The Effects of Soil Parent Material and Nitrogen Fertilization on Tree Growth and Wood Quality of Douglas-fir in the Pacific Northwest

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Abstract

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The influence of four soil parent material types (SPMs) and nitrogen fertilization treatment (224 kg N/ha) on Douglas-fir (*Pseudotsuga menziesii* (Mirb.) plantation growth and wood quality was studied on seven sites across western Washington and Oregon. Six aspects regarding wood quality were assessed and analyzed, (1) tree sonic acoustic velocity (TSAV), (2) log resonance acoustic velocity (LRAV), (3) dynamic modulus of elasticity (MOE_d), (4) specific gravity (SG), (5) latewood percentage (LWP), and (6) rings per inch (RPI). Analysis of tree growth suggests the Mixed SPM type (Sedimentary and Igneous) is the most productive type in terms of timber volume increment. Fertilization has significantly enhanced Douglas-fir lateral growth and volume gain, but a variety of effects upon wood quality attributes were detected. In general, growth increment was negatively associated with quality observed in the breast height region. From the perspective of a whole tree, higher quality wood can be found in the segment from stump height to the live crown base. A strong correlation ($R^2 = 0.92$) between TSAV and LRAV was observed, and TSAV was 8% higher than LRAV.

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Above all, my deepest gratitude to my parents for their greatest love!

CHAPTER 1. INTRODUCTION

The progress of humanity from the primitive state to the present day's highly advanced technology has been closely associated with dependence upon wood. Wood has been essential for human survival (such as being utilized for heat and shelter) because of the relative ease of working on it as well as its almost universal availability.

Wood can be used to address demands from global urbanization and climate change. Instead of using concrete and steel (two materials which contribute up to 8% of greenhouse gas globally) in new constructions, using wood provides additional benefits. It is a renewable resource having a marvelous capacity to sequester and store carbon, and is believed to be a main component in maintaining a high standard of living. Going a step further, a comprehensive understanding of the characteristics of wood is fundamental to its best utilization.

Coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is the predominant plantation species native to the western Pacific Northwest, and can be found naturally almost everywhere west of the crest of the Cascade and Sierra Nevada ranges. Douglas-fir is widely valued as an important tree species in forest management because of its high volume timber production and the rapid growth rates on established stands. Additionally, it is a premium timber resource for structural application and its appearance is appreciated in both domestic and international markets.

One of the major interests in silvicultural practice is to retain the exceptional attributes of Douglas-fir growing in intensively managed plantations. Much research has been conducted to understand how silvilcultural practice influences tree growth and timber yield and as a consequence, many different stand projection models have been instituted (Briggs and Fight 1992).

Silvicultural practices affect wood qualities in terms of reshaping environmental conditions such as nutrients availability, soil water content, light resource and temperature, which will have an effect upon crown vigor, and as a result, will influence the characteristics of wood cells (Figure 1, Briggs and Smith 1986).

Nitrogen is consistently the most limiting factor to the growth of forests in the Pacific Northwest as well as the rest of the world (Hanson and Weltzin 2000, LeBauer and Treseder 2008). Decades of observations in the Pacific Northwest in detecting soil nitrogen and tree growth response to fertilization practices indicate that soil nitrogen tends to be limiting, and is therefore predictive of inherent forest productivity (Littke 2012). Fertilization practices have been developed to cope with insufficient nitrogen availability and stimulate tree growth (Keeney 1980). Research has shown coastal Douglas-fir will respond to 224 kg N/ha applications about 2/3 of the time (Miller et al. 1986, Hopmans and Chappell 1994).

The impacts of the site and management on Douglas-fir wood quality is unclear, especially the effects of soil parent materials (SPMs), stocking, nitrogen fertilization and other conditions. The influence of SPM type and two fertilization treatment levels on timber growth and wood quality of middle age (19 to 32 years old) Douglas-fir have been studied on paired-tree plots (Littke 2012) in the Pacific Northwest with the intention to address the needs in updating wood property models for different site conditions.

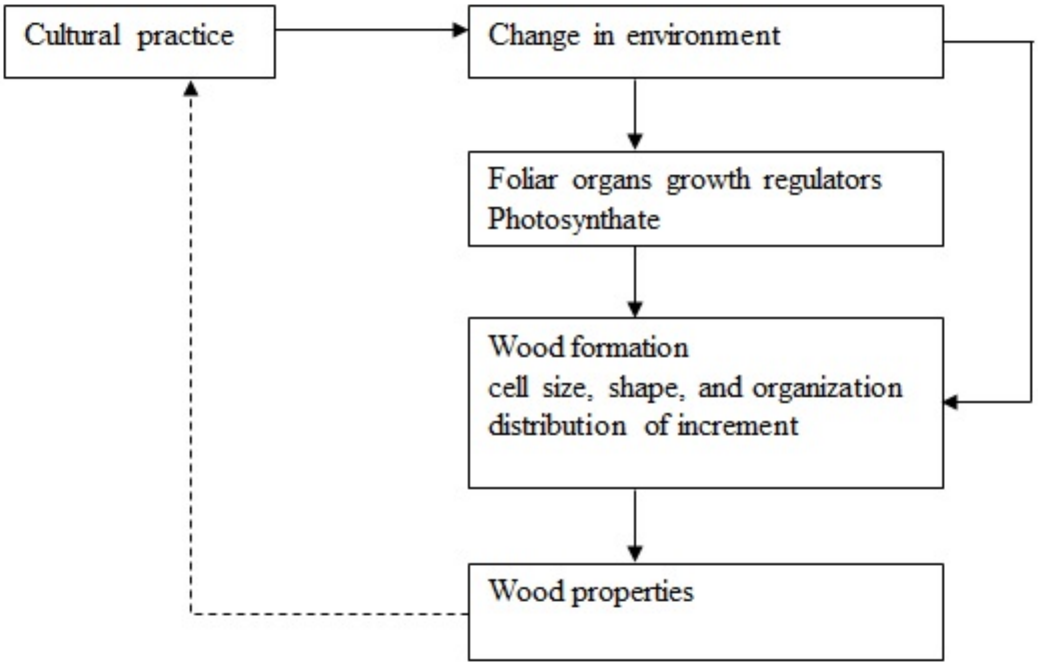

Figure 1. Physiological bases of silvicultural management on wood properties (Briggs and Smith 1986).

CHAPTER 2. LITERATURE REVIEW

2.1 Destructive and Nondestructive Evaluation with Acoustic Wave

Wood is a fibrous organic material with a cellular structure and has different yield stresses along the three directions: radial, longitudinal, and tangential. The dynamic process of wave propagation is governed by fiber orientation, microstructure, and geometric form. Employing the propagation of certain waves in wood materials can be utilized in monitoring important wood properties, such as modulus of elasticity, density, and defects (Meyers 1994, Ross et al. 1999, Wang et al. 2007).

Generally, three types of stress waves are generated when stress is applied toward wood: (1) longitudinal wave (compressive or P-wave), corresponding to the oscillation of particles along the direction of wave propagation; (2) shear wave (S-wave), the motion of the particles carrying the wave perpendicular to the direction of the propagation of the wave; and (3) surface wave (Rayleigh wave), typically restricted to the section adjacent to the surface (Meyers 1994). Among the above waves, the longitudinal wave is measured the fastest and is the easiest to detect in field applications (Harris and Andrews 1999, Meyers 1994). Therefore, the longitudinal wave is the most commonly utilized wave in material property characterization.

For several decades, acoustic sensing technology has been well established and recognized in material evaluation, becoming widely accepted for the purpose of quality control and product grading in the wood industry (Carter et al. 2005, Wang 1999, Wang et al. 2007).

Since wood in the form of standing trees and felled logs has variable external and boundary conditions, methods typically applied in sensing acoustic velocity (AV) are different for assessing standing trees (time-of-flight AV method) and felled logs (resonance AV method) (Carter et al. 2005, Wang 2013).

The resonance-based acoustic method is a well-established and reliable destructive evaluation technique for assessing wood products including logs, poles, and timber. For the field procedure, trees have to be felled beforehand. A mechanic needs to attach the sensor, Hitman HM 200© (Fiber-Gen), at one end of the tree and apply mechanical impact, where a stress wave is initiated which stimulates hundreds of pulse reverberations transferring within the log (Andrews 2003, Harris et al. 2002, Wang et al. 2004). The sensor captures longitudinal waves response. Consequently, an accurate, repeatable, and weighted average log resonance acoustic velocity (LRAV) measurement can be determined (Eq. 2.1.):

Eq. 2.1. $$C_L = 2f_0L$$

Where C_L denotes acoustic velocity of logs (m/s);

f_0 denotes natural frequency of an acoustic wave signal (Hz);

L denotes log length (end-to-end) (m).

Though destructive evaluation provides valuable information assessing wood quality, this method involves expensive techniques, especially in felling sample trees for testing. As an alternative, developing rapid and cost-effective nondestructive evaluation (NDE) techniques to assess standing tree wood quality has been of interest to forest managers and manufacturers (Carter et al. 2005, Mora et al. 2009, Ross et al. 1999, Thienel 2008, Wang et al. 2001, Wang et al. 2007).

A typical time of flight acoustic measurement prototype system (Figure 2.1) includes a set of two probes starter and receiver acoustic sensors, a two-channel scope meter, and a hand-held hammer. The probes need to be inserted into the tree trunk, piercing bark and cambium, at approximately 45 degrees to the bark surface while aligned within a vertical plane at one-meter distance. To obtain acoustic wave travel time through the defined distance, the starter probe is tapped with a hammer to generate stress waves, the receiver probe detects acoustic waves, and the travel time result would be transmitted to the scope meter (Wang et al. 2001). The time-of-flight AV or tree sonic acoustic velocity (TSAV) is calculated with Eq. 2.2:

Eq. 2.2 $$C_T = \frac{S}{\Delta t}$$

Where C_T is tree AV (m/s);

S is distance between the two probes (m) (in this case is 1m);

Δt is time-of-flight (s).

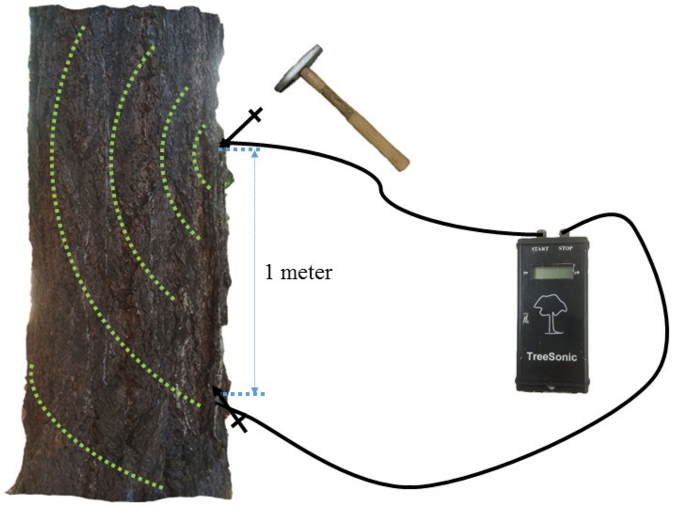

Figure 2.1. Typical experimental set up for standing tree stress wave test.

The use of NDE can help foresters to make management decisions, grow high quality wood, and lead to greater monetary return.

2.2 Dynamic Modulus of Elasticity

Wood's most important characteristics are its mechanical properties, specifically for structural application materials. Modulus of Elasticity (MOE) is a measure of strength describing wood's resistance under compression (Bowyer et al. 2007). Dynamic modulus of elasticity (MOE_d) is a measure of wood stiffness, calculated with time-of-flight AV and density (Eq. 2.3, Wang et al. 2001). In practice, since density of many materials is relatively constant, the velocity of acoustic wave can be utilized as a direct indicator of the MOE_d (Carter et al. 2005).

Eq. 2.3 $\mathrm{MOE_d} = C^2\rho$

Where $\mathrm{MOE_d}$ denotes dynamic modulus of elasticity (Pa);

C denotes velocity of the acoustic wave through the material (m/s);

ρ denotes density of the material (kg/m^3)

2.3 Specific Gravity

Density and specific gravity (SG) are the physical properties used in describing the mass of a material per unit volume. The terms SG and density are often used interchangeably in general discussion as these terms refer to the same characteristic, however, they have different definitions (Bowyer et al. 2007, Shmulsky and Jones 2011).

Density, defined as the mass or weight per unit of volume, is usually expressed as kilograms per cubic meter (kg/m^3), grams per cubic centimeter (g/cm^3), or pounds per cubic foot (lb/ft^3). Specific gravity, or relative density, is one of the single most important physical properties of wood, closely correlated with strength and stiffness, and shrinking and swelling. Specific gravity is calculated as oven-dry mass per unit of green volume relative to the density of water (ρw) at standard temperature (typically 4 °C (39 °F), where ρw is 1.000 g/cm^3 or 62.43 lb/ft^3 (Bowyer et al. 2007, Desch and Dinwoodie 1996, Fielding 1967, Shmulsky and Jones, 2011).

By determining SG of wood, more details concerning the nature of a wood sample can be detected. Specific gravity increases as the proportion of cells with thick cell walls increases for softwood; for hardwood, density is dependent on the combination of fiber wall thickness and the amount of void space, occupied by vessels and parenchyma (Glass and Zelinka 2010).

Wood is a hygroscopic material, both its weight and volume change with gain or loss of moisture content (MC) (Figure 2.2). Specific gravity increases as the MC decreases, because dry weight remains constant while volume decreases in the process of drying. Therefore, the greater the volumetric shrinkage, the greater the difference can be found between green and oven-dry SG.

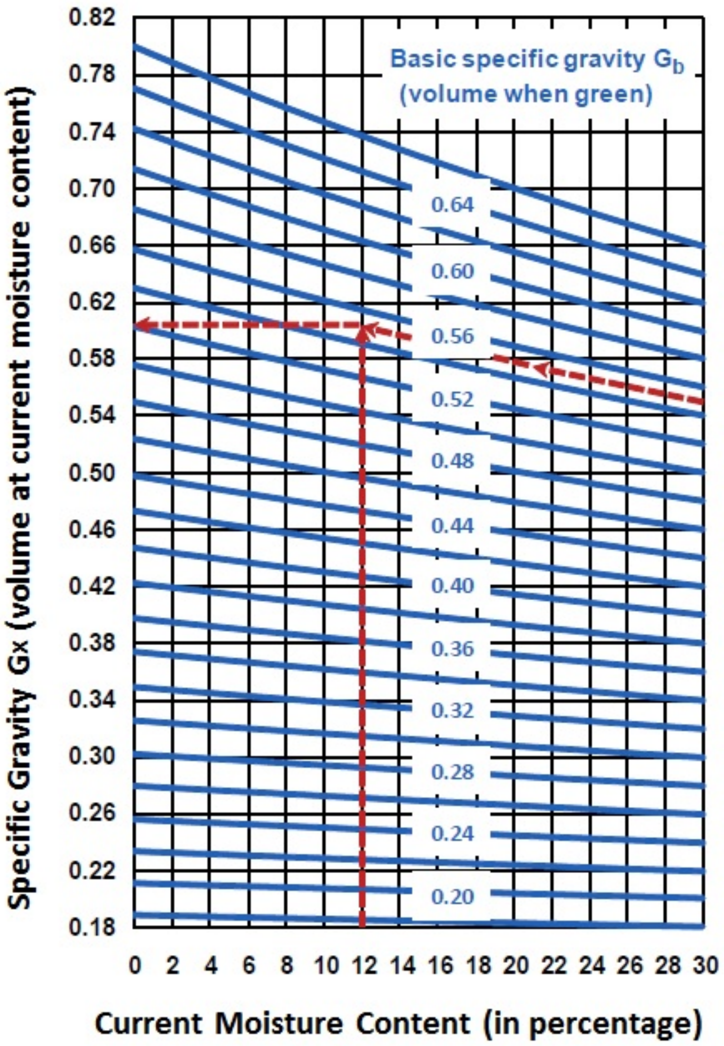

Figure 2.2. Relation of specific gravity and moisture content, Glass and Zelinka (2010), United States Forest Products Laboratory (USFPL).

Significant effort was devoted into discovering the thinning effect on ring specific gravity (Bowyer et al. 2007, Briggs and Smith 1986, Jozsa and Middleton 1994, Megraw 1986). Larson et al. (2001) concluded that the differences are attributed to various factors, including site condition, initial stocking, environmental variables, and age at the time of treatment. Wellwood (1952) studied SG of second-growth Douglas-fir in British Columbia, making comparisons among various productivity sites with different crown classes and heights along the tree stem. His results indicated that lower SG was found on “Good” sites; dominant trees had lower SG than co-dominant and intermediate trees; and wood from the base of tree was denser than at higher levels on the stem.

2.4 Latewood Proportion

Active cambial division generally begins in mid-May to mid-June, initiating the low density earlywood production. After mid-July, a reduction in cambial division leaves more material available in the cell for wall thickening. Concurrently, reduced crown activity limits auxin production, helping the formation of high-density latewood. Latewood production period can last to the end of the growing season, which can be late September or early October (depending on the region), then tree dormancy would start because of lower temperature and reduced photoperiod (Jozsa and Middleton, 1994).

Lateral growth initiates from top of the tree and proceeds downward along the tree trunk. Correspondingly, more earlywood and wider rings can be found in the upper crown section. Latewood transition takes place near the stem base first then proceeds upward. Therefore, latewood proportion or wood fiber density needs to be determined by its relative position to the live crown (Kozlowski 1971).

Timing of the transition from earlywood to latewood is significant in determining latewood proportion or latewood percentage (LWP). LWP is one of the most widely used wood quality characteristics for its ease of detection. Based on growth ring density and color changes, LWP provides a visual index of strength and structural properties and is highly correlated with wood SG. LWP is regarded as a significant component of lumber and heavily weighted in timber grading (Zobel 1972, Kubo and Jyodo 1996, Glass and Zelinka 2010).

Of much interest, extensive research in LWP has been conducted. Brix (1972) suggested that seasonal timing of water stress had an effect upon LWP in irrigated fertilized young Douglas-fir stands. Robertson et al. (1990) studied older Douglas-fir stands and reported that latewood width was related to annual water deficits. Additionally, Antonova and Stasova (1997) worked on larch (*Larix sibirica* Ldb.) in Siberia, and they found that the transition from earlywood to latewood was affected by the growing season precipitation.

2.5 Ring Growth

Annual rings, seen in the cross section area, reflect a tree’s yearly growing activity. Growth ring width, generally stated as rings per inch (RPI) of radial growth, is considered to be a favorable measure of overall growth conditions (Jozsa and Middleton 1994). Trees freed from competition by thinning or enhanced by fertilization can continue a wide ring growth pattern. Irrespective of tree growth, ring width declines eventually, because wood volume of each annual ring is overlaid on an increasing diameter. Growing conditions influence growth ring width significantly and consequently affect yield and quality of the final product (Larson et al. 2001).

Rings per inch has been studied and found to be an important determinant of the flexural properties of softwood timber (Briggs et al. 2005, Person and Ross 1984). Ring width is identified as a category in log grading rules (Northwest Log Rules Advisory Group 2011) and in US softwood lumber grading rules (WWPA 2004). Visually measuring the RPI on site is considered a part of grading in assessing wood material texture and strength.

For standing trees, RPI can be studied based on periodic measurements or increment cores. As for logs, RPI can be counted at the log's smaller end and is commonly assessed on the outer radius (Bowers 1997). Certain expectations toward log RPI have been determined by sawmills, and this number influences a sawmill's price offering. The fast growth limit of Douglas-fir in the PNW is 4 RPI; growth rate higher than this level may be rejected by the purchaser.

Lumber is sorted by specified grade. The West Coast Lumber Inspection Bureau defined Douglas-fir grading in 1991 (revised in 2004). Their standard advises that Douglas-fir with less than 4 RPI on average shall be sorted as "medium grain", approximately 6 RPI as "close grain", and over 6 RPI as "dense material". ALTRUFIR® specializing in Douglas-fir flooring and lumber business suggests lumber 10-25 RPI with associated knot size rules and certain particular color can be evaluated as "superior" boards (Rouse 2011).

2.6 Silvicultural Practice, Fertilization

Fertilization has long been utilized in promoting tree growth, especially on nutrient deficient sites, by artificially supplying mineral nutrients in the natural environment to enhance crown and root development.

Fertilization impacts are similar to those from thinning practices. Trees that have been stimulated in height growth and crown development usually experience increased wood growth due to an increment in earlywood and transition tracheid formation (Megraw 1986). Immediate increment of diameter and volume has been widely reported (Antony et al. 2009, Cahill and Briggs 1992, Fielding 1967, Jokela and Stearns-Smith 1993, Larson 1962, 1968, Sastry 1967).

Decades of research found various impacts of fertilization on wood quality. Van Lear et al. (1973) studied loblolly pine (*Pinus taeda* L.) seedlings in South Carolina and reported that both SG and LWP were not altered by fertilization. Rudman and NcKinnell (1970) analyzed 1,305 kg/ha nitrogen fertilization on 7-year-old radiata pines (*Pinus radiate* D. Don) in New Zealand. They found no significant change in LWP and increased wood density. Larson et al. (2001) suggested that trees that have large foliage mass, increased photosynthetic efficiency, or experience a prolonged seasonal growth period, may have enhanced annual ring width increment without dramatic reduction in LWP. The negative impact of fertilization on wood quality has also been detected in mid-rotation Douglas-fir (Jozsa and Brix 1989, Sastry 1967) and loblolly pine (Antony et al. 2009, Beckwith and Reines 1978, Jokela and Stearns-Smith 1993, Love-Myers et al. 2009) with immediate reduction of SG and LWP.

However, no study to date has analyzed Douglas-fir wood quality in PNW consequent to nitrogen fertilization specialized to different SPM types.

CHPATER 3. OBJECTIVES AND HYPOTHESES

This study is focusing on determining the influences of four SPM types and nitrogen fertilization treatment, especially emphasizing their internal and interactional impacts upon tree growth and wood quality.

An attempt was made to predict the wood quality attributes using a general linear model, analysis of covariance (ANCOVA). The following chapters endeavor to analyze the hypotheses below:

- Soil parent material types would exhibit different effects upon Douglas-fir tree growth and wood quality. Sedimentary SPM type would have the most vigorously growing plantations, while trees cultivated on Glacial SPM sites would grow least;
- Nitrogen application shall have a positive effect on Douglas-fir growth rates. Tree growth rate shall be negatively associated with wood quality, though nitrogen treatment would not necessarily pose a major detrimental influence on Douglas-fir stiffness;
- As the distance between ground and position on the stem increases, wood quality aspects including specific gravity, latewood percentage and rings per inch would decrease;
- Tree sonic acoustic velocity and log resonance acoustic velocity would be positively correlated.

CHAPTER 4. METHODOLOGY

Study sites were established by the Stand Management Cooperative (SMC) and the Center for Intensive Planted-forest Silviculture (CIPS) in western Washington and Oregon. Study sites cover latitudes from 44°29’N to 47°13’N, and longitudes from 122°39’W to 123°34’W (Figure 4.1) with selected dominant and co-dominant Douglas-fir trees in 2007 (five sites) and 2009 (two sites) during the winter season (Table 4.1, Figure 4.2). The soil parent material types and soil effective depth were determined from USGS geologic maps (USGS 2010), NRCS soil series descriptions (Natural Resources Conservation Services 2010), and soil pit observations (Littke 2012, Table 4.3).

At the time of plot set up, selected trees were measured for diameter at breast height (DBH), total height (Ht), and height to the live crown base. Trees with similar DBHs were paired up for CIPS plots. In addition, height to live crown base was also considered in pairing trees for SMC plots. Thereafter, selected trees within a pair were randomly assigned to be either treated with nitrogen fertilization (urea 224 kg/ha) or to be control trees (i.e. no fertilization). Full measurements were obtained at 2 year intervals. Upon the final measurement (prior to the start of the next growth season, Table 4.2), nitrogen applications have had enough time to act upon tree growth and wood quality at each site for its effects to be detected and analyzed. Douglas-fir on the two study sites from CIPS were 6 years post treatment at final measurement in 2013. Three study sites from SMC were 6 years post treatment. The other two sites (Igneous SPM) were 4 years post treatment. Final measurement on SMC sites occurred in 2014.

The DBH distribution at the time of final measurement of control trees was examined and used as the basis for stratified random sampling to obtain sample trees. The selected fertilized pair from the fixed intervals were defined as quartiles of the DBH distribution, which was 1 pair from 0-25% lower end, 2 pairs from 25-50%, 2 pairs from 50-75%, and the last 1 pair acquired from 75-100% upper end. Due to fertilization applications at SMC and CIPS sites were separated, a total of 68 trees were sampled with unbalanced sample sizes, and they were 12, 9, 10, and 3 tree-pairs from Glacial, Igneous, Sedimentary, and the Mixed (Sedimentary and Igneous) SPM types, respectively.

After randomly selecting sample pairs from each quartile, each tree from the selected pair was measured with the Fakopp TreeSonic. Three measurements were obtained and averaged to produce the single result of tree sonic acoustic velocity.

For the five SMC study sites, increment cores were extracted at breast height from selected pairs for further laboratory analysis. For the two CIPS sites, 12 trees were felled with 0.30 m stump after Fakopp TreeSonic measurements.

Further measurements were recorded on CIPS sites. The following sections along the tree trunk were determined: breast height (BH, 1.3 m above ground), height up to 4.88 m (TF16, or top of the first 16 foot log, including trim), the live crown base (LCB), and the top with diameter of 10 cm (TOP). Felled trees were then bucked sequentially, stump to TOP, stump to LCB, and stump to the TF16. After each segment was cut, and prior to the next cut, segments were measured for length to the nearest meter and tested using the resonance acoustic instrument Director® Hitman-200 to obtain log resonance acoustic velocity. Disks with 5 cm thickness were cut from each felled tree at each predetermined section (Stump, BH, TF16, and TOP). In total, 56 disks, half from control trees and half from nitrogen fertilized trees, were obtained and transported to the laboratory.

For tree disks, annual rings and diameter increments were measured along the longest axis and its perpendicular axis. The geometric mean is reliable in acquiring the closest approximation of the original noncircular cross-sectional area from each measured axis (Eq. 4.1, Husch et al. 2003). Each annual ring's radius, diameter, and area increment were calculated thereafter.

Eq. 4.1. $$\left(\prod_{i=1}^{n} a_i\right)^{\frac{1}{n}} = \sqrt[n]{a_1 a_2 \cdots a_n}$$

Two woody blocks containing the treatment response period were sampled out of each disk to obtain green mass. Blocks were submerged in water for a certain period to absorb moisture at its maximum capacity, volume was then measured by applying Archimedes' principle (1 cc = 1 ml = 1 gram under 1 standard atmospheric pressure and at room temperature). Woody blocks were placed in an oven and went through a 48 hour drying process at 105 degree Celsius. Similarly, only the treated increment section from each sampled tree core was used for analysis. They were placed underwater to rehydrate, measured for green mass and volume and oven-dried for dry mass.

The tree ring measuring software ProjectJ2X (VoorTech Consulting 2014) and a microscope were used in determining the width of each annual ring component, earlywood (EW) and latewood (LW), for sample blocks and cores. LWP was calculated from the measurements.

Douglas-fir growth and quality responses for the treated period were quantified statistically for comparison using analysis of covariance (ANCOVA) in R Studio®, Version 0.98.953 (R©, Version 3.0.0) with split plot design. Replication at the whole plot level was the individual study site under the same SPM category; replicate performed at the split plot level was the paired-tree samples. ANCOVA was used to reduce variability from measurable stand parameters, including: (a) study site elevation (EL); (b) site index (SI); (c) soil effective depth of A horizon (A-HZ); (d) breast height age at the time of measurement (BH-Age); and (e) stand density (TPH). The effect of unbalanced sample sizes was addressed by assessing Type II sum of squares in ANCOVA.

Statistical analysis was represented as:

Eq. 4.2. $$Y_{ijk} = \mu + \beta(x_{ijk} - \bar{x}) + \tau_i + \varepsilon_{ij} + \gamma_j + (\tau\gamma)_{ij} + \delta_{ijk}$$

Where Y_{ijk} denotes the response of tree growth or wood quality aspect of the kth sampled tree under the jth fertilization level in the ith replicate of SPM type; μ represents the overall mean; $\beta(x_{ijk} - \bar{x})$ denotes the covariate term; τ_i is the fixed effect of soil parent material; γ_j is the fixed effect of fertilization regime; correspondingly $(\tau\gamma)_{ik}$ represents their interaction term. ε_{ij} is the whole plot error, $\varepsilon_{ij} \sim N(0,\ \sigma_\varepsilon^2)$; δ_{ijk} is the split plot error, $\delta_{ijk} \sim N(0,\ \sigma_\delta^2)$. Only the most statistically significant covariate variable was retained in each split-plot ANCOVA model. Post-hoc pairwise comparisons were conducted with the Holm (1979) adjustment.

Douglas-fir growth and quality responses for the treated period were modeled empirically with a general linear empirical prediction model $Y_i = X_i\beta$ using R Studio®. Y_i is a (n×1) vector of the dependent variables; X_i is a (n×p) design matrix that characterizes known covariates as well as the fixed effect of SPM type and fertilization treatment; β is a (p×1) vector of the corresponding parameters.

Since the number of available sampled trees was limited, sample sizes were unbalanced. An α = 0.10 was applied to test the significant level for both split-plot ANCOVA and general linear empirical prediction model.

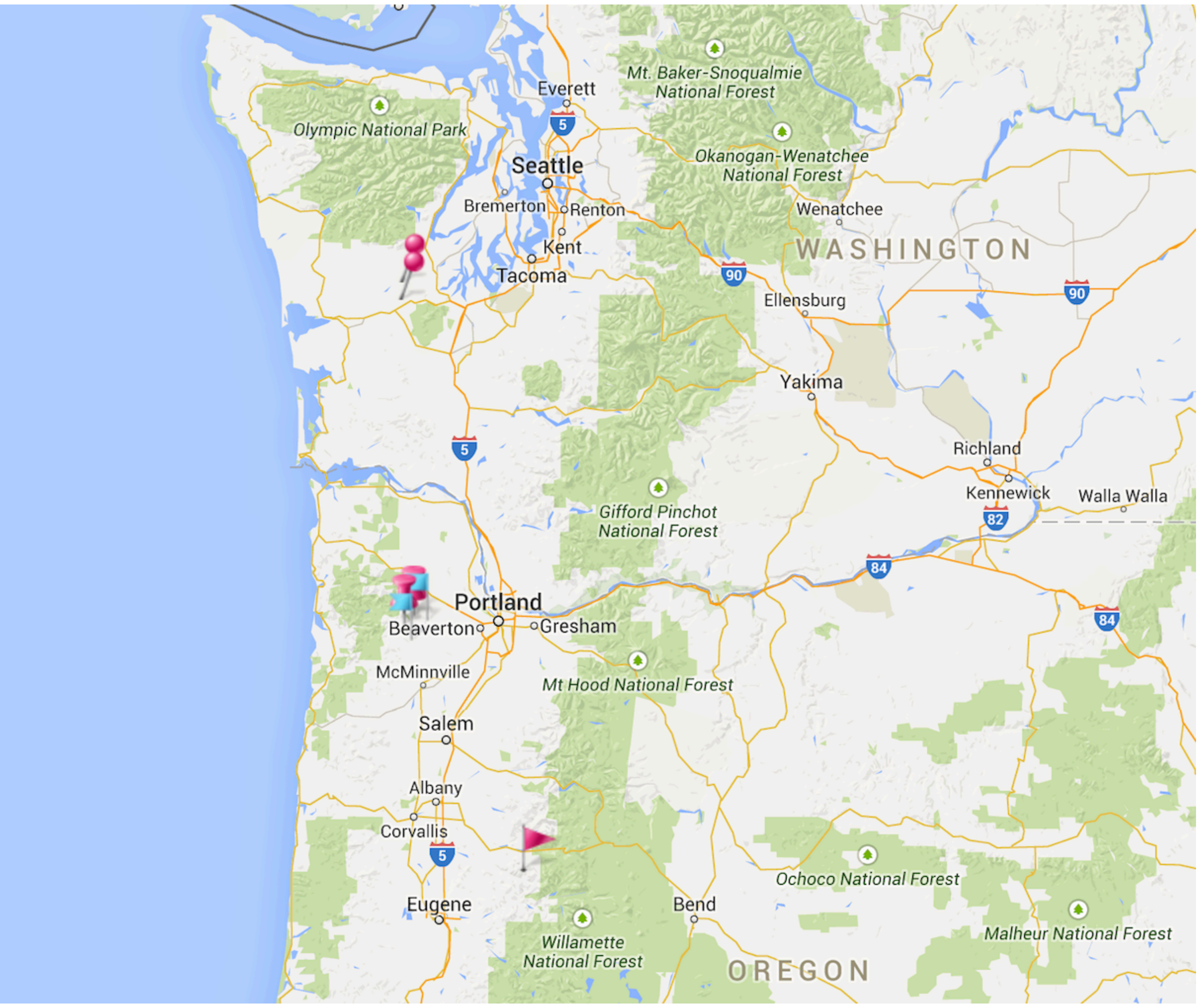

Figure 4.1. Geographical distribution of study plots in the Pacific Northwest. Red circle pins represent Glacial SPM sites; red flag represents the Mixed SPM site; blue flags represent Sedimentary SPM sites; red pushpins represent Igneous SPM sites. Image courtesy of ©2015 Google.

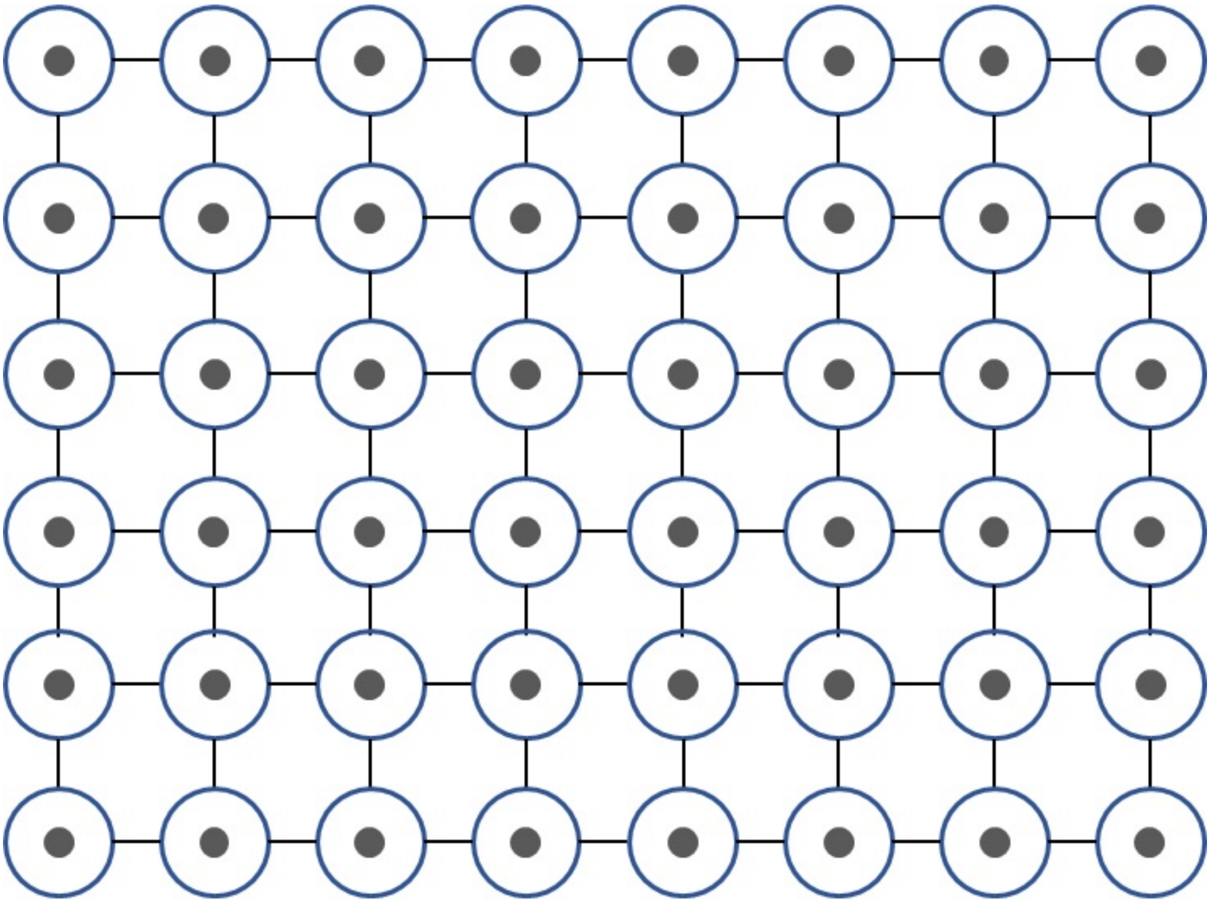

Figure 4.2. Stand layout of selected dominant and co-dominant Douglas-firs in grid with 15 - 20 meter in distance. The center solid circle represents the selected tree; the outer circle represents the treatment area (fertilized or unfertilized, sampled Douglas-fir: SMC Type V Installations treatment area was 78 m^2 (Littke 2012); and those from CIPS had a treatment area of 100 m^2).

Table 4.1. Stand attributes and averaged quadratic mean diameter, height, live crown ratio, height: diameter at the time of establishment.

SPM Location	SPMID	Elevation (m)	Slope (%)	BH Age (year)	Site Index (m)	Density (tree/ha)	TRT	SEL	QMD (cm)	Ht (m)	LCR (%)	HT:DBH
Arrowhead Lake[a]	GLA1	152	15	17	48.64	873.32	CON	6	22.94	19.9	59.5	88.45
							FER	6	23.15	19.8	59.6	87.75
Oppelt Road[a]	GLA2	91	10	17	39.48	820.39	CON	6	22.81	16.6	68.1	73.51
							FER	6	23.14	15.9	68.8	69.61
Sweet Home[b]	MIXED	442	15	23	43.02	976.64	CON	3	27.8	23.5	48.8	43.68
							FER	3	28.1	22.5	54.4	36.41
Vernonia[b]	SED1	244	5	28	37.18	707.41	CON	4	29.1	23.8	57.5	35.78
							FER	4	29.0	24.2	57.2	36.19
Cherry Grove[a]	SED2	335	30	13	38.18	815.98	CON	6	18.65	12.2	88.4	66.37
							FER	6	18.64	11.8	89.9	63.97
Wood Road[a]	IGN1	585	16	22	36.25	648.38	CON	6	25.88	19.2	73.1	74.68
							FER	6	25.77	18.9	72.9	73.95
Les Smith[a]	IGN2	451	14	18	36.29	805.84	CON	3	21.63	15.6	82.4	72.50
							FER	3	21.55	15.6	84.1	72.52

[a]: sites established by the Stand Management Cooperative;

[b]: sites established by the Center for Intensive Planted-forest Silviculture.

SPMID: Soil parent materials identification, where GLA = glacial, SED = sedimentary, IGN = igneous, MIXED = mixture of sedimentary and igneous, suffixed number indicates replicate.

BH Age: breast height age at the time of treatment.

TRT: specifies treatments, where CON = control, FER = 224 kg/ha urea nitrogen fertilization.

SEL: the number of sampling trees selected among each study plot.

Site Index: determined from King, J.E. 1966.

QMD, Ht, LCR: averaged quadratic mean diameter, height, live crown ratio (calculated from individual sample tree).

Table 4.2. Averaged and periodic annual increment (PAI) of quadratic mean diameter (QMD), height (Ht), live crown ratio (LCR), and height: diameter ratio (HT:DBH) at the time of final measurement.

SPM Location	SPMID	TRT	QMD (cm)	PAI.QMD (cm)	Ht (m)	PAI.HT (m)	PAI.Volume (m^3)	LCR (%)	HT:DBH
Arrowhead	GLA1	CON	25.91	0.50	24.4	0.75	0.0300	36.6	97.50
Lake		FER	26.21	0.51	24.9	0.85	0.0333	37.7	99.09
Oppelt Road	GLA2	CON	26.97	0.69	22.6	1.00	0.0383	48.6	85.59
		FER	26.20	0.51	21.3	0.89	0.0316	41.3	81.94
Sweethome	MIXED	CON	31.6	0.64	28.2	0.79	0.0467	44.8	89.87
		FER	33.2	0.85	27.8	0.87	0.0633	49.3	83.92
Vernonia	SED1	CON	31.9	0.47	27.0	0.54	0.0350	46.1	85.6
		FER	32.5	0.59	27.9	0.61	0.0450	49.6	86.2
Cherry Grove	SED2	CON	25.31	1.11	17.8	0.93	0.0350	60.5	72.10
		FER	26.39	1.29	17.3	0.91	0.0367	68.1	65.83
Wood Road	IGN1	CON	28.67	0.70	22.9	0.63	0.0433	54.1	80.87
		FER	30.00	1.06	22.7	0.64	0.0567	54.4	76.69
Les Smith	IGN2	CON	25.16	0.88	19.6	0.66	0.0400	56.8	77.89
		FER	25.86	1.08	19.6	0.67	0.0433	59.4	75.96

Table 4.3. Stand soil type, horizon, and horizon depth

SPM Location	SPMID	Soil type	Horizon	Effective Depth (cm)
Arrowhead Lake[a]	GLA1	Shelton gravelly sandy, loam	A	17
			AB	17
			Bw1	30
			Bw2	19
Oppelt Road[a]	GLA2	Centralla loam	A	24
			Bw	36
Sweethome[b]	MIXED	Honeygrove silty clay loam	A	10
			BAt	28
			Bt1	36
			Bt2	30
			Bt3	33
			Bt4	49
Vernonia[b]	SED1	Mayger silt loam	A1	15
			A2	15
			Bt1	16
			Bt2	33
			BCt	20
Cherry Grove[a]	SED2	Laurelwood silt loam	A	10
			AB	28
			Bt1	51
			Bt2	11
Wood Road[a]	IGN1	Tolke silt loam	A	9
			Bw1	27
			Bw2	20
Les Smith[a]	ING2	Tolke silt loam	A	8
			Bw1	34
			Bw2	47

[a] Effective depth, Stand Management Cooperative.

[b] Resources for effective depth from SoilWeb, USDA-NCSS SSURGO and STATSGO digital soil survey, UC Davis Soil Resource Laboratory, Center for Intensive Planted-forest Silviculture.

CHAPTER 5. RESULTS

This chapter focuses on three analyses: (1) growth assessment through split-plot design and general linear empirical modeling; (2) quality assessment through split-plot design and general linear empirical modeling; (3) examining the nitrogen effect on whole tree quality using the felled sample from two study sites.

5.1 Growth Increment Assessment and Prediction

Averaged periodic annual increments in quadratic mean diameter, height, and volume were calculated for the treated period (Table 4.2). The yield responses of unfertilized groups reflect site's inherent ability in supporting Douglas-fir plantations, and fertilized groups reveals the influences of additional nitrogen.

5.1.1 Periodic Annual Increment in Quadratic Mean Diameter (PAI QMD)

Periodic annual increment is the increment over a short period divided by the years involved in the studied period. PAI of interested attributes can reveal annual increment amounts, providing the differences between observations at the site establishment and the final measurement, and can be used to compare the growth rate under different SPM types and fertilization treatment regimes.

Based on the split-plot ANCOVA, trees that grew on different SPM types had various performances in PAI QMD development. The Igneous SPM site featured the highest PAI QMD, followed by the Sedimentary and the Mixed sites. Glacial sites, on average, exhibited the smallest growth which is 22.4% lower than trees from the Mixed SPM site (derived from Table

4.2). The ANCOVA results indicate that breast height age is the only important covariate, which is logical because older trees usually are larger in diameter, with the same amount of wood volume produced, a smaller lateral increment would be laid onto the larger trees. SPM type was determined as a significant factor (p=0.040, $\overline{X}_{\mathrm{GLA}}$=0.60 cm, $\overline{X}_{\mathrm{Mixed}}$=0.85 cm, $\overline{X}_{\mathrm{SED}}$=0.79 cm, $\overline{X}_{\mathrm{IGN}}$=0.75 cm,) in evaluating QMD growth, meaning that different types of SPM have dissimilar inherent abilities in supporting established Douglas-fir plantations.

Fertilization had a generally positive effect on lateral growth. The PAI QMD increment of fertilized groups exceeded unfertilized counterparts by 31%, 21%, and 15% on Igneous, the Mixed, and Sedimentary SPM types, respectively (derived from Table 4.2). On the other hand, additional nitrogen negatively affected trees growing on Glacial sites. Fertilized trees fell behind unfertilized ones by 0.09 cm in annual diameter growth. Statistical results suggest that nitrogen played an important role in QMD development (p=0.006, $\overline{X}_{\mathrm{Non.FER}}$=0.71 cm, $\overline{X}_{\mathrm{FER}}$=0.84 cm). Nitrogen effect was closely related to SPM types in influencing PAI QMD as well (p=0.012). Using Holm adjustment, there are statistically significant differences in the comparisons of fertilized trees lateral increment between Glacial and Igneous, and between Glacial and Sedimentary. The comparison between Glacial and Mixed sites was not significant, which may due to the small sample size of the Mixed SPM type.

It seems that fertilized trees from Igneous sites experienced a higher rate in lateral growth (also shown in the prediction model, the dashed line in Figure 5.1.1). However, it is possible that this “high rate” increment was a result of different time frames (as mentioned in Chapter 4, there were no available six-year post treatment data for Igneous SPM type site). Previous research suggests that the effect of fertilization could last beyond four growth seasons (Binkley and Reid 1985, Briggs and Smith 1986, Miller and Fight 1979), which means at the time of sampling trees on Igneous sites may still be benefiting from added nitrogen. However, trees from other SPM sites may be left with insufficient remaining added nitrogen to take advantage of.

The linear empirical model indicates that site index, effective depth of soil A horizon, SPM type and nitrogen treatment work together in regulating Douglas-fir lateral growth. All four factors define site ability in supporting plantation trees. Therefore, it seems fair to conclude that lateral increment is governed by the site condition rather than the stand state (such as stand age and density). The model is constructed as follows:

$$\begin{aligned} [5.1] \quad E\,(PAI.QMD) = {} & \beta_0 + \beta_1 SI + \beta_2 A\text{-}HZ \\ & + \beta_3 IGN + \beta_4 Mixed + \beta_5 SED + \beta_6 TRT \\ & + \beta_7 TRT{*}IGN + \beta_8 TRT{*}Mixed + \beta_9 TRT{*}SED \end{aligned}$$

Where β_i are the coefficients, and TRT, IGN, Mixed, and SED are dummy variables.

SI denotes stand site index;

A-HZ represents effective depth of horizon A;

IGN = 1 for Igneous SPM type, IGN = 0 under other SPM types;

Mixed = 1 for the Mixed SPM type (combined Sedimentary and Igneous SPM),
Mixed = 0 under other SPM types;

SED = 1 for Sedimentary SPM type, SED = 0 under other SPM types;

TRT = 0 if nitrogen was not applied, TRT = 1 if 224 kg N/ha was applied;

Correspondingly, TRT*SPMs are the interaction terms of fertilization with different SPM types.

Model fitting statistics						
Residual standard error: 0.2154 on 58 degrees of freedom						
Pr > F: <0.0001;			Adj. R Square: 0.6025			
	β_0	β_1	β_2	β_3	β_4	β_5
Estimate	9.7497	-0.1341	-0.1596	-2.7473	-1.7438	-1.9264
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	β_6	β_7	β_8	β_9		
Estimate	-0.0700	0.3744	0.2733	0.2430		
P-value	0.4293	0.0072	0.1698	0.0675		

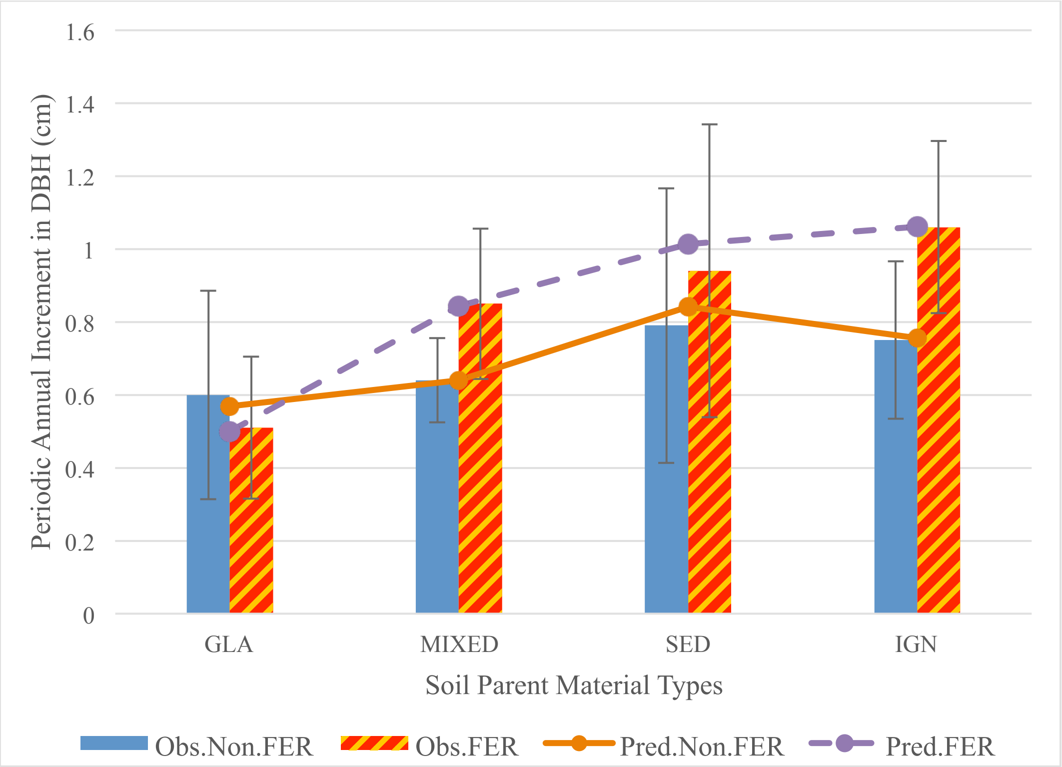

Figure 5.1.1. Periodic annual quadratic mean diameter increment and prediction from model [5.1] according to Soil Parent Material types. Vertical bars represent standard error of the mean.

5.1.2 Periodic Annual Height (Ht) Increment

Field observed periodic annual height increment suggests trees from Glacial SPM type experienced the largest vertical growth rate, Sedimentary and the Mixed SPM sites were in the middle positions, and Igneous SPM sites exhibited height growth that lagged behind (Table 4.2). Statistical split-plot ANCOVA result shows that overall there is no significant difference among SPM types (p-value=0.577). There is no noticeable modification from fertilization treatment by looking into the gaps between control and fertilized groups, meaning that fertilization treatment did not significantly impact height increment (p-value=0.653), nor was the interaction impact of SPM and fertilization significant (p-value=0.822). However, taking a step forward with the Holm adjustment, the results suggest that the comparison of unfertilized and fertilized plantation height increment are statistically significant on Glacial and Igneous SPM types.

Comparing the observed lateral and vertical growth, larger increment in height growth came with smaller increment in diameter, especially on Glacial sites. On the other hand, the Igneous SPM sites had less height growth but ended up with larger growth in QMD. Glacial stands had high stand density. Considering the fact that this type of SPM is featured with a mixture of materials from many kinds of rocks, it is possible that Glacial sites sampled in this study do not contain necessary nutrients in supporting vegetation. Trees in this study experienced intense competition. They allocated most of their photosynthetically produced carbohydrates into the vertical growth race for light, leaving less carbohydrates for lateral growth (height growth comes before lateral growth). In light of making management decisions, high-density Douglas-fir plantations on Glacial SPM site need longer rotations to produce logs with the targeted DBH.

Three significant covariates should be considered according to the linear empirical height prediction model: breast height age, reflecting trees development stage; site elevation, describing the potential environmental impacts on plantation development; and stand density, addressing intra-species competition of Douglas-fir. Not adjusting for SPM type would reduce adjusted R^2 to 0.5003, leaving residual standard error increase to 0.1175 on 64 degrees of freedom.

[5.2] $E\ (PAI.HT) = \beta_0 + \beta_1 BH\text{-}Age + \beta_2 EL + \beta_3 TPH + \beta_4 Mixed$

BH-Age is breast height age at the time of final measurement;

EL represents site's elevation in meters;

TPH denotes stand density, trees per hectare.

Model fitting statistics

Residual Standard Error: 0.0973 on 63 degrees of freedom					
Pr > F: <0.0001;			Adj. R Square: 0.6571		
	β_0	β_1	β_2	β_3	β_4
Estimate	3.3237	-0.0404	-0.0010	-0.0016	-0.0007
P-value	<0.0001	<0.0001	<0.0001	0.0002	<0.0001

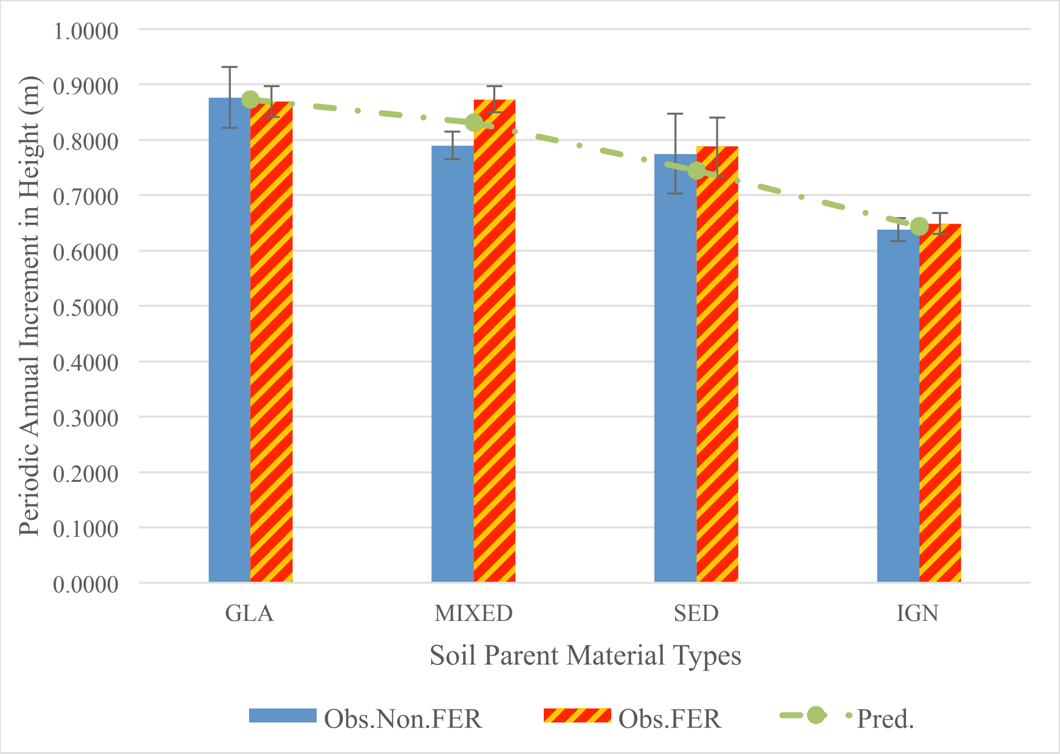

Figure 5.1.2. Periodic annual height increment and prediction from model [5.2] according to Soil Parent Material types. Vertical bars represent standard error of the mean. Overlapped predicted PAI HT growth trend for unfertilized and fertilized groups due to the insignificant nitrogen treatment term from empirical linear model.

5.1.3 Periodic Annual Volume Increment

Periodic annual volume increment was calculated based on measurements of DBH and height. Volume was determined by applying British Columbia Equations (Browne 1962) with coastal Douglas-fir parameters, calculating volume including top and stump (CVTS) for Coastal immature Douglas-fir (less than 140 years) in the following Eq. 5.1, where A = -2.658025, B=1.739925, C=1.133187:

Eq. 5.1. $$CVTS = 10^{A} * DBH^{B} * HT^{C}$$

Statistical analysis indicates stand density is the most influential covariate. SPM type (p-value=0.0046, $\overline{X}_{GLA}$=0.0342 m^3, $\overline{X}_{Mixed}$=0.0467 m^3, $\overline{X}_{SED}$=0.0350 m^3, $\overline{X}_{IGN}$=0.0422 m^3), fertilization (p-value=0.016, $\overline{X}_{Non.FER}$=0.0399 m^3, $\overline{X}_{FER}$=0.0441 m^3), and their interaction term (p-value=0.046) are all important factors in shaping PAI in tree volume. The Holm adjustment results indicate with fertilization, there are statistically significant differences in the comparisons of Glacial and Igneous, and Glacial and the Mixed SPM.

The empirical prediction model [5.3] suggests only SPM types and nitrogen treatment dominate plantations' volume increment. Among all types of SPM, Glacial sites were not favorable in adding volume, matching the field measurements (Figure 5.1.3). The empirical prediction model also suggests that nitrogen has a slight positive effect on volume increment.

Predicting PAI volume without SPM type significantly decreases adjusted R^2 to 0.0178, leaving residual standard error equal to 0.0139 on 66 degrees of freedom.

[5.3] $E\ (PAI.VOL) = \beta_0 + \beta_1 Mixed + \beta_2 IGN + \beta_3 TRT$

Model fitting statistics

Residual standard error: 0.0121 on 64 degrees of freedom

Pr > F: <0.0001; Adj. R Square: 0.2500

	β_0	β_1	β_2	β_3
Estimate	0.0327	0.0198	0.0120	0.0050
P-value	<0.0001	0.0004	0.0008	0.0935

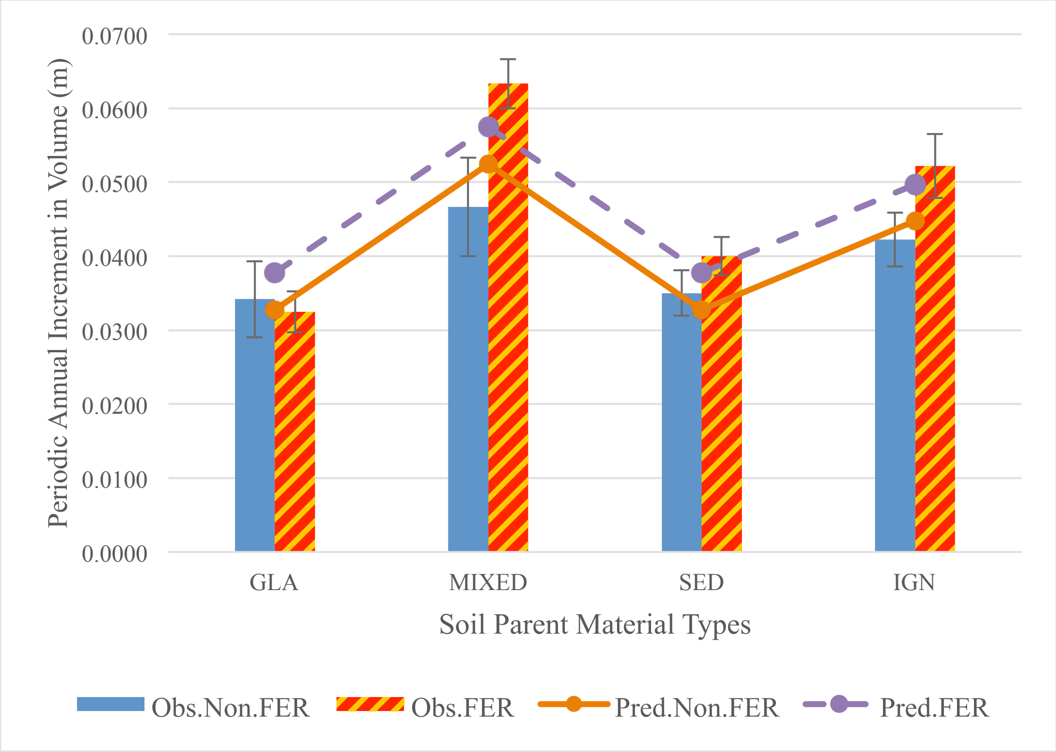

Figure 5.1.3. Periodic annual volume increment observations and predictions from model [5.3] according to Soil Parent Material types. Vertical bar represents standard error of the mean.

5.2 Wood Quality Assessment and Prediction

Five aspects in evaluating wood quality were considered in this section: tree sonic acoustic velocity (TSAV), dynamic modulus of elasticity (MOE_d), specific gravity (SG), latewood percentage (LWP), and rings per inch (RPI).

5.2.1 Tree Sonic Acoustic Velocity (TSAV)

Statistical split-plot ANCOVA analysis indicates that SPM type (p-value=0.899) and its interaction effect with fertilization (p-value=0.473) were not significant factors in defining TSAV. This analysis also indicates that fertilization treatment does not significantly influence TSAV result (p-value=0.249), which agrees with the Holm adjustment findings.

Field measurement (Table 5.2) shows that fertilization treatment does not significantly negatively impact TSAV through all SPM types, even though Douglas-fir growing on Mixed and Igneous SPM seems to have benefited from fertilization with higher TSAV readings. This means that increased tree dimension due to additional nitrogen would not necessarily lower wood quality.

The empirical prediction model [5.4] shows that TSAV can be predicted with covariates of site index and stand density, meaning both site and stand characteristics modify this wood quality aspect. Between the two design variables, SPM type has an essential effect in determining TSAV while fertilization treatment does not. TSAV measured on Glacial SPM type were comparable to Igneous SPM type. Trees from the Mixed and Sedimentary SPM types had higher measured TSAV, which indicating a higher wood density.

Without considering SPM differences, adjusted R^2 would decrease to 0.0687 and increase residual standard error to 0.2590 on 65 degrees of freedom.

[5.4] $E\ (TSAV) = \beta_0 + \beta_1 SI + \beta_2 TPH + \beta_3 Mixed + \beta_4 SED$

Model fitting statistics

Residual standard error: 0.2216 on 63 degrees of freedom					
Pr > F: <0.0001;			Adjusted R Square: 0.3186		
	β_0	β_1	β_2	β_4	β_5
Estimate	4.2315	0.0448	-0.0027	0.6313	0.1547
P-value	<0.0001	<0.0001	<0.0001	<0.0001	0.0199

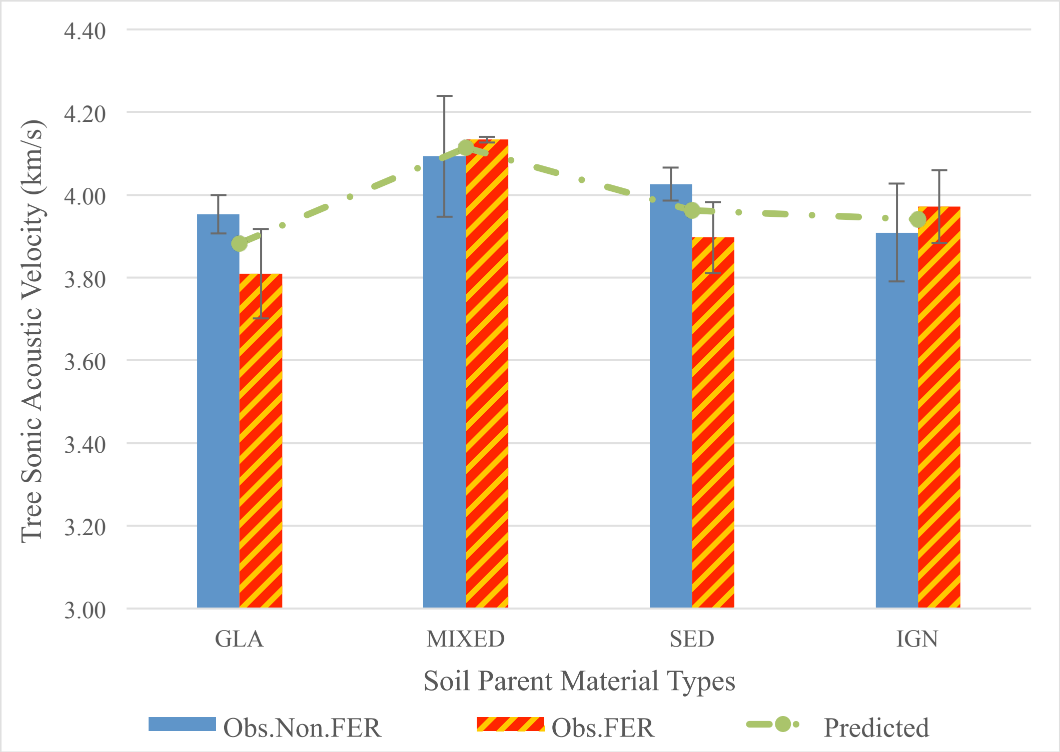

Figure 5.2.1. Tree sonic acoustic velocity response and predictions from model [5.4] according to Soil Parent Material types. Vertical bar represents standard error of the mean. Overlapped predicted TSAV for unfertilized and fertilized groups due to the insignificant nitrogen treatment term from prediction model.

Table 5.2. Tree sonic acoustic velocity, modulus of elasticity, specific gravity, latewood percentage, and rings per inch with mean, standard error, and split-plot ANCOVA according to Soil Parent Material, nitrogen treatment regimes, and their interaction. Only latewood percentage contains a significant covariate, the effective depth of soil A-horizon (A-HZ).

		Soil Parent Material							
Properties	Statistics	Glacial		Mixed		Sedimentary		Igneous	
		CON	FER	CON	FER	CON	FER	CON	FER
Tree Sonic Acoustic Velocity (km/s)	Mean	3.95	3.81	4.09	4.13	4.02	3.90	3.91	3.97
	Std.err	0.046	0.108	0.146	0.007	0.040	0.086	0.118	0.088
	SPM p-value	0.899							
	TRT p-value	0.249							
	Inter p-value	0.473							
MOE_d (GPa)	Mean	7.56	6.43	6.98	6.87	6.93	6.57	7.54	6.78
	Std.err	0.330	0.600	1.318	0.185	0.330	0.465	0.440	0.417
	SPM p-value	0.982							
	TRT p-value	0.026*							
	Inter p-value	0.707							
Specific Gravity (g/cm^3)	Mean	0.4831	0.4337	0.4083	0.4026	0.4267	0.4272	0.4967	0.4273
	Std.err	0.0175	0.0204	0.0493	0.0115	0.0151	0.0150	0.0285	0.0161
	SPM p-value	0.440							
	TRT p-value	0.012*							
	Inter p-value	0.231							
Latewood Percentage (%)	Mean	45.47	42.28	32.89	32.41	32.55	29.11	33.91	30.08
	Std.err	1.98	1.27	0.69	2.76	2.06	1.65	2.75	3.23
	Covariate	Effective depth of soil A-horizon (A-HZ)							
	SPM p-value	0.362							
	TRT p-value	0.041*							
	Inter p-value	0.950							
Rings Per Inch	Mean	17.24	12.62	12.10	10.13	10.42	8.42	12.97	9.28
	Std.err	1.98	1.27	1.21	1.20	2.05	1.64	2.75	3.23
	SPM p-value	0.801							
	TRT p-value	0.010*							
	Inter p-value	0.830							

5.2.2 Dynamic Modulus of Elasticity ($\mathrm{MOE_d}$)

Dynamic modulus of elasticity ($\mathrm{MOE_d}$) is a measure of wood stiffness, the lower the detected $\mathrm{MOE_d}$, the higher the chance of deformation under the applied pressure. $\mathrm{MOE_d}$ was calculated with Eq. 2.3. SPM was determined to be a non-significant factor in defining $\mathrm{MOE_d}$ by the split-plot ANCOVA result (p-value=0.982), nor was the interaction effect of SPM types and nitrogen treatment significant (p-value=0.707). The additional nitrogen decreased $\mathrm{MOE_d}$ (Table 5.2), indicated by statistical analysis of its important influence (p-value=0.026, $\overline{\mathrm{X}}_{\mathrm{Non.FER}}$=7.25 GPa, $\overline{\mathrm{X}}_{\mathrm{FER}}$=6.66 GPa). Using the Holm adjustment, no significant comparison among SPM types was detected.

Site index, stand density, and breast height age were determined to be statistically significant in the empirical prediction model of $\mathrm{MOE_d}$. This implies that Douglas-fir's resistance under compression is subject to both site and stand condition.

For the studied period, $\mathrm{MOE_d}$ could be predicted with the following linear empirical model:

$$[5.5] \quad E\,(\mathrm{MOE_d}) = \beta_0 + \beta_1 \mathrm{SI} + \beta_2 \mathrm{BH\text{-}Age} + \beta_3 \mathrm{TPH} + \beta_4 \mathrm{TRT}$$

Model fitting statistics

Residual standard error: 1.262 on 63 degrees of freedom					
Pr > F: 0.0002;			Adjusted R Square: 0.2430		
	β_0	β_1	β_2	β_3	β_4
Estimate	4.1507	0.1378	0.0973	-0.0059	-0.7168
P-value	0.0340	0.0053	0.0091	0.0119	0.0223

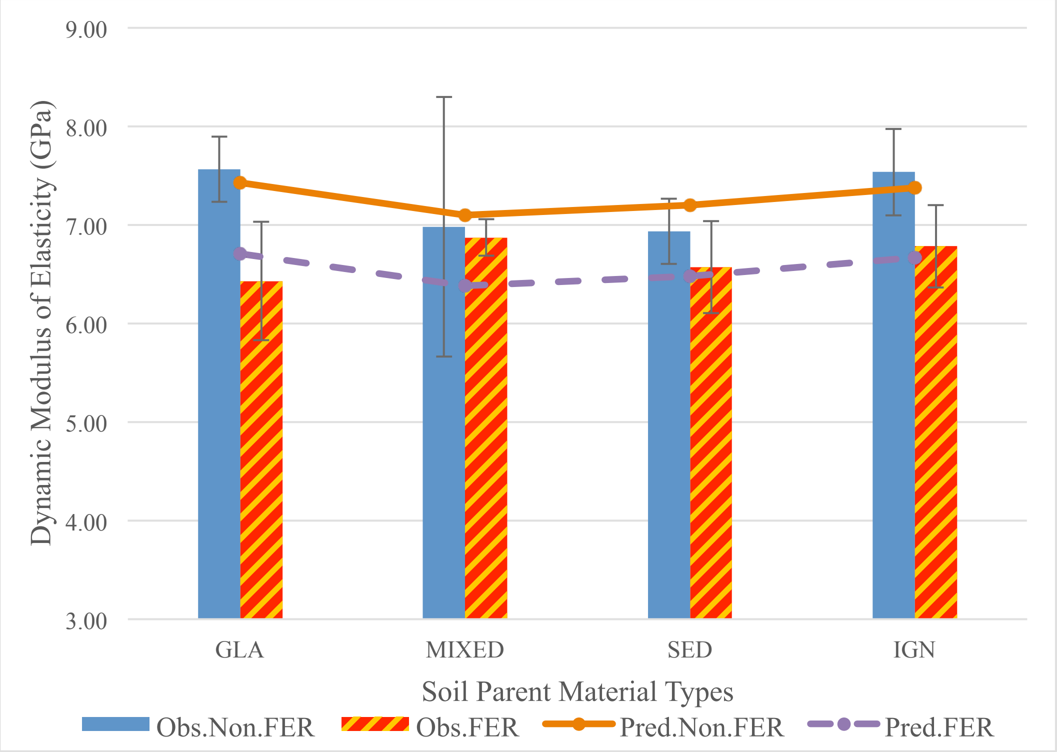

Figure 5.2.2. Dynamic modulus of elasticity derived and prediction from model [5.5] according to Soil Parent Material types. Vertical bar represents standard error of the mean.

5.2.3 Specific Gravity (SG)

The higher the specific gravity of a log, the greater the strength of the wood fibers. Averaged specific gravity according to SPM types (Table 5.2) shows both control and fertilized Douglas-fir fell in the range of 0.4000 to 0.5000 g/cm^3. To be specific, two SPM types, Glacial and Igneous dominate the higher end of the range; whereas Sedimentary and the Mixed SPM types fell in the lower end.

As assessed by split-plot ANCOVA, the SPM type (p-value=0.440) and its interaction with fertilization (p-value=0.231) are not important factors affecting SG, but fertilization treatment significantly influences SG outcomes (p-value=0.012, $\overline{\mathrm{X}}_{\mathrm{Non.FER}}$=0.4538 g/cm^3, $\overline{\mathrm{X}}_{\mathrm{FER}}$=0.4228 g/cm^3). The Holm adjustment results indicate there is no significant difference among SPM types.

Almost all unfertilized Douglas-fir had a higher SG when compared to the corresponding fertilized ones, except for Sedimentary SPM type. To examine two Sedimentary sites, one site had decreased SG after nitrogen treatment ($\mathrm{SED1}_{\mathrm{CON}}$=0.4656 g/cm^3, $\mathrm{SED1}_{\mathrm{FER}}$=0.4593 g/cm^3), the other site positively responded to fertilization ($\mathrm{SED2}_{\mathrm{CON}}$=0.4008 g/cm^3, $\mathrm{SED2}_{\mathrm{FER}}$=0.4058 g/cm^3). Previous research indicates plantations with various stand ages respond differently to fertilization treatment (Antony et al. 2009, Beckwith and Reines 1978, Jokela and Stearns-Smith 1993, Jozsa and Brix 1989, Larson et al. 2001, Love-Myers et al. 2009, Rudman and Nckinnell 1970, Sastry 1967, Van Lear et al. 1973). The older Sedimentary site is the oldest one, and the younger site is the youngest one among all studied sites. Though split-plot ANCOVA model assessed that breast height age is not an important covariate, it seems fair to infer that treatment age does influence SG. However, since no replicate site with similar conditions had been sampled, it is difficult to form any firm conclusion from these data when subjected to the split-plot analysis.

The empirical prediction model indicates that breast height age needs to be included in predicting SG response. Both SPM type and fertilization have a great impact on wood SG. Not including SPM type in the model reduces adjusted R^2 to 0.0650, with residual standard error equal to 0.0637 on 65 degrees of freedom.

[5.6] $E\,(SG) = \beta_0 + \beta_1 BH\text{-}Age + \beta_2 TRT + \beta_3 MIX + \beta_4 SED$

Model fitting statistics

Residual standard error: 0.06008 on 63 degrees of freedom

Pr > F: 0.0034; Adj. R Square: 0.1680

	β_0	β_1	β_2	β_4	β_5
Estimate	0.3919	0.0036	-0.0362	-0.0745	-0.0374
P-value	<0.0001	0.0419	0.0157	0.0094	0.0266

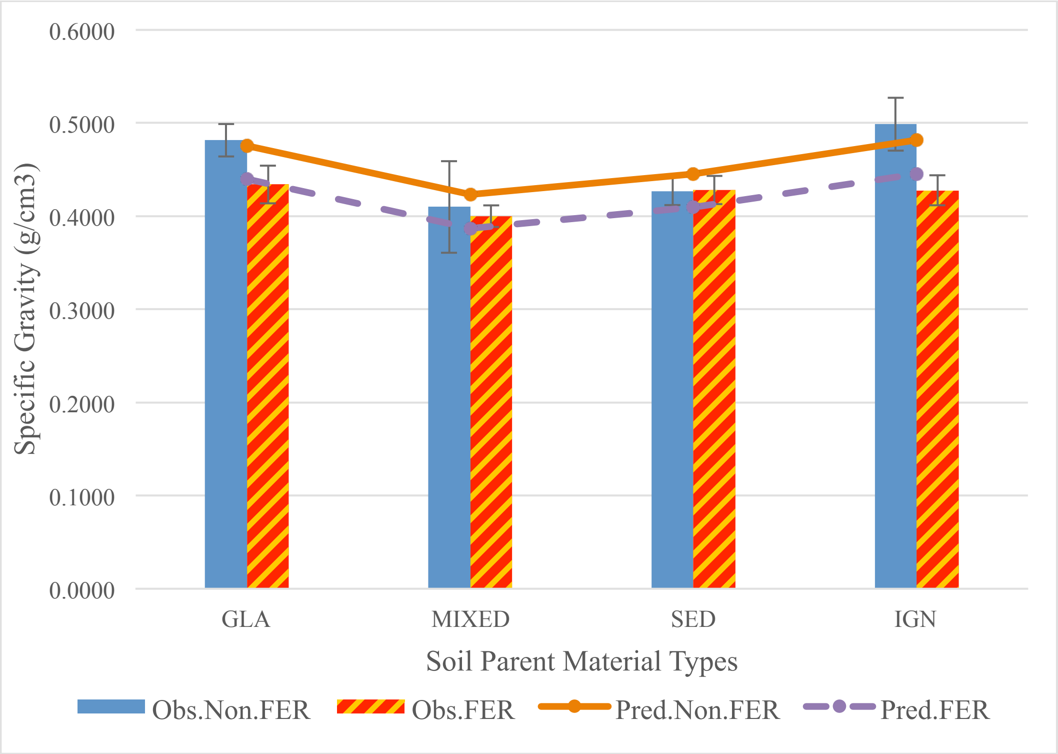

Figure 5.2.3. Specific gravity measured and prediction from model [5.6] according to Soil Parent Material types. Vertical bars represent standard error of the mean.

5.2.4 Latewood Percentage (LWP)

According to assessed increment cores, the highest LWP observations came from Glacial SPM site, while LWP outcomes from other SPM types were fairly close (Table 5.2). Split-plot ANCOVA indicates soil A horizon depth is the critical covariate, but neither SPM type (p-value=0.362), nor SPM and fertilization interaction (p-value=0.950) significantly affected LWP.

Generally, unfertilized Douglas-fir had higher proportion of LW for all kinds of SPM types (Table 5.2), where the highest LWP was observed on Glacial SPM type with the average LWP of 45.47%. Overall, the unfertilized group was 2.73% higher in LWP than fertilized ones. Analyzed by split-plot ANCOVA, fertilization had an essential impact on LWP (p-value=0.041, $\overline{\mathrm{X}}_{\mathrm{Non.FER}}$=36.20 %, $\overline{\mathrm{X}}_{\mathrm{FER}}$=33.47 %).

Detected with the Holm adjustment, Glacial SPM type is significantly different from the other three SPM types without fertilization treatment. With fertilization, the comparisons of Glacial and Igneous, Glacial and Sedimentary SPM are significant.

Fertilization effect was not consistent through all study sites. The oldest site (SED2) had a greater LWP in fertilized groups compared to its counterpart ($\mathrm{SED1}_{\mathrm{Non.FER}}$=30.22 %, $\mathrm{SED1}_{\mathrm{FER}}$=33.08 %). This matches the SG results. It is widely acknowledged that fertilization applied at the early stand development stage can enhance stem growth immediately (Cahill and Briggs 1992, Fielding 1967, Sastry 1967). Nevertheless, the definition or boundary of “early” has not been specified for Douglas-fir as different environmental characteristics and genetic features may affect a tree’s development trend. But the result observed on SED2 may be a positive sign for further research that nitrogen fertilization may not necessarily decrease LWP.

The empirical prediction model [5.7] shows that site features are critical to LWP performance, as LWP can be estimated by soil A horizon depth, site index, site elevation, and fertilization regimes.

[5.7] $E\,(LWP) = \beta_0 + \beta_1 A\text{-}HZ + \beta_2 SI + \beta_3 EL + \beta_4 TRT$

Model fitting statistics

Residual standard error: 6.4740 on 63 degrees of freedom					
Pr > F: <0.0001;			Adj. R Square: 0.4666		
	β_0	β_1	β_2	β_3	β_4
Estimate	-24.7036	1.4855	0.8136	0.0285	-3.1935
P-value	0.0750	<0.0001	0.0004	0.0130	0.0462

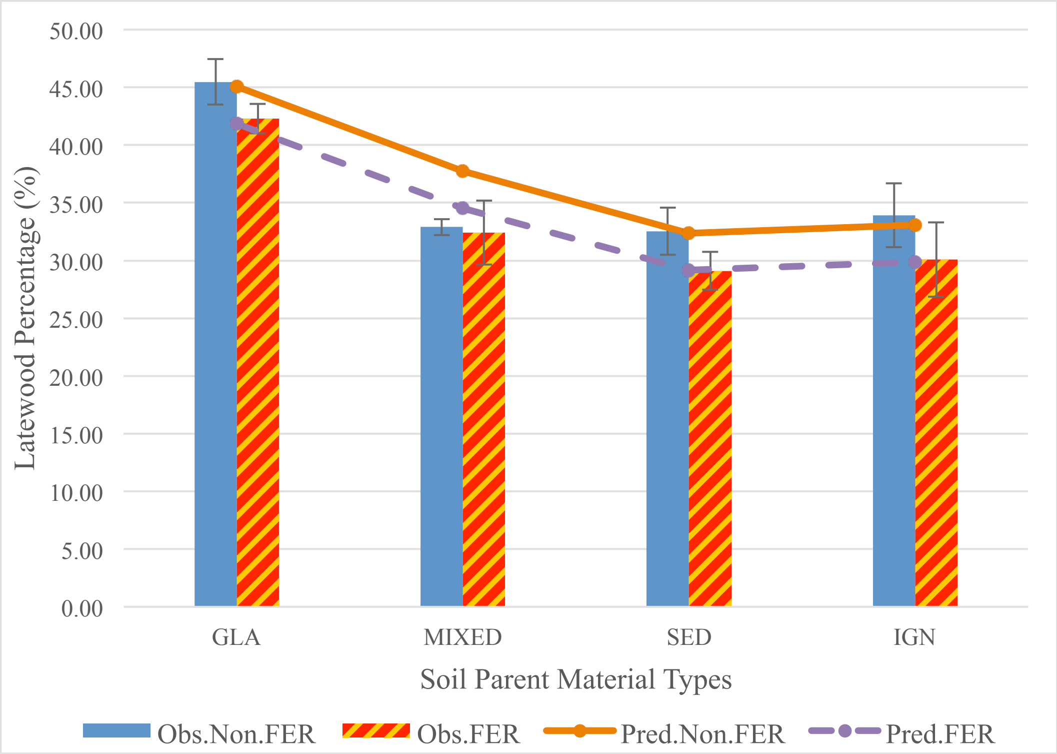

Figure 5.2.4. Latewood percentage measured and prediction from model [5.7] according to Soil Parent Material types. Vertical bars represent standard error of the mean.

5.2.5 Rings Per Inch (RPI)

Rings per inch is one measure of diameter growth. A higher RPI value suggests a slow radial increment, while a lower RPI value indicates that trees grew under favorable conditions. In this study, RPI was calculated based on the treated period, measurement of which was performed on increment cores extracted from breast height region. This is different from log scaling measurement for industrial RPI, which is based on the outer one-third transection of the measured log's smaller end.

According to the field observations, Douglas-fir growing on Glacial SPM sites had the highest RPI value, which is 3.81 rings more than Igneous and the Mixed SPM type, and 5.51 rings more than Sedimentary SPM sites (derived from Table 5.2). Split-plot ANCOVA results suggest the differences from SPM were not significant (p-value=0.801), neither was there any essential interaction effect (p-value=0.830). Fertilization treatment was determined to be an important factor influencing RPI (p-value=0.010, $\overline{\mathrm{X}}_{\mathrm{Non.FER}}$=13.18 RPI, $\overline{\mathrm{X}}_{\mathrm{FER}}$=10.07 RPI). Using the Holm adjustment, no significant comparison among SPM types was detected.

There are two incidences worthy of notice: first, unfertilized trees from one Glacial site had an unusually high RPI ($\mathrm{GLA1}_{\mathrm{Non.FER}}$=22.95 RPI), based on assessed environmental variables and increment cores' attributes. It is hard to fully explain this phenomenon; Second, stand age has a negative relationship to growth rate as indicated specifically by Sedimentary SPM sites. The older site exhibited a slow growth rate for both fertilized and unfertilized Douglas-fir trees (28-year, $\mathrm{SED1}_{\mathrm{Non.FER}}$=18.22 RPI, $\mathrm{SED1}_{\mathrm{FER}}$=14.05 RPI). This is significantly different from the younger site's results that much wider rings were observed for the same treated period (13-year, $\mathrm{SED2}_{\mathrm{Non.FER}}$=5.22 RPI, $\mathrm{SED1}_{\mathrm{FER}}$=4.67 RPI).

The following empirical linear model [5.8] shows that site condition has a dominant influence on RPI response, which is described by site index, fertilization treatment, and SPM type. Breast height age is also important, indicating that the younger and the older site exhibit different growth rates, resulting in dissimilar RPI responses. Disregarding SPM type impact would lower adjusted R^2 to 0.2391, and residual standard error would increase to 7.1790 on 64 degrees of freedom.

[5.8] $E\ (RPI) = \beta_0 + \beta_1 \text{BH-Age} + \beta_2 SI + \beta_3 MIXED + \beta_4 TRT$

Model fitting statistics

Residual standard error: 6.947 on 63 degrees of freedom					
Pr > F: <0.0001;			Adj. R Square: 0.2893		
	β_0	β_1	β_2	β_3	β_5
Estimate	-39.1901	0.7758	0.8600	-7.5065	-3.3674
P-value	0.0003	0.0003	<0.0001	0.0240	0.0500

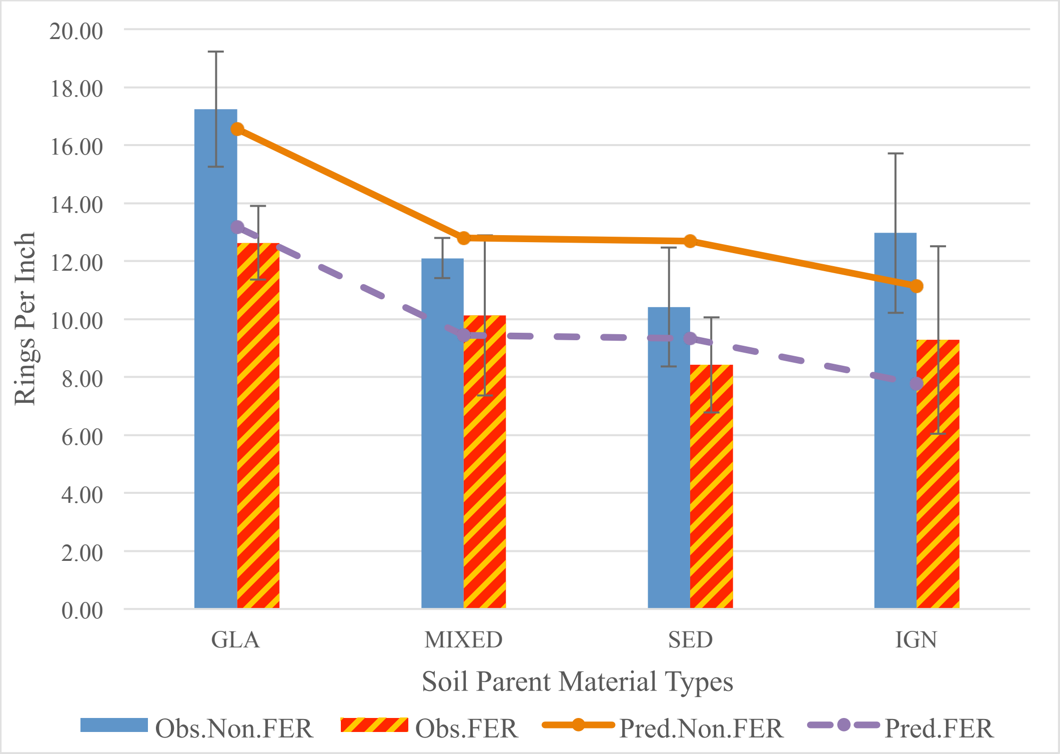

Figure 5.2.5. Rings per inch response and prediction from model [5.8] according to Soil Parent Material types. Vertical bars represent standard error of the mean.

5.3 Whole Tree Wood Quality Assessment

In the previous chapter, differences in wood quality among SPMs at breast height have been evaluated. This section explores two sites with similar SPMs, Sedimentary SPM and the Mixed (Sedimentary and Igneous) SPM. A subset of Douglas-fir trees in this study were felled and bucked for detailed analysis of fertilization treatment effect on wood quality at the whole tree scale. This section presents and evaluates the variances found in wood quality from the entire tree perspective. The primary focus is assessing nitrogen treatment impact on log segments. Trees were sawn from the bottom log up to a 4 inch (10.16 cm) top. Tree sonic acoustic velocity measurements were obtained before felling selected trees. In addition, log segments were assessed with a resonance acoustic instrument (Director® Hitman-200) after felling. These additional measurements allowed a comparison between standing tree and felled trees. Subsequently, the potential effect of SPM on wood quality as inferred from acoustic velocity measurements was estimated.

5.3.1 Tree Sonic Acoustic Velocity (TSAV) and Log Resonance Acoustic Velocity (LRAV)

For both SPM types, TSAV was detected within the range of 4.09 to 4.13 km/s. Fertilized trees had greater values than unfertilized trees, and this gap between the two treatments was 0.04 km/s on the Mixed SPM site, and 0.02 km/s on the Sedimentary SPM (FER > Non.FER). It seems plausible that fertilizing Douglas-fir stands at age 23 and 28 slightly improves wood stiffness (Figure 5.3.1).

Acoustic velocity detected with resonance measurement was compared to log segments according to SPM types and nitrogen treatment regimes. The highest LRAV was found in the segment of stump to the live crown base; followed closely by the butt log section, i.e. stump to the top of the first 16 foot (4.88 m) log (Figure 5.3.2). Both segments of stump to live crown base and butt log had LRAV in the range of 3.7 - 3.9 km/s. LRAV measured within the live crown had the lowest value. The overall tree LRAV (stump to top) was between these two extremes (i.e. LRAV measured from stump to the live crown base, and LRAV measured within live crown), which can be simply explained by reasoning the single log of stump to top contained about 50% live crown on both SPM sites.

In Figure 5.3.3, the sequence of LRAV measurements were rearranged to look at variations for the same log segment according to SPM types and nitrogen treatment regimes. From the whole tree perspective, fertilized Douglas-fir, on average have higher LRAV than control trees for all segments. This corroborates TSAV results in Figure 5.3.1. LRAV from butt logs had very small changes through SPM types and nitrogen treatments. Fertilized Douglas-fir had a slightly higher LRAV, but it is not significant. As the log segment length increased, from stump to live crown base and stump to the 10 cm top, the contrast brought about by fertilization increases. For the live crown to top subdivision, the difference between unfertilized and fertilized trees were quite clear with a difference of 0.26 km/s on the Mixed SPM site and 0.50 km/s on the Sedimentary SPM site.

The correlation between standing tree acoustic velocity measure and felled tree log resonance acoustic velocity was one of the principle interests in previous research. Wang (1999) found on red pine (*Pinus resinosa*) that TSAV was strongly correlated with LRAV

(R^2=0.88). On average, TSAV was about 10% higher than LRAV (the age of wood was not reported). Mora et al. (2009), tested loblolly pine with the age range of 14-19 years in the Southeastern United States, using the same tools in this research, reported a strong correlation (R^2 = 0.81) and a 32% higher TSAV than LRAV. Similar examinations were performed on radiata pine (*Pinus radiata*) in New Zealand. Grabianowski et al. (2006) found young stands (age 8 and 11) had TSAV 12% higher than LRAV. Chauhan and Walker (2006) used the Fakopp TreeSonic and Hitman, which showed gained a positive correlation (R^2 = 0.75-0.91) between TSAV and LRAV.

To date, there is no publicly available, peer reviewed publication that reports on the correlation between TSAV and LRAV for Douglas-fir. On average, TSAV obtained in butt log section was 8.12% greater than the LRAV. A strong correlation (R^2 = 0.92) was identified between TSAV and LRAV for stands aged 23 and 28. Results are consistent with previous studies involving other species.

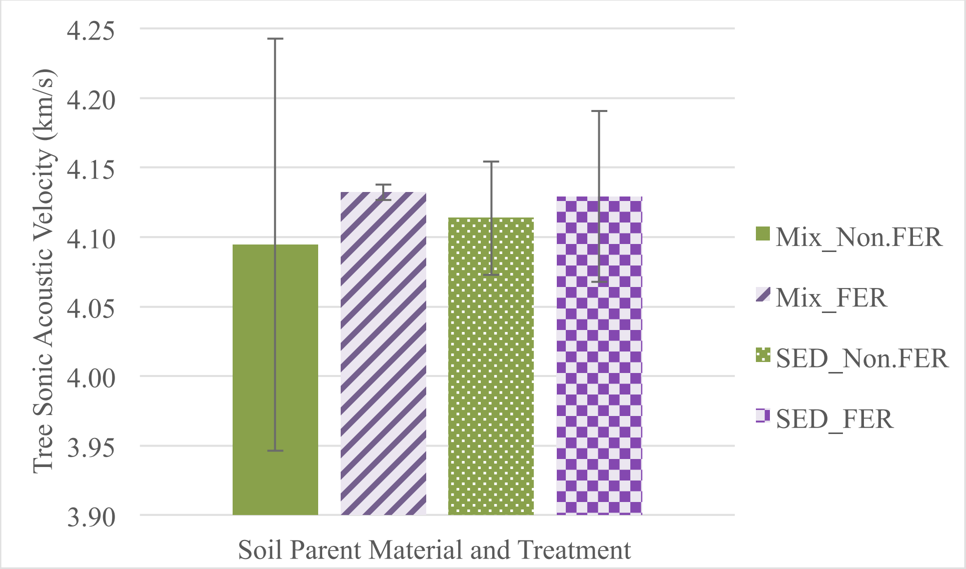

Figure 5.3.1. Tree sonic acoustic velocity on the Sedimentary and Mixed (Sedimentary and Igneous) stands, vertical bars represent the standard error of the mean.

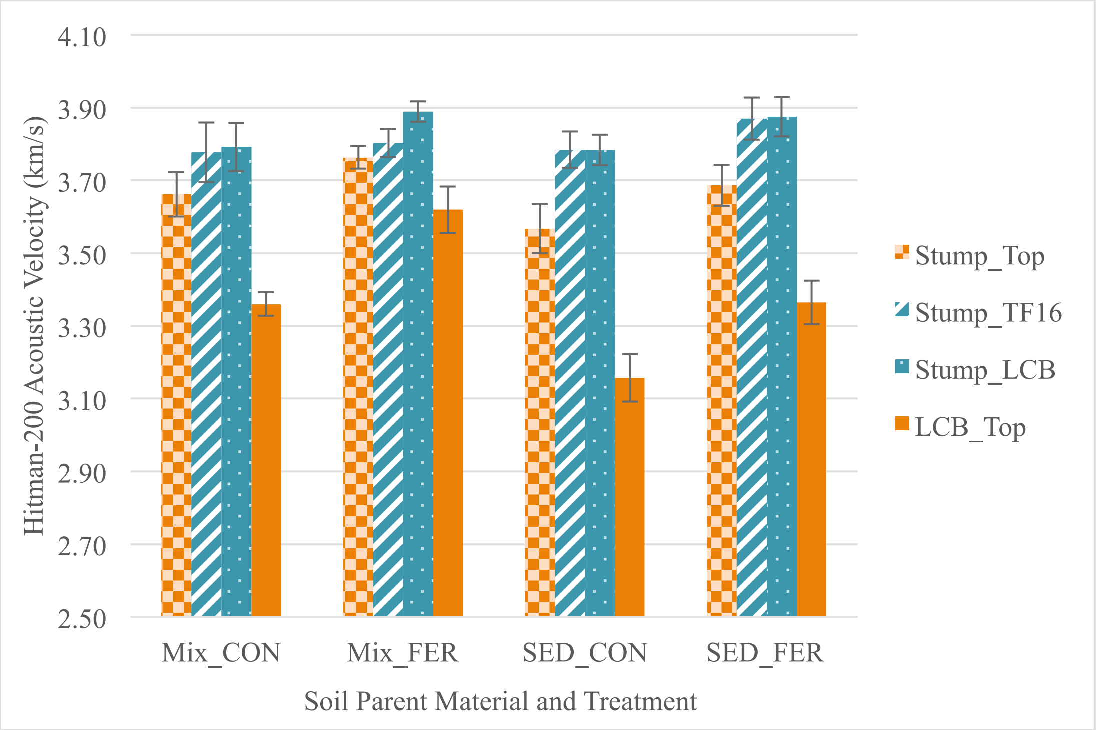

Figure 5.3.2. Log resonance acoustic velocity sorted by log position with the combination of soil parent material and fertilization regimes, vertical bars represent the standard error of the mean.

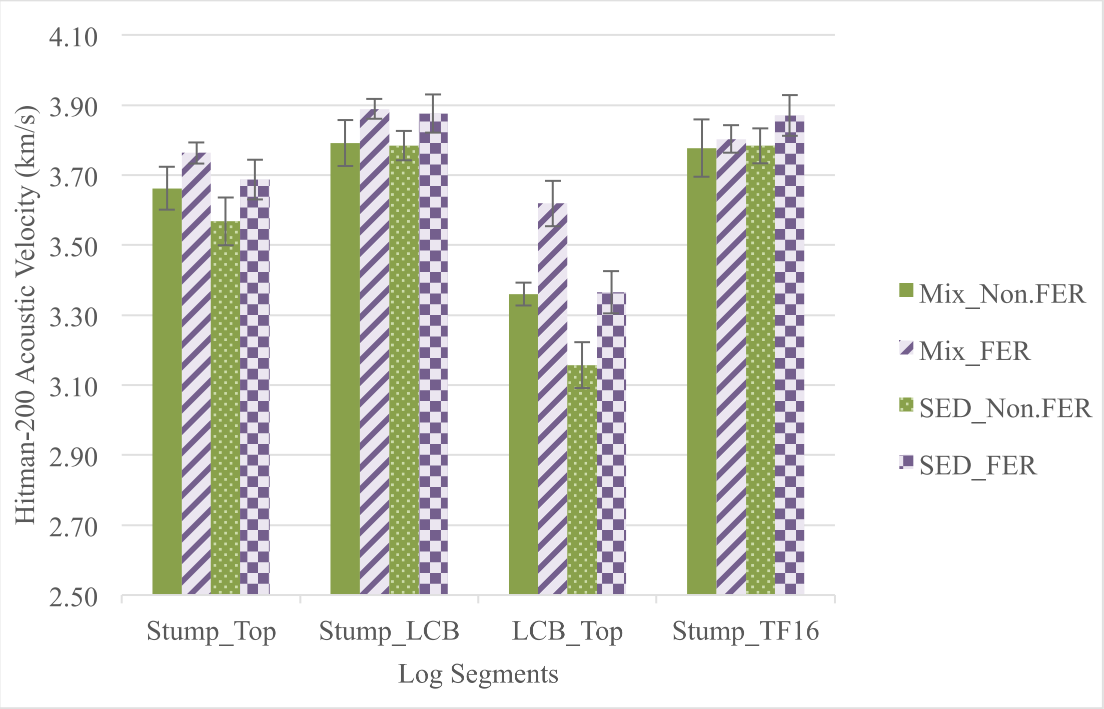

Figure 5.3.3. Log resonance acoustic velocity for Soil Parent Material and fertilization treatment combinations according to log position, vertical bars represent the standard error of the mean.

5.3.2 Specific Gravity (SG), Latewood Percentage (LWP) & Rings Per Inch (RPI)

Specific gravity, latewood percentage, and rings per inch for the treated period were measured through wood blocks obtained from 56 disks from sample trees.

Figure 5.3.4 shows the specific gravity over the entire tree bole on two sites. For the Mixed SPM, unfertilized trees consistently had higher SG than the fertilized trees. Though for the lower close to the stump section, such differences were not obvious. At the top of the first 16 foot log and live crown base, control trees maintained higher SG than those that were fertilized. A different trend was seen on the Sedimentary site. At lower tree sections, control trees had a slightly higher SG value, but the upper segments of the nitrogen treated group presented greater SGs.

For latewood percentage, nitrogen treatment had a positive effect on sampled trees from a whole tree perspective. Almost all segments along the trunk of fertilized trees contained more latewood within the annual ring. The only exception came from the Mixed SPM site at breast height, where control trees had LWP 0.48% higher than the fertilized trees. Additionally, fertilized trees on the Sedimentary site benefited more from the fertilization than trees from the Mixed SPM site, as indicated by the gaps between dashed and solid lines in Figure 5.3.5.

Rings per inch in relation to SPM types and nitrogen treatment regimes along the bole is shown in Figure 5.3.6. Unfertilized trees had the higher RPI than fertilized trees, especially at breast height, where control trees were 1.98 and 4.94 rings higher than fertilized trees on the Mixed and Sedimentary SPM sites, respectively. This reinforces that the growth rate was increased by supplementary nitrogen.

The observation that Douglas-fir on the Sedimentary SPM had higher values of RPI than the Mixed SPM in general, might be explained by three aspects. First, stand age difference. Upon fertilization treatment, trees on the Sedimentary SPM site had grown five more years than trees on the Mixed SPM. Since Sedimentary site trees already had a larger basal area, given similar crown vigor and a comparable amount of carbohydrate allocation, this group tended to have smaller radial growth, corresponding to the result of larger RPI shown in Figure 5.3.6. Second, research documents suggest that the Sedimentary site had 40 more trees in stocking per unit hectare than the Mixed SPM site. Though density effect was not assessed in this section, its influence should be considered. Third, site and environment conditions, which include but are not limited to elevation, slope, precipitation and temperature, may also have had an effect to some extent. However, such factors were fairly impossible to keep constant through all study areas, and were not the focus of this research.

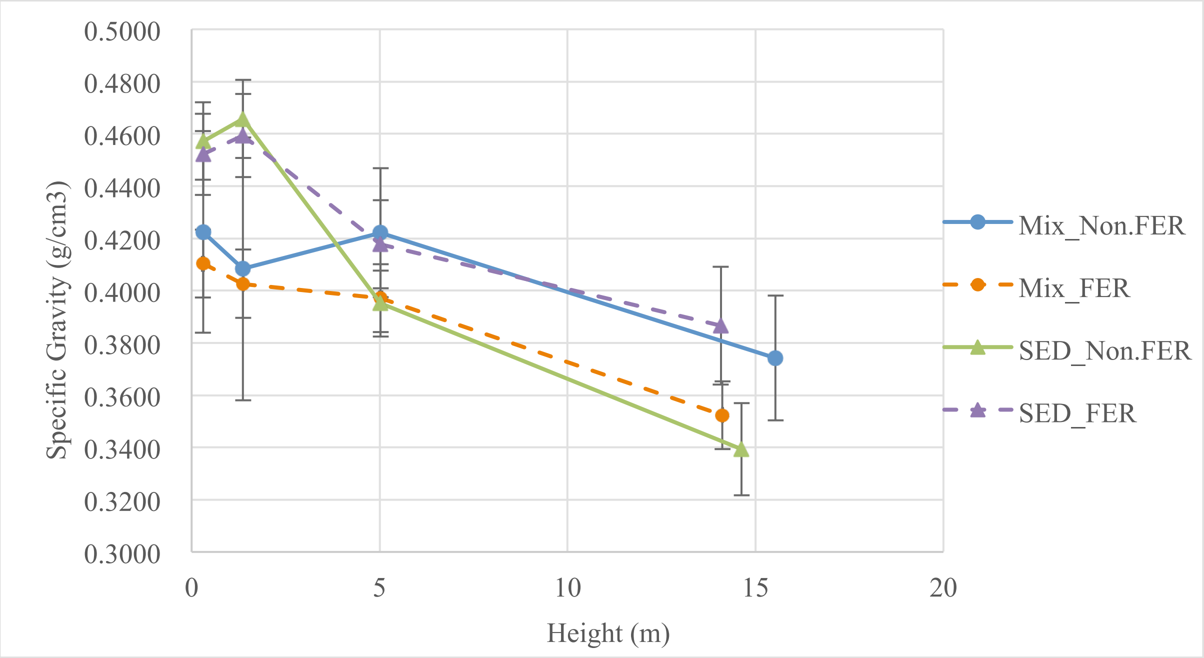

Figure 5.3.4. Specific gravity along height as related to Soil Parent Material and fertilization treatment, vertical bars represent the standard error of the mean.

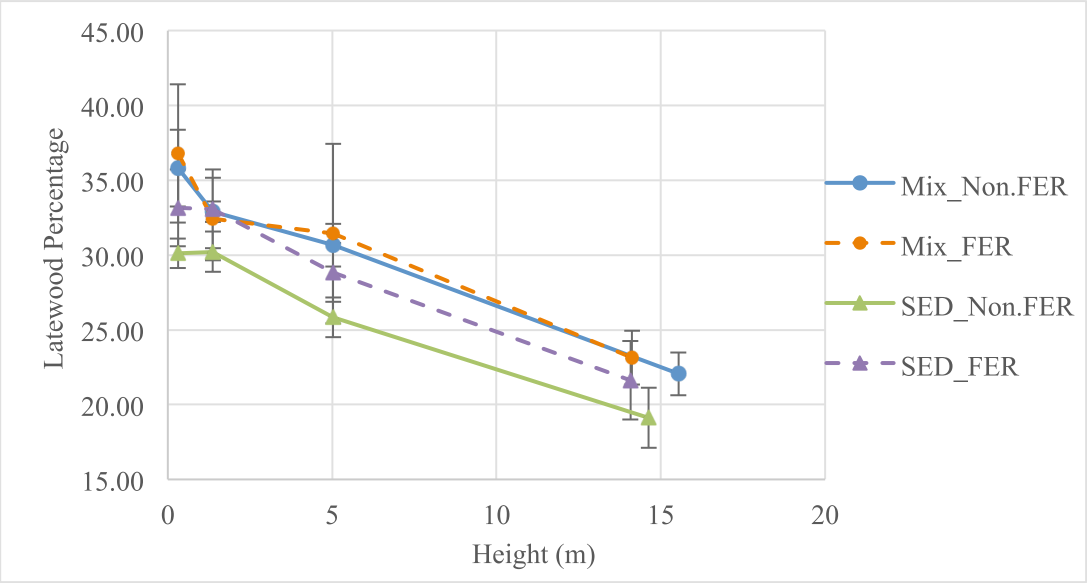

Figure 5.3.5. Latewood percentage along height as related to Soil Parent Material and fertilization treatment, vertical bars represent the standard error of the mean.

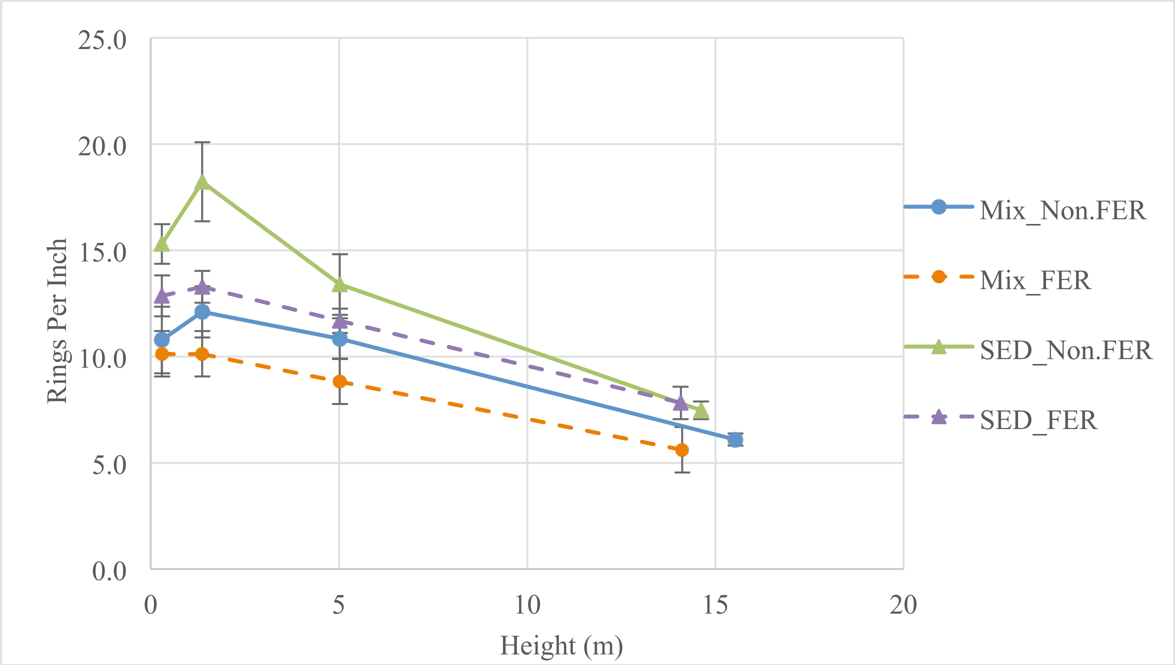

Figure 5.3.6. Rings per inch along height as related to Soil Parent Material and fertilization treatment, vertical bars represent the standard error of the mean.

CHAPTER 6. DISCUSSION

A wide range of locations were included in this study to assess the effect of soil parent material and nitrogen fertilization on Douglas-fir wood increment, quantity and quality. As a consequence of the wide geographic range of the study sites, a variety of site variables (such as slope, aspect) and environmental variables (temperature, precipitation, soil water, soil carbon, etc.) could impact wood quality as well. They are not considered in the analyses conducted in this research

6.1 Soil Parent Material

Soil plays a critical role in plant growth. Its depth, texture, and chemical properties influence its physical support ability, and nutrient and water-holding capacity. These soil properties determine a site's capacity to support plant growth, which in turn determine site index. (Miller et al. 1989, Steinbrenner 1979). In the Pacific Northwest, SPMs were laid down over a long time frame, punctuated by discrete events. Thus distinct mineral soil nitrogen and carbon contents were found in different SPM types (there was vast volcanic activity in and onto the lowlands about 14-17 million years ago and many advances and retreats of continental glaciers, Kruckeberg 1991). Studies have demonstrated that compared to igneous origin, sedimentary soils contain more nitrogen and carbon, have greater soil depths and finer textures. Igneous SPM is usually found at high elevations, in the Cascade Mountain Range, and characterized by lower year-round temperatures and higher precipitation from snow (Littke et al. 2011, Wang et al. 2010,). Littke (2012) found lower effective soil depth for Glacial SPM (especially A horizon) in comparison to Sedimentary and Igneous SPM across Douglas-fir sites from northern Vancouver, British Columbia, to southern Oregon.

Studied Douglas-fir sites show that in periodic quantity development, without additional nitrogen application, Sedimentary SPM type led QMD growth by 32% compared to least growth measured on Glacial SPM type. The Mixed SPM site had a remarkable increment in volume gain, 42% greater than the Sedimentary SPM sites (derived from Table 4.2). Volume increment was not calculated according to merchantable volume procedures. This may alter the consideration in actual stocking. Glacial sites investigated in this study are atypical, and featured high effective depth of soil A horizon (Table 4.3). However, tree’s lateral and volume growth rates were lowest on Glacial SPM.

As for wood quality associated with SPM (without fertilization treatment), results varied among the five measured indicators of wood quality. TSAV suggests dense wood found on the Mixed and Sedimentary SPM type. MOE_d, SG, and RPI indicated the higher quality wood came from Glacial and Igneous SPM types. In general, quantity increment is moderately negatively related to wood quality for all studied SPM types.

Previous studies concentrated on plantation yield. To date no wood quality assessment has been evaluated based on soil parent material. This might be because of the idea that site cannot be drastically altered. As a result, efforts have been devoted to collect current plantation yield information that has already proven its relation to site production potential, and no change will alter the forest outcome without additional silvicultural treatment.

6.2 Nitrogen Fertilization

Fertilization aims at accelerating plant growth rates by adding nutrients. Normally, an immediate effect can be observed upon fertilization application (Brix 1972, Erickson and Harrison 1974). Fertilization applications are mainly targeted to increase timber quantity production.

Surprisingly, tree growth results suggest that additional nitrogen decreased growth rate (QMD, Height, and Volume) for trees on Glacial SPM type. Furthermore, ANCOVA results indicate significant effects were generated by nitrogen treatment on two growth attributes (QMD and Volume). Results of this study agree with Li's conclusions (Li 2005) that fertilization increased diameter and volume production, but did not advance height growth in the Pacific Northwest. Brix (1972) studied 23-year-old Doulas-fir with 448 kg ha^{-1} nitrogen application (fertilized with NH_4NO_3) combined with irrigation. He found that under favorable soil water conditions, tree DBH increased 59% immediately in contrast to untreated trees. White et al. (2012) analyzed a compiled dataset containing 33 individual Douglas-fir trees. They concluded that SPM is informative, and stem volume increment was not significantly influenced by the interaction effect of SPM and fertilization. Variations in study site locations and stand attributes may account for the different results, as the Douglas-fir sites in this study were in the pre-crown closure stage with low stand density (relative density < 20%).

Wood quality results demonstrated that nitrogen treatment decreased Douglas-fir wood quality. Trees on the Glacial SPM sites exhibited the highest wood quality, however, fertilization negatively affected stem growth and their wood quality. For other SPM types, increment in yield is firmly associated with a decrease in quality. To sum up, fertilization contributes to: (1) up to 4% decrease in TSAV; (2) 2%-15% drop in MOE_d; (3) up to 14% reduction in SG; (4) and 16%-27% less RPI (derived from Table 5.2).

Specific gravity and latewood percentage are two quality traits of most interest. In this study, we saw decreased SG and LWP in fertilized groups to varying degrees on Glacial, Igneous, and Sedimentary SPM types. The smallest difference was observed in the Mixed SPM site where SG and LWP were reduced only 1%. Larson (1972) pointed out that excessive fertilization to young saplings does not necessarily increase wood quality, since a fairly high proportion of low strength earlywood would be produced. Erickson and Harrison (1974) studied a 21-year-old Douglas-fir plantation grown on a poor site and reported an increase in specific gravity over a long period. However, the immediate responses showed reduced density and lower latewood percentage. Kantavichai (2009) reported that biosolid fertilization reduced annual ring SG significantly on 55-year-old Douglas-fir trees. Identical results of fertilization treatment decreaseing SG were also reported by Cown (1977) and Megraw (1985) for radiata pine and loblolly pine, respectively.

6.3 Whole Tree

From a whole tree perspective, fertilization treatment increased the magnitude of TSAV and LRAV with the higher quality wood in the section from stump to the live crown base. In contrast, live crown segments were sensed having smaller LRAV values, because low stiffness juvenile wood is produced within this area. For the same log segment, the fertilized trees had a 2%-3% increase in LRAV. In the live crown, this value jumped to 8% and 6% for the mixed SPM and Sedimentary SPM sites. A strong correlation between TSAV and LRAV was seen (R^2=0.92), and TSAV was 8% higher than LRAV in butt log segment.

Fertilization had various impacts on SG along the tree trunk, and there were conflicting results from the two sites. Trees on Sedimentary SPM site benefited from nitrogen application with improved SG. However, wood blocks sawn from fertilized trees exhibited decreased SG at the Mixed SPM site. Such a difference was not great in the lower tree trunk. Another positive result was that additional nitrogen enhanced tree growth with decreased RPI (while all results were above industrial threshold 4 RPI). This did not result in LWP reduction in the corresponding segments. The results are consistent with Jozsa and Brix (1989) and Antony et al.'s (2009) findings that there is no height related pattern in wood quality respects due to fertilization.

6.4 Silvicultural Practices

Silvicultural practices have been studied and proven to be having impacts on quality and properties of wood. Besides nitrogen fertilization, thinning and pruning effects have long been studied (Fielding 1967). Though the impact of thinning, pruning, and the combined application of both thinning and fertilization were not targeted in this study, it is worth noting these practices' potential impacts.

Thinning has long been used in the Pacific Northwest to release crop trees from competition. A variety of responses to thinning have been reported. Kantavichai (2009) found mature Douglas-fir benefited from a thinning treatment with an average of 4% increase in SG. Paul (1958) worked with 80-year-old southern pine and found both increased and decreased specific gravity. Studies in the younger stands of various species, however, showed reduced specific gravity in the range from 5% to 10% (Cown 1974, Gerischer and DeVilliers 1963). Wang et al. (2001) examined four thinning regimes (control, light, medium, and heavy) for western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*) in southeast Alaska with various stand ages. They reported that heavily thinned stands expressed a trend of reduced stress wave and static bending properties.

Pruning is an effective practice to accelerate live crown recession. Reduced photosynthesis hormone generation and accelerated juvenile wood to mature wood transition process can increase wood specific gravity (Fielding 1967, Larson 1968, Marts 1951).

Li (2005) examined stand density and fertilization impact on Douglas-fir, and found no significant interaction effect on yield response. Briggs and Smith (1986) also analyzed the separated and combined effect of thinning and fertilization with data obtained from Erickson and Lambert (1958). They found that light thinning improved specific gravity, fertilization decreased specific gravity about 6%, while their combined treatment resulted in 15% decrease. Considering the treatment costs and their influence upon plant growth, the combination practice of thinning and fertilization is neither widely favored nor well documented.

CHAPTER 7. CONCLUSION

This study investigated the effects of four soil parent material types and two nitrogen fertilization treatment regimes on growth and wood quality middle age (19 to 32 years old) Douglas-fir plantations.

- Height increment was neither affected by SPM types nor fertilization treatment, whereas lateral increment was under strong influence of these two factors. In terms of wood production, i.e., volume, fertilization had a significant impact, enhancing the rate in adding substance.
- SPM type had no significant effect on any aspect of quality assessed in this study, but fertilization had a general negative effect on MOE_d, SG, LWP, and RPI. Non-destructive measure (TSAV) results in assessing fertilization impact is not consistent with the traditional assessments measured from increment core and felled tree samples (MOE_d, SG, LWP, and RPI).
- Growth increment was negatively associated with wood quality at observed breast height region for both fertilized and unfertilized Douglas-fir trees. The interaction effect of fertilization and SPM was not significant for any quality aspect.
- Although fertilization decreased stiffness (MOE_d), from a whole tree standpoint, fertilization decreased RPI (as growth rate improved) but did not necessarily decrease LWP. Higher quality wood can be found in the segment of stump to the live crown base; the live crown region had the lowest quality in every assessed aspect (LSAV, SG, LWP, and RPI).

- A strong correlation ($R^2 = 0.92$) in the butt log section between TSAV and LRAV was detected, besides, TSAV was generally 8% higher than LRAV.

Site and environmental variables were not regulated nor targeted in this research. Previous studies suggest some aspects (temperature, precipitation, forest floor C:N, etc.) would affect SG and tree growth (Antonova and Stasova, 1997, Kantavichai 2009, Littke 2012). Additional research is desirable using a greater replication of study sites with other factors (such as stand age, elevation, site index, etc.) to better understand their impact.

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