Risk to Long-term Site Productivity Due to Whole-tree Harvesting in The Coastal Pacific Northwest

Austin Jacob Himes

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Committee:
Dr. Robert Harrison
Dr. Darlene Zabowski
Dr. Eric Turnblom
Dr. David Briggs

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School of Environmental and Forest Sciences

University of Washington

Abstract

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Austin Jacob Himes

Chair of the Supervisory Committee:
Robert Harrison
School of Environmental and Forest Sciences

The growth of 68 intensively managed, mid-rotation, Douglas-fir stands in western Oregon, Washington, and British Columbia was projected to 50-55 years of age using the SMC variant of the ORGANON growth and yield simulator. From the ORGANON output, component biomass removal was estimated for stem-only harvest and a more intense whole-tree harvest. Utilizing published equations which estimate tree component N content based on biomass and total site nitrogen from the 68 sites, nitrogen removal under the two harvest intensities is expressed as a proportion of total site nitrogen store. Based on the proportion of N removed to the total site store, the 68 sites were assigned a risk rating, and regional patterns were assessed. Based on the simulation results, nearly half of the stands in the study were at risk of N depletion or site productivity loss under whole-tree harvest, while most stand ranked in the lowest risk category under stem-only harvesting. The highest concentration of stands at risk of long term site productivity loss from N depletion is on young glacial soils in Vancouver Canada and the Puget Sound region of Washington. This simulation also suggests that stands of similar planting density and age on sites with less than approximately 9000 and 4000 kg/ha of total site N will be at an elevated risk for long term site productivity loss under whole-tree and stem-only harvests respectively.

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CHAPTER 1

1.1 INTRODUCTION

1.1 Whole-tree harvesting for additional biomass

In the 1970's it was broadly recognized that the biomass of traditional logging residue was going to be an important resource. Demand for energy and wood products was increasing due to the rise in the global population and the development of the non-industrialized world, while at the same time supply dwindled as the land base for production forestry shrank and fossil fuel energy reserves were being depleted (Kimmins, 1977; Sabourin et al., 1992; Wells and Jorgensen, 1979; White and Harvey, 1979). In a keynote paper delivered at a 1979 symposium on the impact of intensive harvesting on forest nutrient cycling, George Staebler predicted, "When [oil] gets to some ridiculous value, say $100 a barrel (and maybe I'm myopic to say $100 is ridiculous), I guarantee the last shreds of biomass will come out of the woods." Staebler pleaded with researches to investigate the value of retaining biomass on site so that it could be compared with the economic value of using biomass for fiber and energy (1979).

In recent years the increase in oil prices has reminded some of the 1970's energy crisis, but we haven't yet depleted the forests of biomass. However, harvesting forest residuals for energy production has become an increasingly regular practice, particularly in European countries attempting to meet Kyoto protocol

requirements (Jacobson et al., 2000; Saarsalmi, 2010; Stupak et al., 2007). Biomass from forests is generally considered carbon neutral when used for energy because it is renewable and replanted trees sequester the CO_2 released by the utilization of the previous rotation. Furthermore, when biomass is used for energy it offsets the use of fossil fuels that are a net source for atmospheric CO_2 (Lattmore et al., 2009; Thiffault et al., 2011). New technologies for converting woody biomass from forests into liquid fuels also encourages accelerated biomass utilization. Liquid fuels from woody biomass have an advantage over corn derived ethanol because they don't displace a potential food source (White, 2009). These recent regulatory and technological demands for forest biomass increase pressure on production forests. This rising demand may increase stress on soils and heighten concerns about sustainable productivity of plantation forestry (Evens, 1999; Fox, 2000). Conversely, actual production from intensively-managed forests has risen over time, as has the efficiency of forest product utilization (Howard, 2007).

The use of wood and other biomass for energy is projected to grow more than any other renewable energy source in the next two decades (U.S. Department of Energy, 2009). The largest source of available biomass for energy not currently being utilized in the US comes from forest product residues (White, 2009). With logging residue removal for bioenergy projected to increase we still have a very limited quantifiable understanding of the value of that material if it is left on site. Managers considering biomass harvest will have to weigh the costs and the

benefits of removing logging residues. The potential economic benefits of exporting logging residues will depend on developing bioenergy markets, government subsidies, and the cost of traditional energy sources which are constantly fluctuating. The benefits in terms of reducing CO_2 emissions are being investigated by other researchers through forest product life-cycle assessments and carbon budgets (Puettmann et al., 2010). Therefore, this thesis will focus on a regional evaluation of the long-term productivity costs of intensifying forest harvests for biomass utilization.

1.2 Concerns over Whole-tree Harvesting

With the development and increased use of mechanized whole-tree harvesting (WTH), a number of researchers immediately expressed concerns about the increased export of nutrients due not only to the higher total export of biomass from the site but also due to the higher nutrient concentration of branches and foliage that were traditionally left on site compared to stem wood (Benjamin, 2010; Kimmens, 1977; Malkonen, 1976; Marion, 1979; Sabourin et al., 1992, Wells and Jorgensen, 1979; White, 1974). In a review of European studies of different tree species Malkonen (1976) found that WTH removed 2-4 times as much N, 2-5 times as much P, 1.5-3.5 times as much K, and 1.5-2.5 times as much Ca as stem-only harvesting (SOH). Despite the increase in losses, a number of researchers using nutrient budget evaluations found that soil reserves, weathering, and atmospheric inputs were enough to replace most nutrients lost

during WTHs over a standard rotation length, with the common exception being Ca (Boyle et al., 1973; Johnson, 1982; Turner, 1981; Weetman and Webber, 1972). Nitrogen is typically the most limiting nutrient in many forest systems (Fisher and Binkley 2000), but it is not as frequently identified as a nutrient that is at risk of being depleted as a result of higher-intensity harvesting (Johnson 1983; Evans 1999). However, for a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stand in western Washington, Cole (1978) predicted N depletion following WTH would result in adverse growth impacts on an Inceptisol soil.

In studies that looked at the growth of successive rotations following varying harvest intensities Bigger and Cole (1983) found increased harvest intensity only negatively impacted growth of two-year-old Douglas-fir seedlings on very low productivity sites, while other sites suffered no loss of production. Similarly, Jacobson et al. (2000) found a 5% and 6% reduction of growth in *Pinus sylvestris* and *Picea abies* respectively following WTH compared to SOH which they attributed to reduced N supply. In contrast Saarsalmi et al. (2010) found no growth reduction in *Pinus sylvestris* 22 years following WTH compared to SOH. Re-growth one year following WTH and SOH was greater after WTH on two out of three sites reviewed by Mann et al. (1988). In a summary of 26 sites in North America, Powers et al. (2005) found no significant difference in biomass accumulation as a result of different removal intensities after 10 years. However, in a related study in North Carolina, *Pinus taeda* stands on the lowest quality sites

had an 18% volume reduction following WTH after only five years (Scott et al., 2004).

The high variability in observed response of forest growth to elevated levels of biomass removal has many potential causes, including 1) type of tree species, 2) total soil nutrient stores, 3) soil nutrient availability, 4) soil physical characteristics, 5) climate, 6) stand stocking and development, 7) method of site preparation, 8) rotation length and 9) harvesting practices, all of which can affect subsequent tree growth (Benjamin, 2010; Grigal, 2000; Johnson, 1983). While not all sites are likely susceptible to productivity loss following WTH, there is reason for concern in low-productivity stands, particularly those with existing nutrient deficiencies (Lattimore, 2009).

In addition to WTH, biomass demands may push managers toward shorter rotations. Shorter rotations put additional stress on a site because younger trees have a larger ratio of nutrient rich foliage, branches, and bark to low nutrient wood. The result is that WTH of a young stand exports more nutrients per unit of biomass than it would if the stand were harvested when it was more mature (Ranger et al., 1995; Wells and Jorgensen, 1979). In addition, while younger stands have lower total nutrient demand, they primarily utilize site reserves while older stands often depend more on internal cycling as a source of nutrients for growth. Researchers have suggested that the internal nutrient cycling of

mature stands can actually lead to a net accumulation and higher reserves of site nutrients (Ranger et al., 1995; Turner, 1981; White and Harvey, 1979).

1.3 Whole Tree Harvesting in the Pacific Northwest

Due to high productivity and standing reserves of forests, the coastal Pacific Northwest (PNW) is one of the key areas in the US for potential energy production from biomass (White, 2009). In 2010, approximately 6 billion board feet of timber was harvested in Oregon and Washington (Warren, 2011). Associated with the region's timber harvests is approximately 6 million tons of utilizable biomass in the form of logging residue normally left on site during harvest (White, 2009). The main production species, Douglas-fir, is a good candidate for WTH because it has a relatively-high nutrient use efficiency compared to other forest plantation species in other regions (Marion, 1979). However, in much of the PNW tree growth is limited by N, which potentially increases the risk for N depletion and loss of productivity following WTH (Chapell et al., 1991; Miller, 1986; Turner, 1977). Stem-only harvests in the PNW should be sustainable (Fox, 2000; Talbert and Marshall, 2005) due to low nutrient removals, but there is evidence that WTH of Douglas-fir on poorer quality sites may lead to a loss in productivity in some cases (Bigger and Cole, 1983; Compton and Cole, 1991). Compared to the tropics, much of Europe, or the Eastern US, N inputs through atmospheric deposition and N-fixation are low in the PNW (Bormann et al., 1989). Furthermore, the ability of Douglas-fir to grow under

poor nutrient conditions coupled with continued enhancements in tree stock and silviculture may mask the decline of site N stores until after significant depletion has occurred (Lattimore et al., 2009).

1.4 Current methods and the need for regional assessments

Regional risk assessment models of nutrient depletion following whole-tree and conventional harvesting are necessary for land managers to make informed decisions about resource utilization (Sollins et al., 1983). Methods that have been utilized to assess the risk of WTH on productivity are costly, time consuming, and typically site-specific. These methods generally fall into two categories: 1)nutrient balance assessments, or 2) assessment of soil nutrient stores (Hansen et al., 2007). Nutrient balance assessment methods involve inventorying inputs and outputs of a particular nutrient to a system including harvesting export under different measured or simulated intensities. If inputs are equal to or exceed outputs then nutrient depletion is not a concern, and if outputs exceed inputs you can divide the total accessible soil pool of the nutrient in question by the difference to estimate the number of rotations that can be supported by the site. The limitations of this method are that it is site specific, inputs and outputs are difficult to measure and may fluctuate with stand development, and it is very difficult to assess all input and output mechanisms as shown by so called "occult inputs" of N (Binkley et al., 2000). The problem of stand development has been

addressed using chronosequence studies, but these studies also come with inherent problems because of site variation (Johnson and Curtis, 2001).

Soil nutrient store assessment methods involve sampling nutrient pools at fixed points in time. For example, soil nutrient pools could be sampled before and after harvesting of different intensities to determine if there are reductions and whether or not any reductions are different by treatment. To account for differences in stand development this method should be employed over a full rotation or longer (Hansen et al., 2007). Soil nutrient store studies are also site specific, and they only show problems after nutrient depletion has already occurred.

Recently attempts have been made to produce region-wide predictive models using geospatial analysis (Akselsson et al., 2007; Kimsey et al., 2011). These models utilize regional soil surveys, geological surveys, climate data, and topography to identify areas with high risk of nutrient depletion following intensive harvesting. These models can be very powerful tools for land managers because they are easy to use and identify areas at high risk for nutrient depletion without any field sampling. The shortcomings of these models are that they lack precision, they are limited to data that are included in survey maps and the substantial inaccuracy inherent in such maps.

Evans (1999) proposed an alternative risk assessment metric developed to evaluate "narrow-sense" sustainability which has potential to be applied on a regional scale. Evans (1999) described sustainability in the "narrow-sense" as the ability to grow trees on the same site, rotation after rotation, indefinitely without losing productivity. Evans (1999) promoted a "stability ratio" as one way for evaluating forest plantation sustainability. The stability ratio (SR) is the amount of a given nutrient removed by harvesting relative to the total site store of that nutrient. A stability ratio of 0.1 for N would mean removing the equivalent of 10% of the site store of N at harvest. Evans (1999) further suggests that an SR less than 0.1 posed little or no risk to long term productivity. An SR greater than 0.3 potentially represents a significant risk to productivity but the realization of nutrient depletion or productivity decline may not become evident immediately, and an SR greater that 0.5 will likely result in significant and immediate site productivity decline (Evans 1999). This simple risk assessment was applied to simulated harvests of different intensities of 68 intensively managed Douglas-fir stands across the coastal PNW region. The objectives of this study are to present an easily replicated site-specific method of assessing the sustainability of SOH and WTH using the SR and apply that method to 68 representative sites within the Douglas-fir regional of the coastal PNW to identify region patterns in sustainable harvesting.

2. METHODS

2.1 Study Sites

Beginning in 2008 the Stand Management Cooperative (SMC), a research cooperative of universities, government agencies, and private timber companies, began installing paired-tree fertilizer trials in 15-30 year old Douglas-fir plantations in western Oregon, Washington, and British Columbia (Littke et al. 2011). The objectives of that study were primarily to understand relationships between site factors and productivity, and to potentially predict sites with high likelihood of response to fertilization. The 68 sites cover a range of latitudes and site conditions representative of Douglas-fir plantations in the region (see Appendix 1). At each plot 19-40 Douglas-fir trees from the dominant or co-dominant canopy class were selected. For all study trees the diameter at breast height (DBH), average breast height age, height, and height to live crown were measured. A 0.0078 ha circular plot was established centered on each of the study trees and the diameter of all trees within that plot were also measured (K. Littke personal communication). Soil characteristics including total site N were measured and calculated as described by Littke et al. (2011) (see Appendix 2).

2.2 Individual tree growth model

ORGANON-SMC, an individual tree computer growth model specifically developed from stands within the same region as the study sites, was used to simulate the future growth of the stand at each plot (Hann, 2011). Given basic

tree measurement data and site information ORGANON simulates the growth of a stand in five year intervals using multiple species specific growth models developed from tree age, height, and DBH measurements collected throughout the coastal Pacific Northwest. Some tree parameters such as height and live crown ratio can be estimated by ORGANON from DBH using regional and species specific allometric relationships. Hann (2011) provides more details on inputs required by ORGANON and how missing values are estimated. The stand level inputs for ORGANON used were Bruce (1981) site index for Douglas-fir, stand age, and breast height age.

Site index values were calculated for each of the 68 plots using King (1966) methods from the heights of the 10 largest DBH trees. King (1966) site index values were converted to Bruce (1981) site index values using an iterative method. Bruce (1981) site index was used because the SMC version of ORGANON is based on Bruce (1981) values.

Plots with 38-40 trees were separated into two equal and adjacent groups, all other plots had all trees in a single group resulting in the total area represented by each group ranging from 0.15-0.29 ha which provided a similar scale to the 0.20 ha plots used for developing the SMC ORGANON variant. After the growth simulation of individual trees the data from plots that had been split were merged.

The heights of individual Douglas-fir trees that were not measured were estimated using the allometric equation:

$$\ln(ht-1.5)=a+b(1/DBH)$$

Where ln=the natural logarithm, ht=height (m), and DBH=stem diameter (cm) at 1.5 m. The a and b terms were derived for each stand using all measured tree heights from that stand. For some plots the slope of the function was very small owing to low variability of trees with measured heights. The small slopes resulted in unrealistic projections of height for very small diameter trees, so in these instances unmeasured heights were left blank for ORGANON to estimate using regionally and species specific equations built into the software. The heights of all species other than Douglas-fir were also estimated by ORGANON.

The ORGANON simulation was carried out in R statistical software using dynamic link libraries (dll) as described by Gould and Marshall (2011). The ORGANON dlls were edited and compiled using free FORTRAN software "gfortran" to be compatible with R statistical software. Running the simulation in R allowed for the customization of output data and allowed us to automate ORGANON input procedures so that the files for the 68 plots could be run without having to manually interface with ORGANON between runs. The R statistical software interface also allowed us to alter the ORGANON volume calculations so Bruce and DeMars (1974) total stem volume estimates for Douglas-fir were used rather

than the default ORGANON stem volume estimates. In previous work throughout the same land base, Bruce and DeMars (1974) volume was found to be the best estimator of actual volume (E. Turnblom, personal communication). For all species other than Douglas-fir, the default ORGANON stem volume estimates were used with the log top diameter set to zero.

2.3 Biomass and Nutrient Calculations

The biomass of tree components was estimates by first determining the biomass of the stemwood:

$$B_{stem}=1000*SG*SV$$

Where B_{stem} is the biomass of the stemwood (kg), 1000 is the mass in kg of one m^3 of water, SG is the specific gravity of Douglas-fir in the specific region containing the plot estimated with the regional map of Douglas-fir density in the western wood density survey (USDA, 1965)(Appendix 3), and SV is the Bruce and Demars (1974) stemwood volume (m^3). The estimated stemwood biomass was then divided by the stemwood ratio derived from Jenkens et al. (2003) biomass equations for softwood species to estimate the total aboveground biomass (TAB) for all trees (see appendix 4). Finally, the TAB was used to estimate the biomass of all other tree components using Jenkins et al. (2003) equations for softwood species component biomass.

For species other than Douglas-fir appropriate component biomass was estimated from Jenkins et al. (2003) equations adjusted for volume as described above, only different specific gravity values were used and the volume was estimated with the default volume model in ORGANON. The specific gravity used for hardwood species was an average of specific gravities of all hardwood species in the study with published average specific gravity values (Miles and Smith, 2009). The same method was applied to all softwoods not coded as Douglas-fir (see Appendix 5). Average values were selected because there were no specific gravity values available for some species within the plots, furthermore, many species were already grouped in order to match the limited species ORGANON recognizes. Species other than Douglas-fir were a small component of most plots, making up on average less than 4% of the stems on a plot with a range from 0-18%, with only three plots having more than 15% of species other than Douglas-fir.

2.4 Harvest simulation

ORGANON simulated tree growth on a five year interval so each plot was simulated to a stand age of 50-55 years. Estimates of total above-ground biomass and stemwood+stembark biomass of each tree were summed for each plot. The N content of Douglas-fir TAB and stemwood+stembark was estimated using equations from Augusto et al. (2000) at each plot (see Appendix 6). N export from

the site was estimated assuming the removal of TAB of all trees to simulate WTH and total stemwood+stembark of Douglas-fir to simulate SOH. The estimated N exported for both simulated harvest intensities was expressed as a percent of total site N store (soil N to hardpan or 1m+forest floor N).

The N content of all other species were estimated using the same equations which are specified for Douglas-fir. The lower precision involved in estimating N content of species other than Douglas-fir was deemed acceptable because they were only a small portion of the study trees. Furthermore, using Douglas-fir specific equations for all species should result in overall conservative estimates of the sum of N accumulated in the above ground part of trees because Douglas-fir has relatively-high N use efficiency (Augusto et al., 2000; Marion, 1979; Palviainen and Finer, 2011). Also, appropriate biomass and nutrient content equations do not exist for species in the region other than Douglas-fir.

3. RESULTS

The stand stemwood volume estimates ranged from about 300 to 1130 m^3/ha with a mean of 830 m^3/ha for the 68 plots. Yield tables for managed Douglas-fir in the region predict a total stand volume of 297-1246 m^3/ha for 50-55 year-old unthinned stands planted at 300-400 trees/ha for the range of site index values in this study (Curtis et al., 1982). Normal yield tables from McArdle et al. (1949) suggest a lower range, but they were developed from unmanaged naturally-

regenerating stands that had lower levels of productivity than modern intensively-managed Douglas-fir plantations.

The TAB estimated from stemwood volumes and the Jenkins et al. (2003) biomass equations ranged from 220 to 810 Mg/ha with a mean of 580 Mg/ha, and stemwood+stembark biomass estimates ranged from 160 to 620 Mg/ha with a mean of 430 Mg/ha. Figure 1 shows that the large range of TAB closely follows site index. Table 1 shows all biomass values from the literature of Douglas-fir stands between the ages of 45 and 60.

Estimated harvest exports of N from WTH ranged from 366 to 1218 kg/ha of N with a mean export of 886 kg/ha of N. Stem-only harvest N export estimates ranged from 165 to 737 kg/ha of N with a mean of 495 kg/ha of N. Table 1 compares the N export estimates of this study with those of similar aged stands in the literature.

Figure 2 shows harvest export estimates relative to site nutrient stores and lines representing the critical SR values of 0.1 and 0.3. Eighteen of the 68 sites would exceed an SR of 0.1 with SOH by removing more than the equivalent of 10% of site N stores, whereas WTH is estimated to exceed an SR of 0.1 at 33 of 68 sites. A SR of 0.3 was exceeded at only one site under SOH (0.47), and at six sites under WTH (0.37, 0.40, 0.45, 0.45, 0.49, and 1.02) by our estimates. Table 2 summarizes SR estimates and Appendix 7 has details and estimates for all plots.

Spatial patterns are apparent in the distribution of SRs throughout the coastal PNW based on these 68 sites. The only large area that shows a potential concern for nutrient depletion or productivity loss using SOH based on SR is in northern British Columbia (BC)(see Figure 3). With WTH, coastal BC, large parts of the Puget Sound and Olympic Peninsula, and a southern section of Oregon are at a potential elevated risk for N depletion based on our evaluation of SR. These regions correspond to younger glacial soils in areas covered by the Vashon Ice-Sheet during the last ice age, except for the area in southern Oregon.

A strong relationship between site N stores (soil+forest floor N) and estimated SR was also found (see Figure 4). This relationship permits prediction of SR for stands 50-55 years of age. Using the regressions in Figure 4 sites are predicted to have an SR less than 0.1 and be at low risk of N depletion or productivity loss if there is more than 9113 kg/ha of total belowground N for WTH and more than 4127 kg/ha total belowground N for SOH.

Table 1. Comparison of biomass and N content reported in the literature with that found in this study

Source	Stand Age	Trees/ha	Stand Volume (m^3/ha)	Stemwood Biomass (Mg/ha)	Total Aboveground Biomass (Mg/ha)	Total N content of trees (kg/ha)	50 yr Site Class	Specific Gravity
Ares et al., 2007	47	DF=303 WH=324 Total=627	DF=500 WH=414 Total=914	DF=182.2 WH=126.2 Total=308.4	DF=234.2 WH=158.6 Total=392.8	DF=375.9 WH=228.6 Total=604.5	High 2	DF=0.36 WH=0.30
Bigger and Cole, 1983	55			281* 134*	318 165	728 325		
Ponette et al., 2001	54	243	747	293	363	440		0.39
Homann et al., 1992	50	1100		275	216			
Ranger et al., 1995	60	312		307	418	694		
Heilman, 1961**	52	1000	339	148	216	361	4	0.43
Turner, 1980	50	1110		319	404	737		
Turner and Long, 1975	49	1070		178	234		High 4	
Range for this study (mean)	50-55	353-1280 (698)	302-1120 (829)	162-624 (429)	220-804 (577)	366-1220 (886)	Low 4-High 1 (High 2)	0.44-0.47 (0.45)***

Comparison of all studies found with biomass calculations of Douglas-fir stands between the ages of 45-60. When stand volume was included in the publication it was used to calculate the specific gravity by the equation described in Methods. Fifty-year site class is King (1966). DF is Douglas-fir, WH is western hemlock, and values in parenthesis are the mean values from this study. The two numbers from Bigger and Cole are from two different stands of Douglas-fir.

*includes bark

**natural stand

***based on Western Wood Density Survey (1965)

Table 2. Summary of Stability Ratio findings for the region. A SR of 0.1 means the quantity of N removed at harvest is equivalent to 10% of the site N store (forest floor N+mineral soil N to a depth of 1m or impenetrable layer)

	Whole-tree Havesting	Stem-Only Havesting
# of sites w/SR ≥ 0.1	33	18
# of sites w/SR ≥0.3	6	1
% of sites w/SR ≥0.1	49	26
% of sites w/SR ≥0.3	9	1
Bellow Ground N (kg/ha) above which SR is predicted to be <0.1	9113	4127

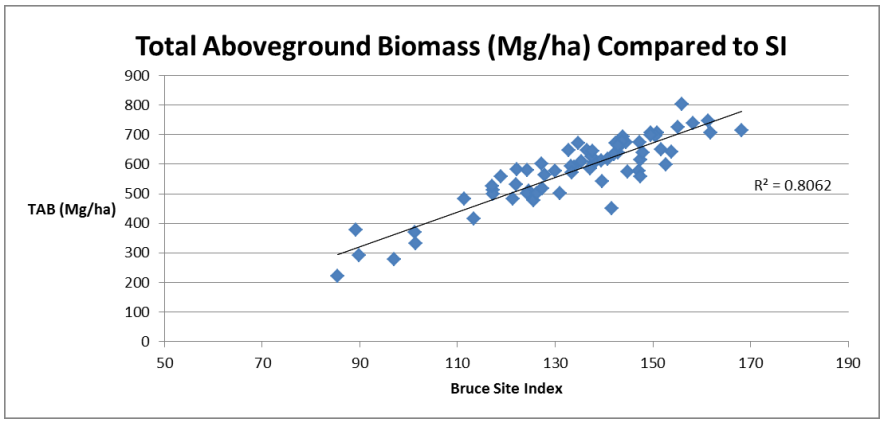

Figure 1. Total aboveground biomass increases with site index. Total aboveground biomass (TAB) is equal to the sum of all above ground parts of all trees in a plot. The relationship between TAB and Bruce (1981) 50-year site index for Douglas-fir is significant ($p<0.01$).

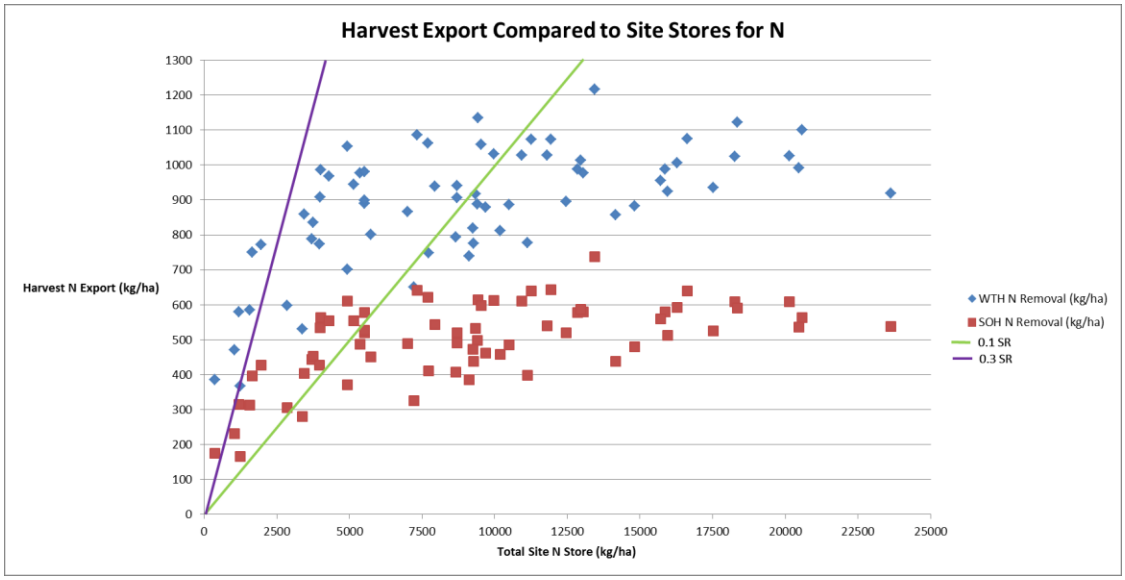

Figure 2. Harvest export of N under whole-tree harvesting (WTH) is assumed to be equivalent to total aboveground N content of all trees in a plot. The total site N store is the total N in the mineral soil to one meter depth (or impenetrable layer) plus the forest floor. If a marker is above or to the left of the 0.1 or 0.3 SR line it represents a site that exceeds that stability ratio.

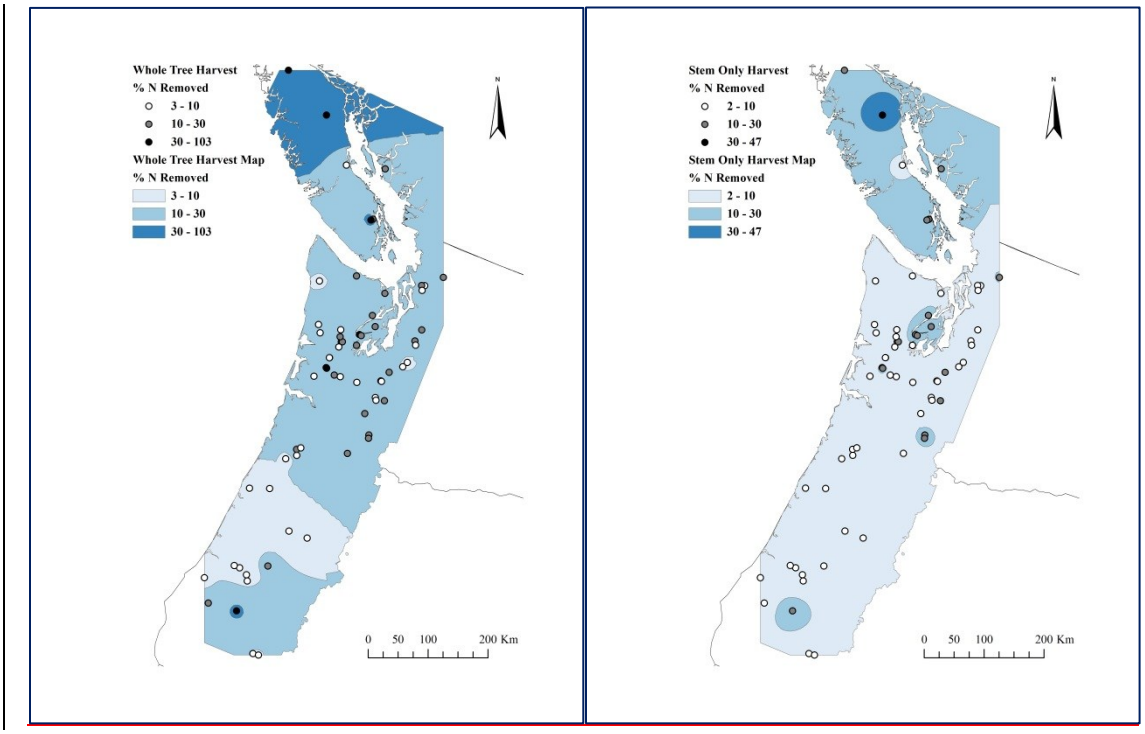

Figure 3. Spatial distribution of N removal expressed as a percentage of total site N store for whole-tree harvesting (WTH), left and stem-only harvesting (SOH), right. Percent N removed is the amount of nitrogen removed at harvest expressed as a percentage of the total site store of N and it is equivalent to the stability ratio (SR)*100. Dots indicate the location of sites. The maps do not take into account any variables other than the percent of N removed. Site N store is defined as the sum of soil N to a depth of 1 m (or impenetrable layer) and forest floor N.

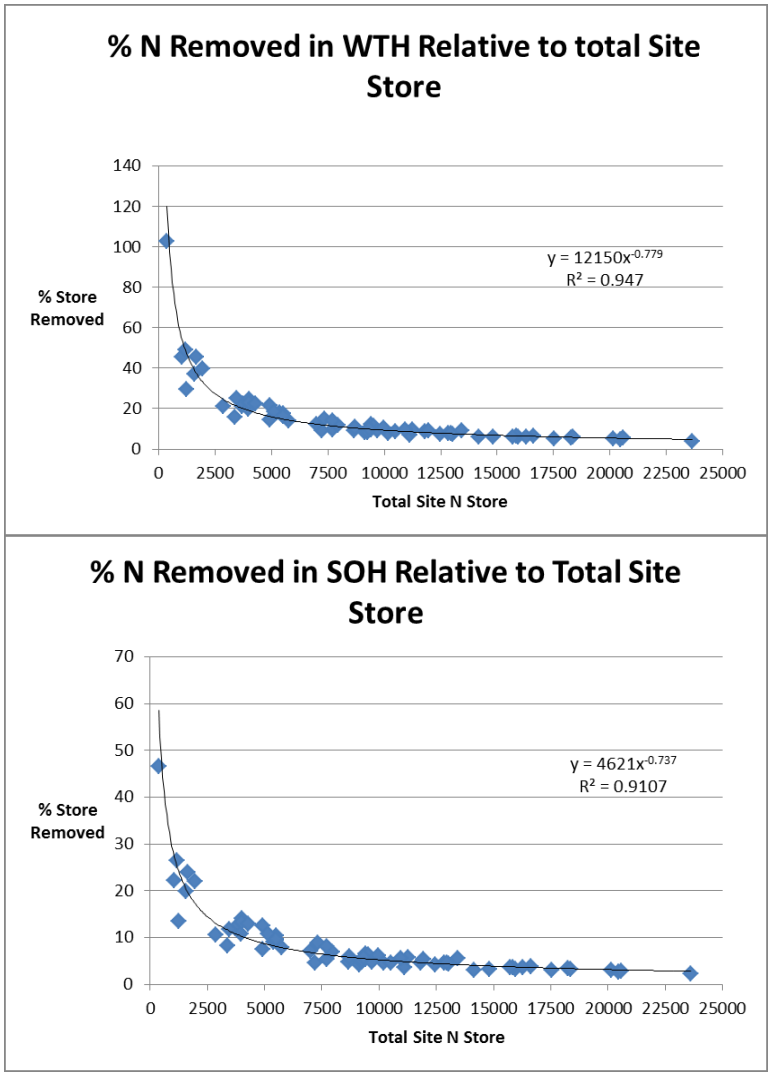

Figure 4. Percent of nitrogen removed vs. total site store for different harvest intensities. Percent Store Removed is equal to the stability ratio (SR)*100. Total site N store equals the total N in the mineral soil to one meter or impermiable layer plus the forest floor and is shown in units of kg/ha of N. The relationship of percent store removed to total site N store is significant for both stem-only harvesting (SOH) and whole-tree harvesting (WTH) with $p<0.01$ for both.

4. DISCUSSION

4.1 Biomass

The average and maximum resulting biomass for stemwood and TAB exceed all values found in other studies that evaluated stand level biomass and nutrient pools for similar aged trees. The minimum values estimated in this study, however, compare well with the lowest values found in other studies of Douglas-fir. Part of this discrepancy can be explained by the low site quality associated with most of the published numbers. Although Homann et al. (1992), and Bigger and Cole (1983) do not report the site class of the stands in their studies, they are likely very low quality sites based on the soil type (Inceptisol) and nutrient content reported (less than 3000 kg/ha of N). Turner (1980), is also likely on a low site class based on the soil N content reported, and the stand was also in Australia, outside the native Douglas-fir range which makes it difficult to compare to sites in the coastal PNW USA.

Both the Ranger et al. (1995) and Ponette (2001) studies were on stands growing in fertile soils, but there were no site indexes reported and the stands had very few trees/ha as a result of thinning, which would contribute to low total stand biomass at a specific age. The Ranger et al. (1995) and Ponette et al. (2001) studies were also conducted in France, outside of the natural range of Douglas-fir. The only in-region study on a higher productivity site was by Ares et al. (2007), and the stand has similar trees/ha, volume, and site index to the plot averages found in our simulations, yet the biomass estimates are much lower.

The discrepancy between our findings and Ares et al. (2007) can be explained by wood density. The specific gravity of stemwood in the Ares et al. (2007) stand (calculated by dividing the stemwood biomass by the volume of the stand and mass of water per unit of volume) is 0.36 for Douglas-fir and 0.30 for western hemlock. The western wood density survey (USDA, 1965) suggests the specific gravity of Douglas-fir for that area should be 0.43-0.45 and Miles and Smith (2009) report that the average wood density for Douglas-fir and western hemlock are 0.45 and 0.42 respectively. The smallest specific gravity found in the western wood density survey (USDA, 1965) for Douglas-fir was 0.33. Faster growing genetic stock, high occurrences of precipitation and fertilizer additions may account for the low specific gravity of the Ares. et al. (2007) site. However, Yoursy et al. (2011) measured the wood density of 32 year-old Douglas-fir with diverse genetics and a range of silvicultural treatments on site class I (King, 1966) stands in British Columbia and found specific gravity averaged 0.44 with a range of 0.34-0.54 which suggests that the range of values and mean specific gravity of the western wood density survey (1965) is reasonable for high quality sites, modern Douglas-fir strains, and intensive silvicultural practices. Gartner et al. (2002) also found specific gravity values close to 0.45 in 35 year old Douglas-fir from stands that had been thinned and fertilized. Kantavichai et al. (2010) found the mean specific gravity of 55 year-old Douglas-fir in western Washington treated with biosolids was 0.47 eleven years after application, while trees in the control group had a mean specific gravity of 0.51 for the same growth period.

These other studies suggest the specific gravity calculated for the Ares et al. (2007) study is very low for the region. If the Douglas-fir in the Ares et al. (2007) study had the average specific gravity for the region (0.45), the stemwood biomass would be 411 kg/ha which is similar to our average estimated stemwood biomass of 429 kg/ha.

Another contributing factor to the lower biomass estimates in the literature may be the methodology employed by other studies to calculate biomass. All the studies listed in Table 1 used a regression model with DBH as the only input to estimate the biomass of the stand. Homann et al.(1992) used Gholtz et al. (1979) for regional equations which Kantaviachai et al. (2010) found underestimated biomass by 45%. All the other studies except for Ares et al. (2007), developed site specific regression models to estimate biomass based on a subset of destructively sampled trees that were selected by DBH or basal area. Sampling by DBH or basal area and developing regression equations with DBH as the only input for estimating biomass assumes all trees with the same DBH will have the same biomass and ignores height variability (Kantaviachai et al., 2010), as well as variability in specific gravity resulting from silvicultural treatments.

There is also the potential that utilizing specific gravity values from the western wood density survey (1965) may be erroneous because of changes to Douglas-fir production. Improved genetic stock, silviculture, and fertilizer additions all result in faster growing trees (Talbert and Marshall, 2005). Climate change has altered

temperature and likely precipitation patterns over the same time (IPCC 2007). Age, growth rate, temperature, precipitation, and water balance changes over time all affect specific gravity (Kantavichai et al., 2010). However, exactly how these variables interact and the potential net effect on specific gravity is unclear, particularly on a regional scale. As stated above, contemporary studies on the specific gravity of Douglas-fir throughout the coastal PNW, over a range of site classes, genetics, and silvicultural regimes support the range of values found in the western wood density survey (1965). Since there is no other regional assessment of Douglas-fir wood density the western wood density survey (1965) is the best available source for estimates of specific gravity on this scale.

In most studies nitrogen content is estimated by multiplying the concentration of N in different sampled tree components by the biomass of each component. Similarly, our method of estimating kg/ha of N in TAB and stemwood was determined by a regression model that uses component biomass as an input (Augusto et al., 2000). Because our maximum biomass estimates are higher than those reported in the literature for reasons discussed above, our average and maximum N content was also higher than previously-reported estimates.

4.2 N export with SOH and WTH

If we assume that a site with an SR less than 0.1 is at low risk for N depletion or loss of productivity, the majority of the coastal PNW is at a low risk of damaging

site productivity with SOH. However, under WTH nearly half the plots in the study had SRs greater than 0.1 and 9% had SRs greater than 0.3, suggesting a possible decline in site productivity over time. It is important to note that SR's are a simplified method of assessing risk of productivity loss and have not been widely validated. A useful and conservative approach to SR is to consider further nutrient inventory on sites with SR greater than 0.1 before planning WTH for multiple rotations.

The spatial relationship of sites with higher SR seems to be related to soil age. Sites on less developed glacial soils are at a greater risk of losing productivity following intensive harvesting than sites on older soils in the region. The exception is in southern Oregon where there is a higher concentration of sites with elevated SR estimates that were not covered by glaciers during the last ice age. This area in southern Oregon does have a geological history distinct from the rest of the region with metamorphic and sedimentary parent material which may account for the anomalous concentration of higher SR estimates (spatial distribution patterns of SR estimates correspond to the strong relationship of SR with site stores since younger glacial soils have lower site N stores than older soils derived from sedimentary or igneous parent material). The correlation of SR with site stores of N also allows reasonable estimates of SR based on soil N content alone is significant because it gives land managers the power to predict the SR of a given stand planted at approximately 700 trees per hectare at harvest age 50-55 without having to run a growth and yield simulation.

4.3 What is the Nutrient Store?

When promoting SRs as a method to assess the risk of harvesting regimes, Evans (1999) emphasizes the difficulty of defining a "nutrient store." In this study the nutrient selected was N because it is the most commonly limiting nutrient for forests in the region. We defined the store as the total N in the mineral soil to a depth of 1m or an impenetrable layer plus the forest floor. The nutrient store could have been made larger if we included the N in the standing trees, understory, and roots. Likewise the total site store could have been made smaller by estimating the amount of N mineralized during a rotation rather than total N. A larger store would have resulted in smaller SR estimates for harvest removal and a smaller store would have resulted in larger estimates.

Because the goal of the study was to determine nutrient depletion risk under a plantation system with continuous rotations it did not seem appropriate to include standing tree N as part of the site store. Rather we considered it a temporary pool that is always going to be removed. For the SOH treatment the N content of limbs and foliage may have been added to the store, but for almost all the sites it was a very small amount compared to the soil pool and some of it is likely to be rapidly mineralized and leached following harvest (Ares et al. 2007). Roots were not included as part of the site store because there are no equations in the literature for estimating root N content that are not stand specific. A rough

calculation using Jenkins et al. (2003) biomass equations for coarse root biomass and the conservative assumption that roots have an N content proportional to their biomass compared to the whole tree results in no plots shifting below an SR of 0.1 for SOH or WTH. If roots and branches and foliage are added to the total site store for SOH, 5 plots that previously had SRs greater than 0.1 and the one SOH site that exceeded an SR of 0.3 fall below those thresholds.

4.4 Rotation Length

For this study a rotation length of 50-55 years was used. Many land managers in the region currently utilize shorter rotations, and the SR for a shorter rotation will be smaller for the same site. However, as previously discussed the risk of site degradation may increase with repeated shorter rotation periods because young trees are disproportionately rich in nutrients. This being the case it is difficult to compare different rotation lengths. One possibility is to divide the harvest export of N by the age of the stand at harvest to get annual N removal. This method is useful for comparing absolute N export, but not for assessing SRs. An alternative would be to divide N export at harvest by the ratio of the stand age to 50 years and then dividing by the site store to get an SR at 50 year harvest estimate. This method is easy to use and allows for a direct comparison of SR at different harvest ages, but should be used cautiously because trees at different stages of development affect N cycling differently. For example, young stands are thought to consume soil stores of nutrients while mature stands may depend more on

internal cycling to meet their nutrient demands and may actually contribute nutrients to a site over time (Ranger et al., 1995;, Turner, 1981; White and Harvey, 1979).

Nutrient balance methods have been employed in the past in this region to estimate N accumulation over time and could prove useful when considering rotation length. If the accumulation of N over a 50-55 year rotation is less than the quantity of N removed by harvesting at the end of a rotation the harvest method may not be sustainable indefinitely on the site. Annual inputs from atmospheric deposition and precipitation in the region are generally less than 3 kg/ha/yr of N and range from 1-10 kg/ha/yr N (Johnson et al. 1982; Gessel and Cole 1973; Grier, 1978). Plants with N fixing symbionts, most notably red alder, also contribute to annual inputs in the region. Red alder stands have been estimated to accumulate 41 to 321 kg/ha/yr of N (Tarrent and Miller, 1963; Newton et al 1968; Johnson et al. 1982). Additional N is fixed by free living N fixers and ranges from 0.01-12 kg/ha/yr of N in temperate forests (Reed et al., 2011). The only major loss of N besides harvest export on these sites is leaching. Gessel and Cole (1973) found annual leaching of N below the rooting zone was 0.6 kg/ha/yr, and Strahm et al. (2005) found annual leaching rates were as high as 4.5 kg/ha in an intact Douglas-fir stand on a higher quality site.

The largest percentage of species in any stand that is not Douglas-fir in this study is 18%, and if we assume that all trees that are not Douglas-fir are red alder and

assume N accumulation by red alder is 181 kg/ha/yr, the middle of the range reported in the literature, then the maximum accumulation of N by red alder in any of these stand would be 33 kg/ha/yr. If we add the highest estimate of atmospheric input (10kg/ha/yr) and free living N fixation (12 kg/ha/yr) the total annual N input would be 55 kg/ha. With this high input rate we also assume a high leaching rate and subtract 4.5 kg/ha/yr of N for a total of 50.5 kg/ha/yr which multiplied by a 55 year rotation equals a total rotation length accumulation of 2700 kg/ha of N. Conversely, if we use the conservative estimate of N accumulation proposed by Gessel and Cole (1973) of 1.1 kg/ha/yr and subtract the low leaching rate of 0.6 kg/ha/yr of N and multiply by a 55 year rotation it yields a low estimate of about 30 kg/ha of N accumulating during one rotation. Therefore, a reasonable estimated range of N accumulation during a 55 year rotation for the region based on published studies would be 30 to 2700 kg/ha. This large range demonstrates the difficulty of applying nutrient balance methods to a regional scale model.

The range of N accumulation estimated above using nutrient balance methods and N input and leaching values from previous studies does support the SR risk assessment used in this study. If ten percent of total site N stores are calculated for all sites in this study the range of those values is 38 to 2364 kg/ha which is similar to the range of N accumulation in the region estimated above to be 30 to 2700 kg/ha. This suggests that it is reasonable to expect the equivalent of 10% of a site's N store in this region to accumulate in 55 years meaning that harvest

systems with an SR of 0.1 or less would be sustainable indefinitely, at least in terms of site N stores. There is, however a large amount of uncertainty and variability in N accumulation. A useful and conservative approach may be to consider further nutrient inventory on sites with SR greater than 0.1 before planning WTH for multiple rotations.

4.5 Harvest Effects

There are other sources of N loss following harvestinf besides the removal of N in trees. Nitrification and leaching can increase following clear-cut harvesting in the region and the amount of N lost from the site depends largely on harvest methods and site preparation (Johnson and Curtis, 2001; Grigal, 2000). For example, losses of site N can also occur through soil erosion which can increase following harvests. If slash is burned after SOH, a large portion of the N conserved using SOH over WTH can be lost. Likewise, broadcast burning can increase N loss if it is hot enough to volatilize N in the forest floor or mineral soil (Nambiar, 1996).

4.6 Fertilization

Adding fertilizer has been suggested as a means of preventing site degradation from increased nutrient export associated with WTH (Fox, 2000; Malkönen, 1976). In the coastal PNW, N fertilization with urea to increase growth is a widely

established practice (Footen et al., 2009). Microbial uptake, leaching loss and volatilization results in fertilizer N uptake of 6-30% for Douglas-fir in the region (Mead, 2008). The low uptake efficiency of Douglas-fir suggests that fertilizer N addition may need to be greater than the N removed by harvest to maintain productivity on sites experiencing N depletion. Some researchers have concluded fertilizer N is transient and has no effects after 5-10 years (Binkley, 1986; Miller, 1988), but a recent study in western Washington Douglas-fir shows that some heavily fertilized stands showed increased productivity in the following rotation (Footen, 2009). Additions of N fertilizer will likely make it possible to maintain production on a site that has experienced N depletion, but whether it is an effective means of restoring or augmenting site N pools (and the necessary rates of fertilizer application) remains uncertain.

5. CONCLUSION

Using the ORGANON growth and yield simulator in combination with biomass and nutrient content equations we developed a method of estimating N export under different harvest intensities. This method is easily replicated for a specific site with basic stand information that most land managers already have or can acquire inexpensively. The method was applied to 68 Douglas-fir stands throughout the coastal PNW to provide a regional analysis of risk based on site stability ratios for N depletion and productivity loss associated with WTH and SOH. Conclusions from this study include:

- There is generally a low risk of N depletion or productivity loss with SOH, but nearly half the plots had some risk of N depletion or loss of productivity with WTH as indicated by an SR greater than 0.1.
- Stands with elevated risk of N depletion or productivity loss tend to be concentrated on young glacial soils of B.C and the Puget Sound region.
- Based on the strong relationship of total site N to SR, it is predicted that sites with greater than about 9000 and 4000 kg/ha N are at low risk of productivity loss or N depletion throughout the region with WTH and SOH respectively.
- Rotation length, harvesting methods, and site preparation can have effects on N losses and should be considered in conjunction with harvest intensity.
- Fertilization may be a viable means of maintaining site productivity and nutrient stores under WTH regimes, but it may necessary to fertilize at a higher rate or more often than currently practiced.

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Appendix 1.

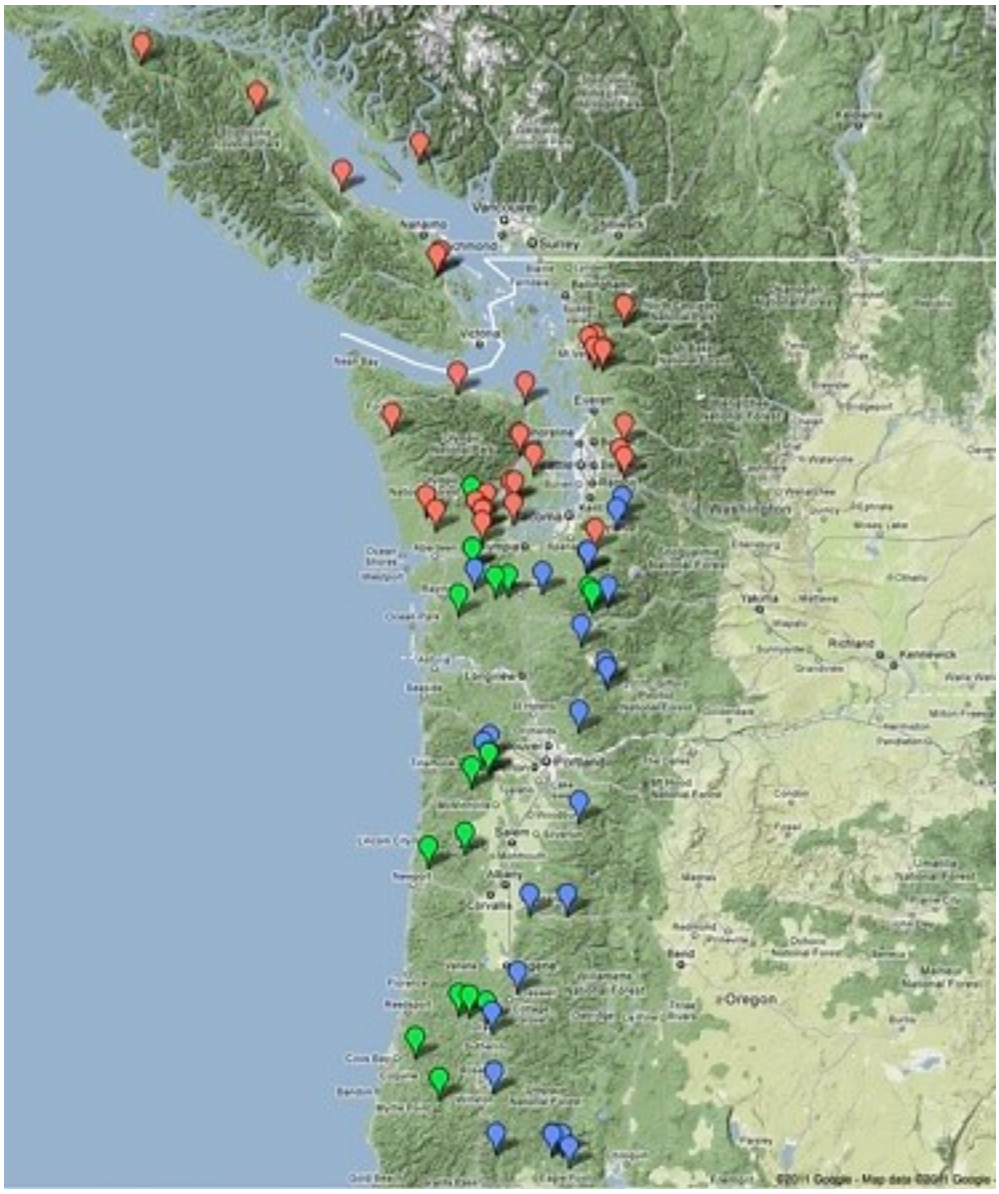

Figure A1. Map of the original 71 stands from the Littke et al. (2011) study. Red markers indicate glacial parent material, blue markers indicate igneous parent material, and green markers indicate sedimentary parent materials.

Appendix 2.

Table A2. Site characteristics for the 68 stands

STAND	BH AGE 2011	Bruce SI	Trees/ha	Total Site Store of N (kg /ha)	Stand Volume (m^3/ha)
822	26	126	844	9128	777
823	21	147	692	8706	1004
824	19	131	744	11122	798
825	16	122	734	12463	874
826	17	111	846	7730	697
827	19	133	612	12845	987
828	19	139	758	7948	1035
829	18	147	736	11809	1221
830	19	142	595	18262	1105
833	19	117	719	8656	797
834	16	113	986	7220	641
835	19	151	627	11253	1193
836	16	150	608	16625	1192
837	19	168	601	7338	1183
838	21	125	758	3715	792
839	20	140	588	3747	820
840	21	124	708	9273	751
841	22	138	844	15949	948
842	16	136	728	15864	1014
843	18	127	679	23638	903
844	16	137	746	15713	979
845	14	135	680	20130	1058
847	19	161	662	9426	1184
848	25	147	579	9408	874
849	22	147	931	3444	896
850	30	121	953	1656	742
851	26	97	1092	375	412
852	22	119	690	14167	892
853	24	138	353	4008	638
854	22	117	834	1950	775
855	19	128	717	6999	914
856	19	117	748	10188	829
857	25	142	571	4928	715
858	20	144	535	4922	1061
859	22	126	712	3958	741
860	22	134	799	8712	955

861	25	148	629	5372	1040
862	24	154	439	5524	1003
863	25	162	440	11945	1112
864	22	152	700	20471	1167
865	20	143	561	13039	1048
866	26	127	695	5746	830
867	19	133	521	4001	931
868	16	141	754	5146	1027
869	22	151	662	9531	1150
870	24	145	696	14824	953
871	21	158	792	18358	1251
872	27	142	545	4285	982
873	19	133	672	9683	934
874	22	143	643	16285	1048
875	17	155	658	20578	1271
876	17	130	833	10504	979
877	24	124	584	5511	841
878	20	122	682	9253	782
879	19	145	527	10940	997
880	19	135	758	17526	1042
881	21	153	573	9347	974
882	19	144	636	9961	1071
883	18	101	679	1575	546
884	21	85	785	1234	310
886	14	101	747	3386	491
887	21	137	674	5510	938
888	16	143	754	12962	1167
889	22	89	1278	2860	564
890	22	90	638	1038	409
891	8	156	616	13439	1381
892	18	150	747	7702	1133
893	19	96	542	1188	519

Appendix 3.

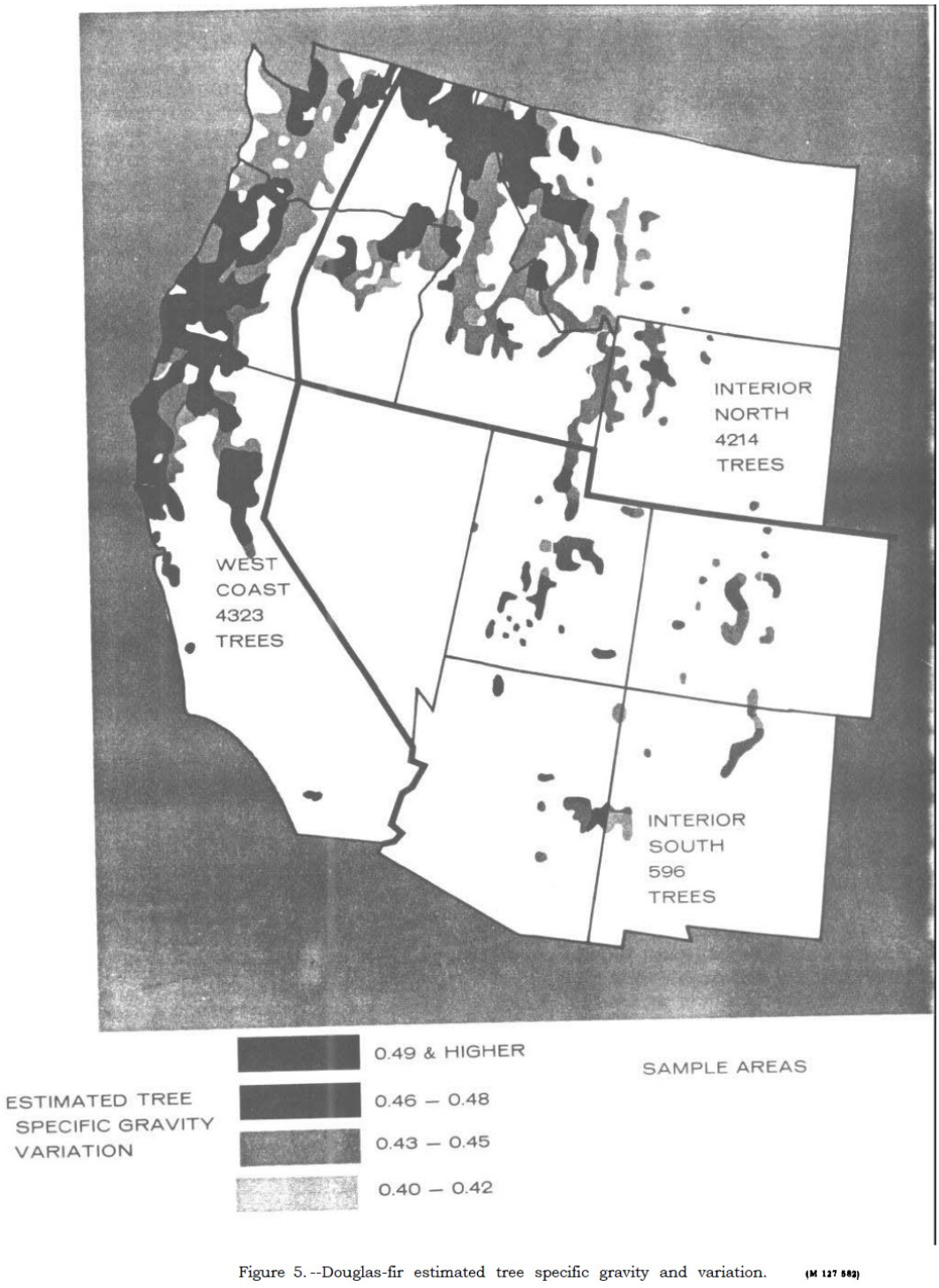

Figure 5.--Douglas-fir estimated tree specific gravity and variation. (M 127 582)

Figure A3. Western wood density survey map showing regional variation in Douglas-fir specific gravity (USDA, 1965).

Appendix 4

Table A4. Jenkins et al. (2003) equations for estimating component biomass.

Table 6. Parameters and equations* for estimating component ratios of total aboveground biomass for all hardwood and softwood species in the United States.

Species class	Biomass component	Parameters β_0	Parameters β_1	Data points†	R^2
Hardwood	Foliage	–4.0813	5.8816	632	0.256
	Coarse roots	–1.6911	0.8160	121	0.029
	Stem bark	–2.0129	–1.6805	63	0.017
	Stem wood	–0.3065	–5.4240	264	0.247
Softwood	Foliage	–2.9584	4.4766	777	0.133
	Coarse roots	–1.5619	0.6614	137	0.018
	Stem bark	–2.0980	–1.1432	799	0.006
	Stem wood	–0.3737	–1.8055	781	0.155

* Biomass ratio equation:

$$ratio = \mathrm{Exp}(\beta_0 + \frac{\beta_1}{dbh})$$

where

ratio = ratio of component to total aboveground biomass for trees 2.5 cm dbh and larger

dbh = diameter at breast height (cm)

Exp = exponential function

ln = log base e (2.718282)

† Number of data points generated from published equations (generally at 5 cm dbh intervals) for parameter estimation.

Appendix 5.

Table A5. Specific gravity of other species on site and averages for softwoods and hardwoods taken from Miles and Smith (2009).

Hardwoods		Softwoods	
Species	SG	Species	SG
Red Alder	0.37	Western Red Cedar	0.31
Bigleaf Maple	0.44	Western White Pine	0.36
Pacific Dogwood	0.58	Ponderosa Pine	0.38
Pacific Madrone	0.58	Pacific Yew	0.60
Oregon Ash	0.50	Western Hemlock	0.42
Chinkapin	0.42	Sitka Spruce	0.33
Black Cottonwood	0.31	Grand Fir	0.35
		Pacific Silver Fir	0.40
Average	0.457	Average	0.393

Appendix 6

Table III. Relation between biomass and nutrient amount.

Table IIIa. Douglas fir

NUTRIENT (kg ha^{-1})	Total Aerial Biomass (TAB) (t ha^{-1})					Stem Biomass including Bark (SBB) (t ha^{-1})				
	a	*b*	*r*	*p*	*n*	*a*	*b*	*r*	*p*	*n*
N	1.456	+ 46.0	0.90	< 0.001	26	1.237	– 35.4	0.87	< 0.001	20
P	0.135	+ 34.5	0.40	0.07	26	0.175	– 4.9	0.67	< 0.01	20
K	0.680	+ 63.0	0.74	< 0.001	26	0.615	+ 3.8	0.79	< 0.001	20
Ca	0.952	+ 96.1	0.71	< 0.001	22	0.983	– 34.6	0.76	< 0.001	18
Mg	0.168	+ 10.2	0.65	< 0.01	21	0.138	– 4.2	0.76	< 0.001	17

a and *b* from the equation: (nutrient amount) = ($a \times$ biomass) + *b*.

Figure A6. Augusto et al. (2000) equation used to estimate the N content of total aboveground biomass and stemwood+bark for whole-tree harvest and stem-only harvest respectively. Correlation coefficient (r), p-value, and sample size used to develop the regressions are also listed.

Appendix 7.

Table A7. Biomass, N removal and stability ratio (SR) estimates for all plots

Plot #	TAB (Mg/ha)	STEMS (Mg/ha)	Corse Roots (Mg/ha)	WTH N Removal (kg/ha)	SOH N Removal (kg/ha)	WTH SR	SOH SR
822	476.7	339.8	101.8	740.0	384.9	0.00	0.04
823	614.2	449.1	130.5	940.3	520.1	0.11	0.06
824	502.3	349.6	107.0	777.3	397.1	0.07	0.04
825	583.6	449.1	124.7	895.8	520.2	0.07	0.04
826	482.4	360.3	102.9	748.4	410.3	0.10	0.05
827	646.7	495.4	137.8	987.6	577.4	0.08	0.04
828	613.0	467.1	130.8	938.6	542.4	0.12	0.07
829	674.0	465.2	142.7	1027.4	540.1	0.09	0.05
830	672.2	521.1	143.4	1024.8	609.2	0.06	0.03
833	513.5	356.9	109.3	793.6	406.1	0.09	0.05
834	415.1	291.4	88.9	650.4	325.1	0.09	0.05
835	706.0	545.8	150.6	1074.0	639.7	0.10	0.06
836	706.9	546.0	150.7	1075.3	640.0	0.06	0.04
837	714.3	547.5	152.3	1086.0	641.9	0.15	0.09
838	509.7	387.4	109.0	788.2	443.9	0.21	0.12
839	541.8	394.1	115.7	834.9	452.1	0.22	0.12
840	501.6	382.8	107.3	776.3	438.2	0.08	0.05
841	603.3	442.7	129.0	924.4	512.2	0.06	0.03
842	646.7	496.6	138.1	987.6	578.9	0.06	0.04
843	600.2	463.7	128.3	919.9	538.2	0.04	0.02
844	624.7	480.7	133.5	955.5	559.2	0.06	0.04
845	672.6	520.2	143.7	1025.3	608.1	0.05	0.03
847	747.8	525.5	159.4	1134.7	614.7	0.12	0.07
848	578.3	431.5	123.2	888.0	498.3	0.09	0.05
849	558.2	355.0	118.3	858.8	403.8	0.25	0.12
850	483.6	349.4	103.3	750.1	396.8	0.45	0.24
851	277.2	204.4	59.5	384.8	174.5	1.03	0.47
852	556.9	381.9	118.9	856.8	437.0	0.06	0.03
853	645.3	484.0	83.0	985.6	563.3	0.25	0.14
854	498.3	374.4	106.4	771.5	427.7	0.40	0.22
855	563.4	424.3	120.2	866.3	489.5	0.12	0.07
856	525.9	399.2	112.2	811.7	458.5	0.08	0.04
857	450.2	327.9	96.0	701.5	370.3	0.14	0.08
858	692.1	522.5	147.5	1053.8	611.0	0.21	0.12
859	500.4	374.0	106.8	774.6	427.2	0.20	0.11
860	590.4	425.0	125.7	905.6	490.3	0.10	0.06

861	639.0	421.6	135.3	976.3	486.1	0.18	0.09
862	641.4	495.3	136.6	979.8	577.3	0.18	0.10
863	705.7	548.3	150.3	1073.5	642.9	0.09	0.05
864	649.5	462.3	138.8	991.7	536.5	0.05	0.03
865	639.8	496.4	136.4	977.5	578.6	0.07	0.04
866	518.7	393.5	110.7	801.2	451.3	0.14	0.08
867	591.9	460.6	126.1	907.8	534.3	0.23	0.13
868	616.8	476.0	131.9	944.0	553.4	0.18	0.11
869	695.7	511.5	148.1	1059.0	597.4	0.11	0.06
870	574.4	415.7	121.9	882.4	478.8	0.06	0.03
871	738.6	506.5	157.1	1121.5	591.2	0.06	0.03
872	633.8	476.0	135.0	968.8	553.4	0.23	0.13
873	572.5	402.4	121.6	879.5	462.3	0.09	0.05
874	660.0	507.9	140.9	1007.0	592.9	0.06	0.04
875	724.0	483.2	154.3	1100.2	562.4	0.05	0.03
876	577.3	420.0	123.2	886.5	484.1	0.08	0.05
877	579.8	449.1	123.8	890.1	520.1	0.16	0.09
878	531.2	409.9	113.6	819.4	471.6	0.09	0.05
879	674.7	522.1	143.7	1028.4	610.4	0.09	0.06
880	610.5	453.5	129.9	934.8	525.5	0.05	0.03
881	598.8	459.6	127.8	917.9	533.1	0.10	0.06
882	677.1	523.8	144.6	1031.9	612.5	0.10	0.06
883	370.4	280.7	79.3	585.3	311.8	0.37	0.20
884	220.0	162.4	47.3	366.3	165.4	0.30	0.13
886	332.7	255.0	71.3	530.5	280.1	0.16	0.08
887	586.3	454.0	125.2	899.7	526.2	0.16	0.10
888	664.5	503.4	142.0	1013.6	587.3	0.08	0.05
889	378.3	274.8	81.4	596.9	304.5	0.21	0.11
890	292.1	214.6	62.3	471.3	230.1	0.45	0.22
891	804.7	624.5	171.7	1217.6	737.1	0.09	0.05
892	698.6	531.3	149.1	1063.2	621.9	0.14	0.08
893	367.0	283.4	78.4	580.3	315.2	0.49	0.27