparius* (L.) Link growth rate (CYSC) represented by its mean of 56.21 ($cm \cdot yr^{-1}$) with *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* in the presence (PSME with CYSC) or absence (PSME Only) of *Cytisus scoparius* (L.) Link with varying concentrations of silt at depths of 30-60cm, occurring on PSME plantations between ages 2-7 years across western Washington, USA.

Scotch broom presence creates a significant interaction with silt concentrations to predict Douglas-fir heights. This results in higher silt plots having increased Douglas-fir growth rates in the presence of Scotch broom than on plots with no Scotch broom present. On plots with only Douglas-fir, growth rates on low-silt plots ($\beta_1 = 27.7 \pm 13.0$) outpace those on high silt plots (β_1

= 15.2± 15.7). On plots with Scotch broom present, Douglas-fir growth rates on high silt plots (β_1 = 33.0± 12.1) surpass low silt plots (β_1 = 20.2 ± 18.2). Scotch broom growth (β_1 = 35.3± 7.2), which is unaffected by changes in silt (t = -0.41, *p* = 0.69) outpaces the Douglas-fir growth regardless of the silt content of the soils Douglas-fir occurs on.

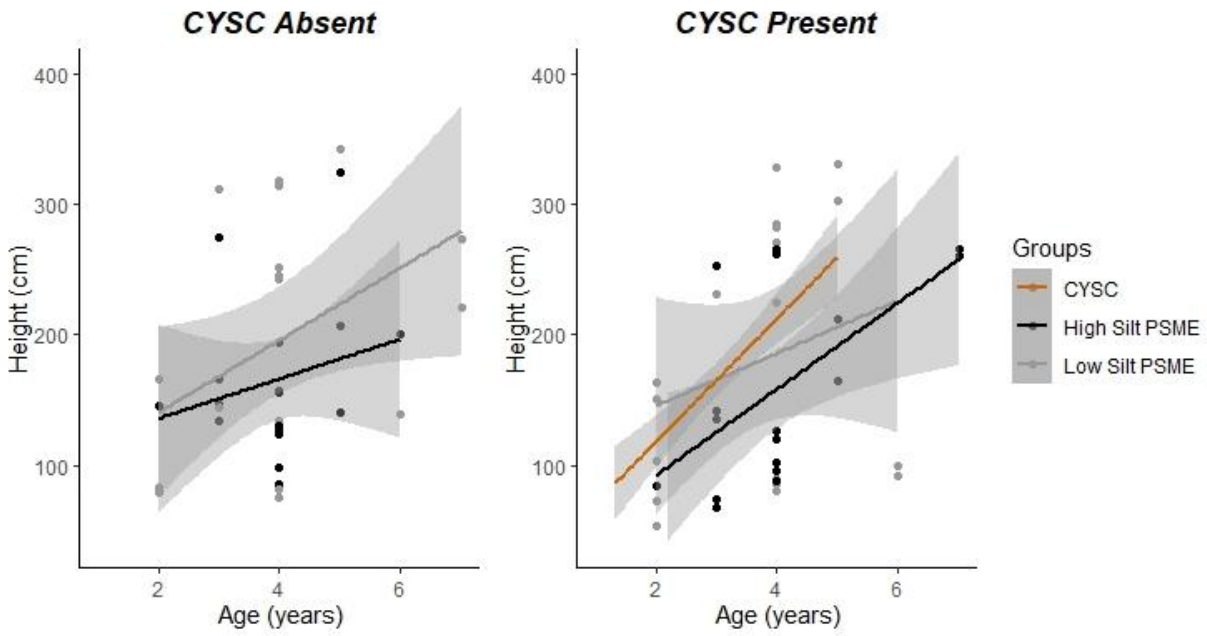

Figure 2.2. Comparison of *Cytisus scoparius* (L.) Link height (CYSC) represented by its relationship with age, with *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* (PSME) in the presence (CYSC Present) or absence (CYSC Absent) of *Cytisus scoparius* (L.) Link and on plots with either high silt (24.5%<Silt<58.5%) or low silt (4.5%<Silt<24.5%) in the 30-60cm depth, occurring on PSME plantations between ages 2-7 years across western Washington, USA.

Both P concentrations at 0-30cm and 30-60cm depths showed significant interactions with Scotch broom presence/absence and Douglas-fir age when predicting Douglas-fir height (*F* = 5.3, *p* = 0.02; *F* = 4.4, *p* = 0.04). Low P (30-60cm) plots yielded more rapid growth than high P Douglas-fir plots regardless of Scotch broom presence (Figure 2.3). However, there is an apparent shift in the range of this relationship as the low P Douglas-fir plots show more rapid

growth in the presence of Scotch broom (β_1 = 79.8± 21.2) than in the absence (β_1 = 46.4 ± 18.5). Similarly, we see a drop off in growth on the high P Douglas-fir when Scotch broom is present (β_1 = 18.5 ± 7.5) at a plot compared to when Scotch broom is absent (β_1 = 21.7 ± 6.6).

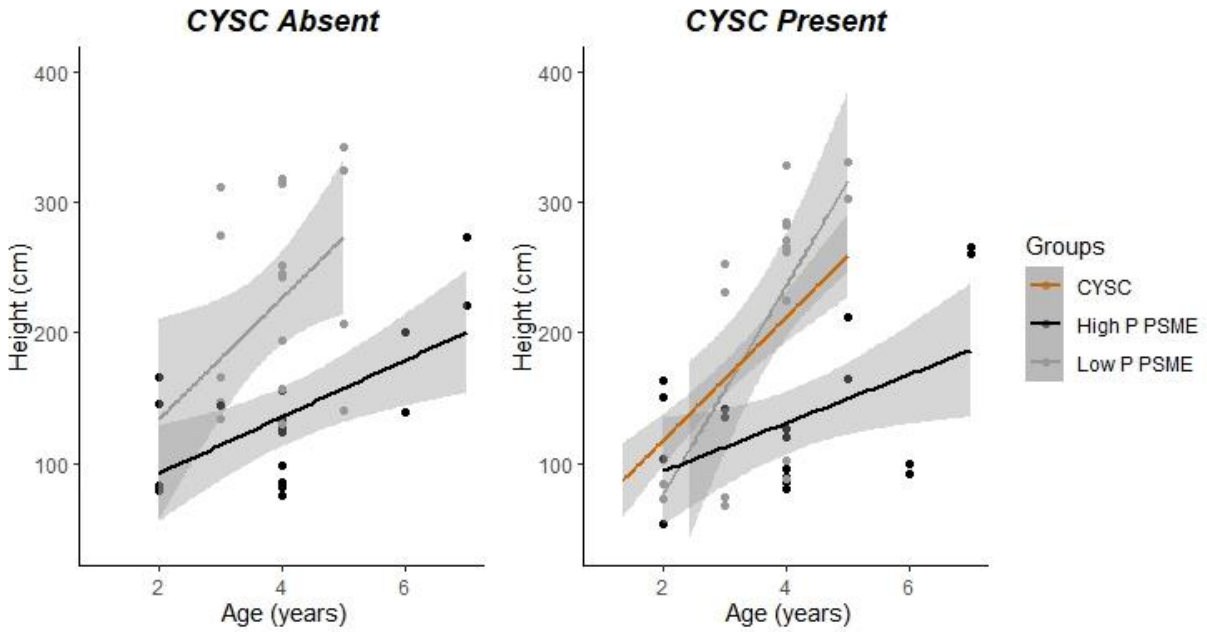

Figure 2.3. Comparison of the height of *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* (PSME) in the presence or absence of competitor *Cytisus scoparius* (L.) Link (CYSC), with varying concentrations of soil phosphorus at depths of 0-30cm, occurring on PSME plantations between ages 2-7 years across western Washington, USA.

Scotch broom growth rate and height were both significantly related to C (β_1 = 3.08±1.47, p= 0.01; β_1 =7.8±3.74, p= 0.05) and N (β_1 = 73.53±32.64, p <0.01; β_1 =182.98±83.23, p = 0.04) in the 30-60cm depth (Table 2.3). In the 0-30cm depth, Scotch broom heights were shown to have a significant negative relationship with P concentration (β_1 =-1.77±0.94, p=0.09).

Table 2.3. Main effects for various plot variables predicting *Cytisus scoparius* (L.) Link (CYSC) growth rate (cm yr^{-1}) and height (cm) collected for 19 field sites located in western Washington, USA, on *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* plantations. Significant relationships are shown in bold font. TWI and DWI represent topographic wetness index and downslope wetness index, respectively.

Variable	Depth	CYSC Growth Rate (cm yr^{-1})		CYSC Height (cm)	
		t-Value	P-value	t-Value	P-value
Sand %	0-30cm	0.55	0.58	0.91	0.37
	30-60cm	<-0.01	1.00	-0.70	0.49
Silt %	0-30cm	-0.22	0.83	-0.41	0.69
	30-60cm	0.02	0.98	-0.31	0.76
Clay %	0-30cm	-0.74	0.46	-1.20	0.25
	30-60cm	-0.02	0.99	1.10	0.29
Nitrogen %	0-30cm	1.63	0.11	0.88	0.39
	30-60cm	3.94	***<0.01***	2.2	***0.04***
Carbon %	0-30cm	1.47	0.15	0.96	0.35
	30-60cm	2.96	***<0.01***	2.09	***0.05***
Phosphorus (mg/kg)	0-30cm	-1.58	0.13	-1.88	***0.09***
	30-60cm	-0.61	0.55	-1.21	0.25
Elevation (m)	N/A	-1.02	0.32	-0.43	0.67
TWI	N/A	-0.83	0.42	-1.43	0.18
DSI	N/A	-0.20	0.84	1.48	0.16

Scotch broom growth rates had a relatively strong correlation with the N concentrations in the 30-60cm depth range (R^2=0.4) (Figure 2.5). These N levels at the 30-60cm depth were not strongly correlated with the average plot age of the Scotch broom (Figure 2.5). Additionally, paired t-tests showed no significant difference between the N concentrations in the 30-60cm depth on plots with and without Scotch broom within a given site (t = 0.36, p = 0.72).

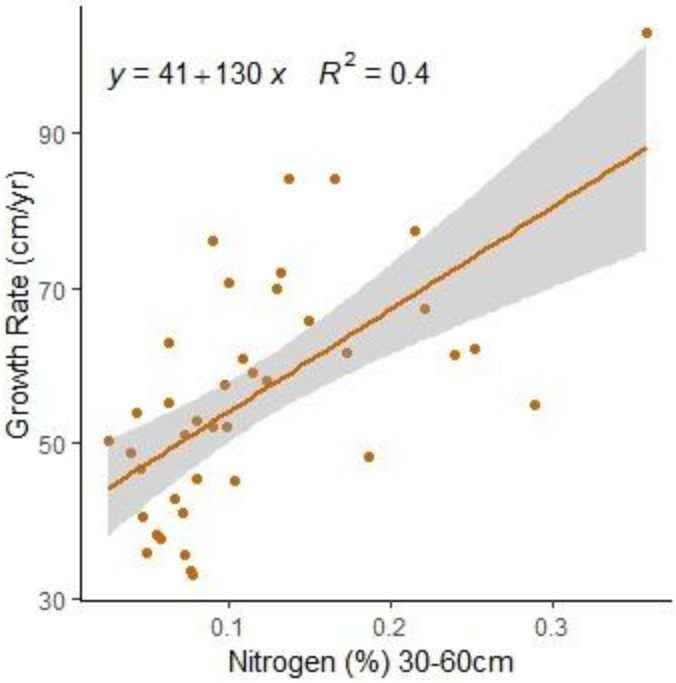

Figure 2.4. Relating *Cytisus scoparius* (L.) Link (CYSC) growth rates to varying concentrations of soil nitrogen at depths of 30-60cm, occurring on *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* plantations between ages 2-7 years across western Washington, USA.

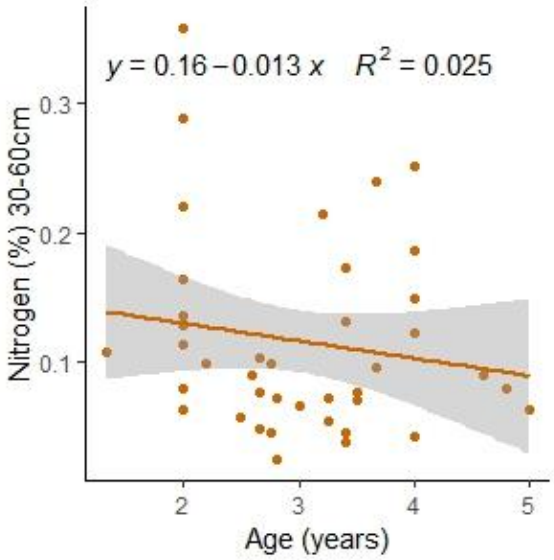

Figure 2.5. Relating *Cytisus scoparius* (L.) Link (CYSC) ages to varying concentrations of soil nitrogen at depths of 30-60cm, occurring on *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* plantations between ages 2-7 years across western Washington, USA.

In the 0-30cm depth, lower concentrations of C were associated with greater Scotch broom growth rates than Douglas-fir (Figure 2.6). While both species' growth rates increased with increasing concentrations of C, the greater increase in Douglas-fir led its predicted growth rate to exceed Scotch broom after concentrations of 8%. A similar pattern is seen in the 30-60cm depth, although the Douglas-fir never exceeds the modeled Scotch broom growth rate at this depth.

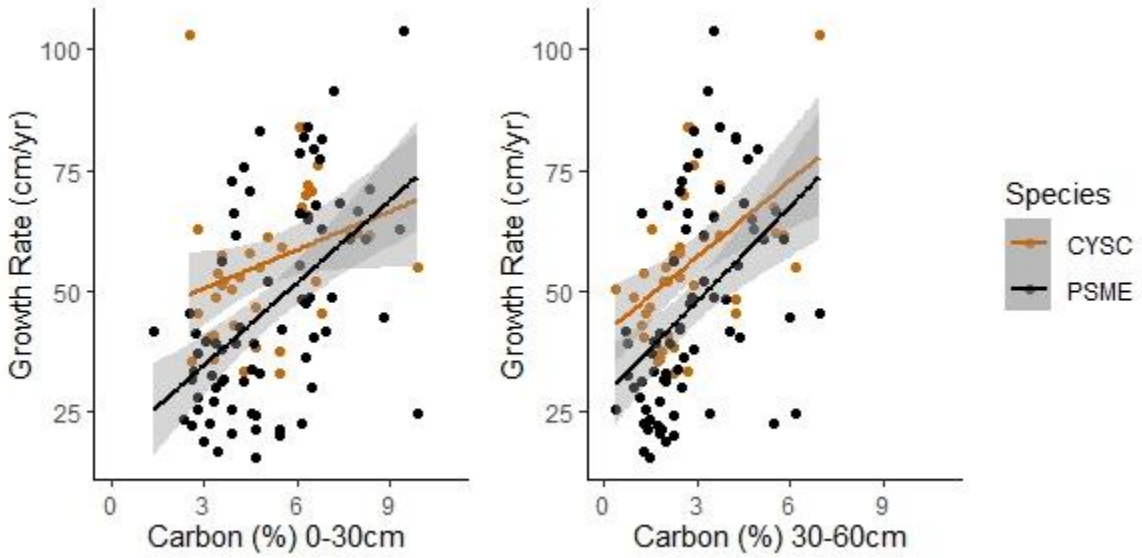

Figure 2.6. Comparison of growth rates of *Cytisus scoparius* (L.) Link (CYSC) and *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* (PSME) with varying concentrations of soil carbon at depths of 0-30cm, and 30-60cm, occurring on PSME plantations between ages 2-7 years across western Washington, USA.

Douglas-fir and Scotch broom growth rates both decrease with increasing phosphorus concentrations in the 0-30cm and 30-60cm depths. In the 30-60cm depth, the Douglas-fir growth rate decreases at a more rapid rate with increasing P concentrations than Scotch broom (Figure 2.7).

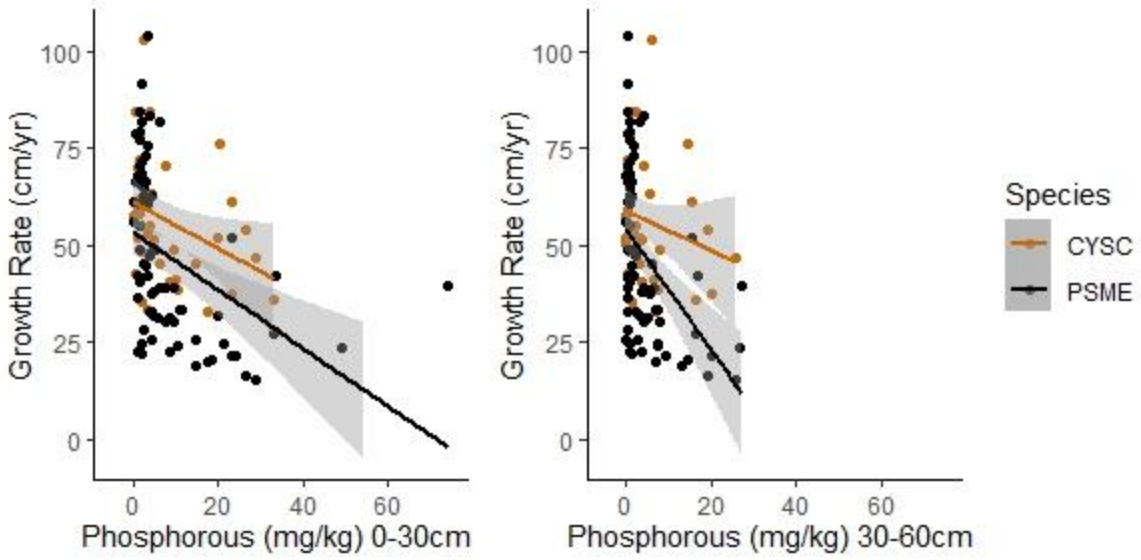

Figure 2.7. Comparison of growth rates of *Cytisus scoparius* (L.) Link (CYSC) and *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* (PSME) with varying concentrations of soil phosphorus at depths of 0-30cm, and 30-60cm, occurring on PSME plantations between ages 2-7 years across western Washington, USA.

Across these plots sand is a significant predictor of soil P presence at both the 0-30cm ($\beta_1 = 0.37 \pm 0.13$, $p<0.01$) and the 30-60cm depths($\beta_1 = 0.14 \pm 0.05$, $p<0.01$). The highest P concentrations in both the 0-30cm and 30-60cm depths are located on plots with sand fractions exceeding 70%.

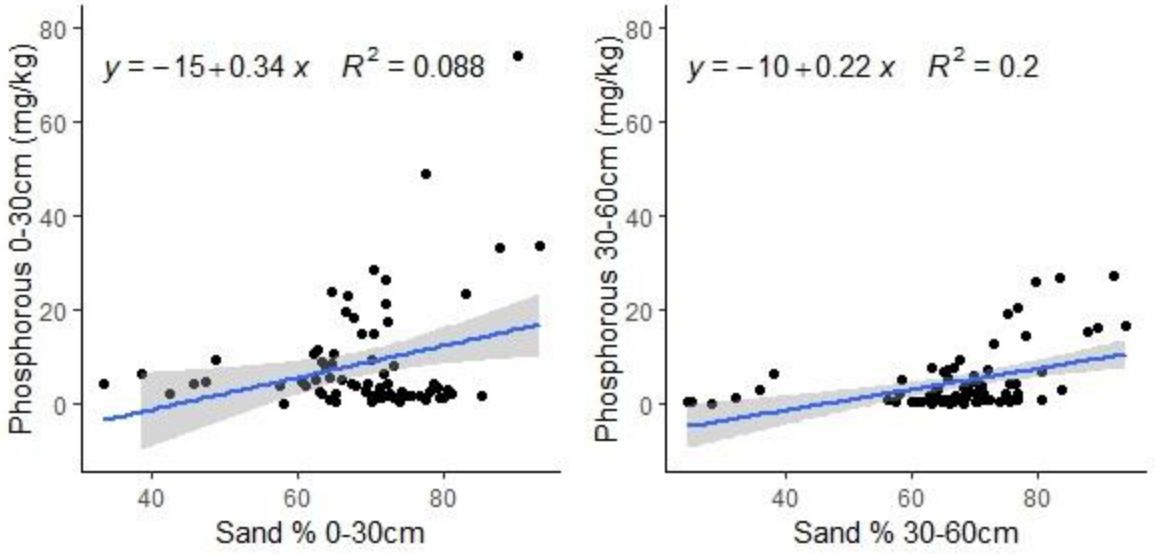

Figure 2.8. Comparison of growth rates of Sand percent and soil P concentrations with varying concentrations of soil phosphorus at depths of 0-30cm, and 30-60cm, occurring on PSME plantations between ages 2-7 years across western Washington, USA.

The best performing Douglas-fir growth rate model was based on Douglas-fir age, Phosphorus 30-60cm, and Scotch broom presence. For Scotch broom, N at depths of 30-60cm was significant when predicting both height and growth rate. Models for Scotch broom – with marginal R^2 values of 0.58 and 0.47 -- vastly outperformed their Douglas-fir counterparts -- which only produced R^2 values of 0.19 and 0.06.

Phosphorus concentrations at 30-60cm (β_1 = -2.55 ± 0.97; t= -2.62; *p*=0.01), Douglas-fir age (β_2 = 25.93 ± 12.95; t= 2.00; *p*=0.06), and the presence of Scotch broom (β_3 = -12.83 ± 5.64; t= -2.28; *p*=0.03) combined to create the strongest model (R^2 marginal=0.19) for predicting Douglas-fir height. When predicting Douglas-fir growth rate, C 0-30cm (β_1 = 1.26 ± 0.68; t= 1.86; *p*=0.07), phosphorus concentrations at 30-60cm (β_2 = -0.50 ± 0.26; t= -1.87; *p*=0.07), and the presence of Scotch broom (β_3 = -3.60 ± 1.54; t= -2.34; *p*=0.03) formed the strongest model (R^2marginal=0.06).

The models with the highest R^2 values predicting Scotch broom height included Scotch broom age (β_1 = 42.64 ± 6.47; t= 6.59; p<0.01) and N 30-60cm (β_2 = 260.63 ± 73.97; t= 3.52; p<0.01) (R^2marginal=0.58). While Scotch broom growth rate was best predicted when only utilizing N 30-60cm as a predictor (β_1 = 122.60 ± 27.21; t= 4.51; p<0.01).

Table 2.4. Multiple regression models predicting growth rates and heights of *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* (PSME) and *Cytisus scoparius* (L.) Link (CYSC) occurring on ages 2-7 years old PSME plantations in western Washington, USA ((+) indicates positive effect, (-) indicates negative effect).

Response Variable	Model	Marginal R^2	Conditional R^2
PSME height (cm)	+ Douglas-fir age - Phosphorus 30-60cm - Scotch broom presence	0.19	0.91
PSME growth rate (cm·year^{-1})	+ Carbon 0-30cm - Phosphorus 30-60cm - Scotch broom presence	0.06	0.89
CYSC height (cm)	+ Scotch broom Age + Nitrogen 30-60cm	0.58	0.79
CYSC growth rate (cm·year^{-1})	+ Nitrogen 30-60cm	0.36	0.50

2.5 Discussion

This study demonstrated a handful of factors that may be related to Douglas-fir height growth keeping pace with, or surpassing, Scotch broom growth such as soil C, P, and Silt concentrations. It also indicated that Scotch broom presence is associated with reduced Douglas-fir growth rates and total Douglas-fir height in trees between 2-7 years of age. This led to Scotch broom presence being a common variable in models predicting both Douglas-fir growth rate and height along with P concentrations in 30-60cm depths. Scotch broom presence was not only associated with reduced Douglas-fir height, but also Douglas-fir's magnitude of

reaction to changes in certain plot characteristics. Scotch broom presence created increasingly negative relationships for factors such as silt fraction and P 0-30cm with Douglas-fir height, although relationships were weak overall. Scotch broom itself appeared to have growth patterns largely dependent on available N, a significant divergence from previous evidence on Scotch broom growth (Helgerson et al., 1984; Carter et al., 2019a; Carter et al., 2019b).

Contrary to my hypothesis, Douglas-fir growth rates seemed to show little relation to soil texture variables. There was no clear indication that Douglas-fir benefitted from growing on fine-textured soils. This contradicts the findings of chapter 1 in addition to those of Carter et al., (2022) who demonstrated that soil texture, specifically sand content, was a significant predictor of young Douglas-fir growth patterns. Some evidence in this study shows that increasing silt content in soils may lead to greater Douglas-fir height growth in the presence of Scotch broom. This finding agrees with those of Carter et al., (2022) who demonstrated that as silt content of soils increased, Douglas-fir would eventually outcompete Scotch broom on the same sites. However, Carter et al., (2022) examined comparisons between Scotch broom and Douglas-fir that were not actively competing, suggesting that the impact of Scotch broom on Douglas-fir growth may have played a role in the differences between these findings. This study demonstrated some alteration of the response of Douglas-fir growth to soil silt content in the presence of scotch broom, a pattern that appeared in several nutrient analyses as well.

A strong correlation between N and Scotch broom height and growth rate was found. This led to a hypothesis that Scotch broom was producing a fertilization effect by enriching the soils with N, similar to those results found by Haubensak et al. (2004) and Shaben & Meyers (2010). However, the lack of correlation between the greater N values and increasing Scotch

broom age implies that N is not accumulating in greater quantities the longer broom is present. Furthermore, the paired analysis examining the difference in the amount of N present at both the 0-30cm and 30-60cm depth between plots with and without Scotch broom at a given site showed no significant difference. Instead, it appears that the amount of soil N is related to other site level factors and Scotch broom growth is in turn being improved by this soil N or other factors related to it. This leads me to concur with the findings of Carter et al. (2019a), Slesak et al. (2016), and Littke et al. (2020) where, despite active N fixation by Scotch broom, little if any N is deposited into the soil while the plants are living. It seems that the relationship between increased soil N and increased Scotch broom growth may be related to resource use efficiency. N fixation is associated with high resource demands in plants to support this process (Vitousek et al. 2002). Most N fixing plants will only actively fix N when the cost is lower than extracting N from the soil (Vitousek et al. 2002). With this in mind, it is likely that on plots with higher N concentrations, Scotch broom is downregulating N fixation and increasing resource use efficiency and growth.

My study hypothesized that Douglas-fir growth would be surpass Scotch broom on plots with high soil moisture. We attempted to estimate soil moisture through soil particle size analysis and geomorphic variables such as topographic wetness index and downslope index. Only topographic wetness index demonstrated significance when predicting Douglas-fir height, and, unexpectedly, topographic wetness index was negatively correlated with Douglas-fir height. It is possible that the topographic features and soil particle analyses only captured portions of the regional variability and fell short of accurately describing soil moisture among my sites. My study did show a strong positive relationship between Douglas-fir growth and soil

C, which has been linked to greater soil moisture-holding capacity through its strong correlation with soil organic matter (Rawls et al. 2003). Other studies, such as Harrington et al. (2018) and Carter et al. (2022), have demonstrated that soil moisture and variables relating to increased organic matter, such as downed woody debris, are likely dominant factors in the Douglas-fir-Scotch broom competitive relationship. The mean growth rate of Douglas-fir exceeded Scotch broom as 0-30cm soil C concentrations increased could be due to soil moisture but my data cannot be used to test this. While these metrics did not indicate soil moisture as a primary cause for this relationship, some other factors such as soil silt content and additionally soil P concentrations may indicate soil moisture is still a factor.

The negative associations between phosphorus and Douglas-fir growth rate and height were unexpected. This finding contradicts a body of research suggesting that available phosphorus is an important positive driver of Douglas-fir growth (McComb & Griffith 1946;Van Den Diessche 1979; Van Den Diessche 1985; Radwan & Shumway 1985; Zas 2003; Mainwaring et al. 2014). While there are some studies that have shown phosphorus to not increase growth (Steinbrenner 1981; Heilman & Ekuan 1973) there are none, to our knowledge, that demonstrate a significant negative relationship between phosphorus availability and Douglas-fir growth. A possible explanation for this marked departure from expected responses is that soil phosphorus is not the main driver of this decreased growth but instead a corollary of a more important variable to Douglas-fir growth that our study was unable to capture. Ding et al. (2021) demonstrated available soil phosphorus to be strongly correlated with negative growth of woody species in Australia, where available soil P strongly correlated with increasing coarseness and aridity. Our study did demonstrate that soil sand content was a significant

predictor of soil P across both depths, perhaps indicating that these relationships may hold true. The majority of studies found regarding the relationships between phosphorus and Douglas-fir were fertilization trials (McComb & Griffith 1946; Van Den Diessche 1979; Van Den Diessche 1985; Radwan & Shumway 1985; Zas 2003; Mainwaring et al., 2014; Steinbrenner 1981; Heilman & Ekuan 1973). It is possible that the relationship of site-level available P has been overlooked by these studies, and that, similar to the results of Ding et al. (2021), available soil phosphorus is actually related to variables more closely associated to site aridity.

Perhaps the most significant findings were the impacts of Scotch broom on Douglas-fir growth as Scotch broom not only significantly reduced Douglas-fir height growth but also altered its relationship with site characteristics. On sites with Scotch broom Douglas-fir's improved growth pattern on higher silt sites may indicate some reaction to water stress created by Scotch broom presence. On Pacific Northwestern soils in Douglas-fir forests, pedo-transfer functions have shown a strong correlation between increases in silt percent and soil water holding capacity (Warren et al. 2004). In addition, the evidence that Douglas-fir growth rates may exceed those of Scotch broom on sites with higher soil C may support this. Soil C has also been shown to be a strong indicator of soil water retention through its strong relationship with soil organic C (Rawls et al. 2003). The ability of a site to retain soil water may be of increased importance for Douglas-fir when Scotch broom is present. While the exact mechanism of which the importance of silt to Douglas-fir may not be clear, our results do show that Scotch broom is altering the environment similarly to the findings of a wealth of previous studies demonstrating microsite alteration by Scotch broom (Fogarty and Facelli 1999; Weidenhamer and Callaway 2010; Slesak et al., 2016).

My study measured a variety of indirect variables that may show some evidence that factors relating to soil moisture may be at the root of Douglas-fir's competitive success. Studies have shown that variables such as maximum soil water content, texture, and coarse woody material that led to moist microclimates can be important predictors of growth for these species (Harrington et al. 2018; Carter et al., 2022). Further studies in this area should aim to identify whether potential underlying mechanisms related to site soil moisture are influential predictors. The next step in identifying potential mechanisms which may predict competitive outcomes between these two oft-competing species should examine soil water retention at the highest water stress time periods in summer and relate these values to the growth rates of Scotch broom and Douglas-fir. A similar field study could lead to identifying variables which accurately predict soil moisture retention under high tension and in turn lead to accurate predictors of success in this competitive relationship.

2.6 Conclusion

This study confirms previous findings that Scotch broom is creating a negative impact on Douglas-fir growth patterns. In addition, we demonstrate that Scotch broom influences the relationship between Douglas-fir growth and site factors such as silt content, and soil P concentrations . This study demonstrates that Scotch broom growth rates are highly dependent on available soil N, and that Scotch broom itself appears to offer no fertilization impact from N-fixation. The relationships identified in this study indicate that there is potential for sites with siltier soils to be beneficial to Douglas-fir when it is grown in the presence of Scotch broom.

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