SUSTAINABLE FEEDSTOCK PRODUCTION

Authors	ORGANIZATION
Doug Maguire	Oregon State University College of Forestry — Oregon State University
Doug Mainwaring	Oregon State University College of Forestry — Oregon State University
David Hann	Oregon State University College of Forestry — Oregon State University
Andrew Bluhm	Oregon State University College of Forestry — Oregon State University
Kristin Coons	Oregon State University College of Forestry — Oregon State University

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AGB	Above Ground Biomass
Bark	Tree-level bark biomass (kg)
BH	breast height (1.37 m)
BL	“Clear” bole length (Ht-CL)
BN	“Beyond Nitrogen” fertilization trials
BO	Bole only harvest scenario
BrD	Branch diameter (mm)
CB	Crown base
CIPS	Center for Intensive Planted-forest Silviculture (Oregon State University)
CL	Live crown length (m)
CR	Live crown ratio (CL/Ht)
Deadmass	Branch-level dead branchwood mass, wood + bark (g)
DBRW	Tree-level dead branchwood mass, wood + bark (kg)
DBH	Tree diameter at breast height (cm)
DINC	Depth into crown (m)
FOL	Tree-level foliage biomass for a given age class of needles (kg)
folp	Tree-level proportion of foliage mass above height h in the tree
GCM	Global Circulation Models
h	Arbitrary h on the tree (0≤h≥Ht)
HLLB	Height to the lowest live branch (m)
Ht	Total tree height (m)
HRWD	Tree-level heartwood biomass (kg)
LBRW	Tree-level live branchwood mass, wood + bark (kg)
Mass	Biomass of a given tree component (kg)
Merch	Harvest scenario removing only merchantable portion of tree with some associated branches
N	Nitrogen
NADP	National Atmospheric Deposition Program (NADP)
NARA	Harvest scenario that removes entire bole plus 66% of branchwood that does not break off during felling and yarding
rdinc	Relative depth into crown ([Ht-DINC]/CL)
RHACB	Relative height above crown base
RSAP	Tree-level sapwood biomass as a proportion of total stem biomass, inside bark (TSib)
SMC	Stand Management Cooperative (University of Washington)
SPWD	Tree-level sapwood biomass (kg)
TSib	Total main stem biomass inside bark (kg)
woodp	Tree-level proportion of woody mass above height h in the tree
WT	Whole tree harvest scenario

EXECUTIVE SUMMARY

Any assessment of the suitability of using forest residuals as a feedstock for a regional biofuels industry must take account both the ability of the region to produce an adequate supply of feedstock in the short term, but also the likelihood of maintaining the region's productive capacity to continue providing that supply of feedstock in the long term. In the context of NARA, sustainable supplies of feedstock depend on projected levels of timber harvesting, continuation of harvesting methods that ensure that the location and spatial distribution of logging residues does not change dramatically, and continued levels of forest growth and yield that generate approximately the same amount and quality of timber and associated logging residues well into the future. Sustainability of forest growth, yield, and general net primary production of managed forest ecosystems depends to a large extent on the long-term balance between removals of nutrients in harvested biomass (both timber and logging residuals), unutilized biomass removed from the site in the process of yarding timber, decomposed/recycled inputs from logging residuals left on site, potential leaching losses during the period of vegetation recovery, and inputs from dry and wet atmospheric deposition, weathering of parent material, and biological fixation of atmospheric nitrogen. The phase of the NARA project reported on here does not address predicting trends in timber harvest levels or harvesting methods, but does quantify biomass and nutrient removals under various utilization intensities in westside Douglas-fir forests and compares these removals to estimates of current nutrient pools and best available estimates of natural rates of nutrient replenishment.

The first step involved in our assessment of long term sustainability was construction of improved allometric biomass equations for trees growing in units representative of the intensively managed stands constituting the major source of the westside timber harvest. The second step required nutrient analysis of the biomass components included in these equations, enabling a more accurate estimation of the quantity of biomass and nutrients removed under any level of harvest intensity. In the third step we gleaned previously published estimates of the nutrient inputs and outputs associated with managed forest ecosystems of the region, generally concluding that there is little evidence that the proposed utilization intensity of forest residuals poses a threat to long term aboveground productivity of managed Douglas-fir ecosystems and hence to the long term supply of biofuel feedstock. While there is some evidence that relatively high removals of calcium from some calcium-poor coastal soils may be a concern under the most intensive removal of harvest residuals, evidence from other studies identifying similar potential calcium deficiencies have not found evidence of diminished productivity. Finally, speculation of changes in long term productivity due to climate change range from a scenario predicting a complete failure of Douglas-fir to survive across much of its current range, to a scenario which estimates a limited (<9%) reduction in Douglas-fir productivity by the end of the century.

INTRODUCTION

Sustained long term productivity of the region's forests is a pre-requisite for the establishment of a biomass energy industry reliant on logging residuals produced during the course of conventional timber harvesting. Determination of the forest's ability to produce residuals of a sufficient quantity and quality has necessitated a quantitative approach, incorporating newly constructed equations to provide estimates of the current and future supply of harvestable aboveground tree biomass using standard measurements found in operational forest inventories. Because of limited data in regard to nutrient fluxes across the highly variable landscape of western Oregon and Washington, and to the effects of a changing climate upon future conditions, it is necessary to be conservative in attempting to answer questions about the region's continued productivity. In this phase of NARA research, we provided a framework to assess natural fluxes and climate change effects so that as new data become available, the context and consequences of our relatively accurate estimates of nutrient removals can be improved.

TASK 1: DEVELOP ALLOMETRIC EQUATIONS FOR MANAGED STANDS

Task Objective

In a recent effort to investigate the practicalities of converting post-harvest forest residuals into liquid biofuels, the Northwest Advanced Renewables Alliance (NARA) has funded the construction of new allometric biomass equations for intensively managed Douglas-fir west of the Cascade Mountain crest (NARA, 2016).

Estimation of potential feedstock supplies in westside Douglas-fir forests requires that biomass equations and nutrient concentrations represent the population of trees and stands typical of timber harvest. According to the Oregon Forest Resources Institute, nearly 80% of the Oregon timber harvest in 2015-2016 was from private land, with 66% of the total harvest from large private landowners. Surveys among industrially owned forestland indicate that land management is increasingly intensive on these ownerships (Briggs 2007). Any accurate estimate of available biomass must be based on trees sampled from across the region and from stands subjected to these practices. In short, these harvested trees are younger and represent a wider range of diameter, height, and crown length combinations than natural stands for which earlier biomass equations were constructed.

Due to the more limited range of diameter/height/crown length combinations typical of natural stands, earlier estimates of tree biomass components were adequately achieved by developing equations using tree diameter as the sole predictor variable. Because height and diameter were so closely correlated in unmanaged stands, the resulting biomass estimates provided sufficient accuracy for many types of ecosystem dynamics studies. However, application of equations developed for unmanaged stands can introduce potentially extreme bias when used in stands that are actively managed under widely varying stand density regimes, silvicultural treatments, and resulting height-diameter relationships (Harrison et al., 2009; Kantavichai et al., 2010). Diameter therefore becomes an insufficient descriptor for partitioning biomass among component parts, given that allocation depends upon crown length and total tree height, which are not so closely correlated with diameter among stands of varying density. In addition, variables such as other aspects of stand structure, climate, nutrient availability, and management history can also cause significant shifts in allometric relationships between biomass components and tree diameter (Poorter et al. 2012). Potential biofuel feedstock will almost certainly come from branches and tops left over after conventional timber harvest, which are allometrically dependent on the management history of the trees and stands (Weiskittel et al., 2007). These recognized shortcomings of current biomass equations necessitate new biomass equations targeting the intensively managed stands most likely to supply biofuel feedstock. Biomass sampling of coastal Douglas-fir in the Pacific Northwest was undertaken across as wide a range in tree diameter, height, and crown length (D-H-CL) combinations that could be found on research trials testing tree growth responses to fertilization, thinning, and competing vegetation control, and on operational units that were a necessary source of larger trees but still under active and varied management regimes. Given that the mission of silvicultural research is most often to test the limits of treatment regimes, the resulting NARA sample provided a wider distribution of D-H-CL combinations than is typical of only operational stands managed under a narrower range of regimes.

Methodology

Field work

A total of 227 trees were sampled from 24 stands, covering a range in geography (Figure PS-1.1), allometry (Figures PS-1.2 and PS-1.3), and management history (thinning, fertilization, and early competing vegetation control). The 24 sites included research installations (15) and operational timberlands (9), and were distributed from 42.80° to 47.20° N latitude, from 123.98° to 121.67° W longitude, and from 140 to 790 m above sea level.

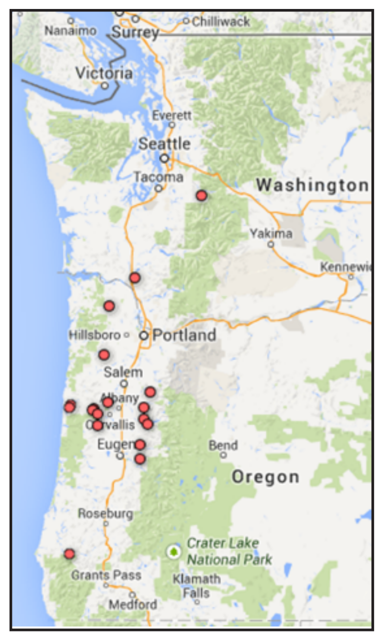

Figure PS-1.1. Site locations for biomass sampling

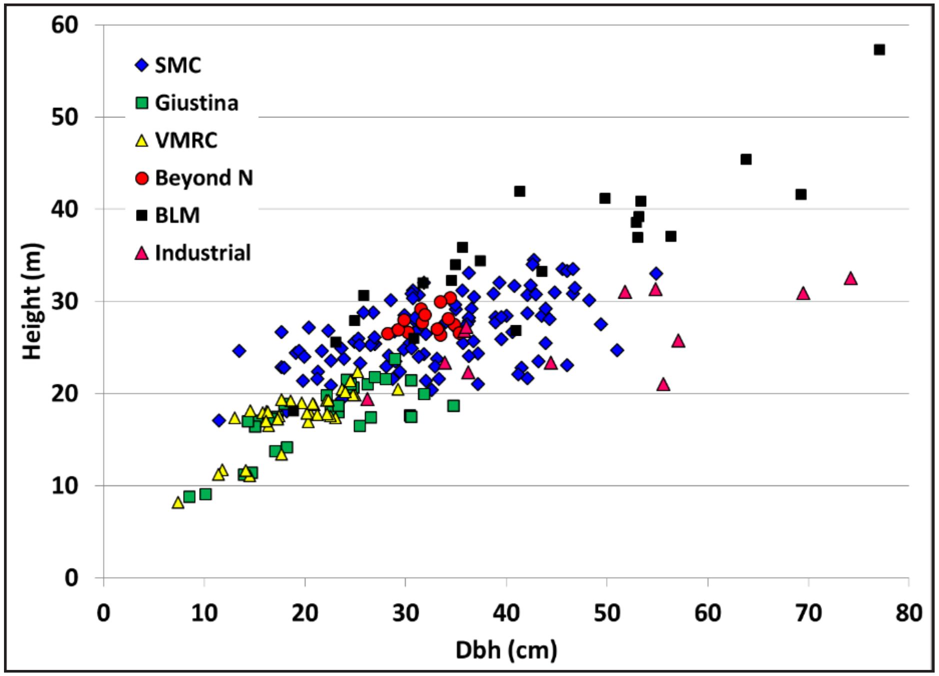

Figure PS-1.2. Relationship between DBH and Ht for sample trees

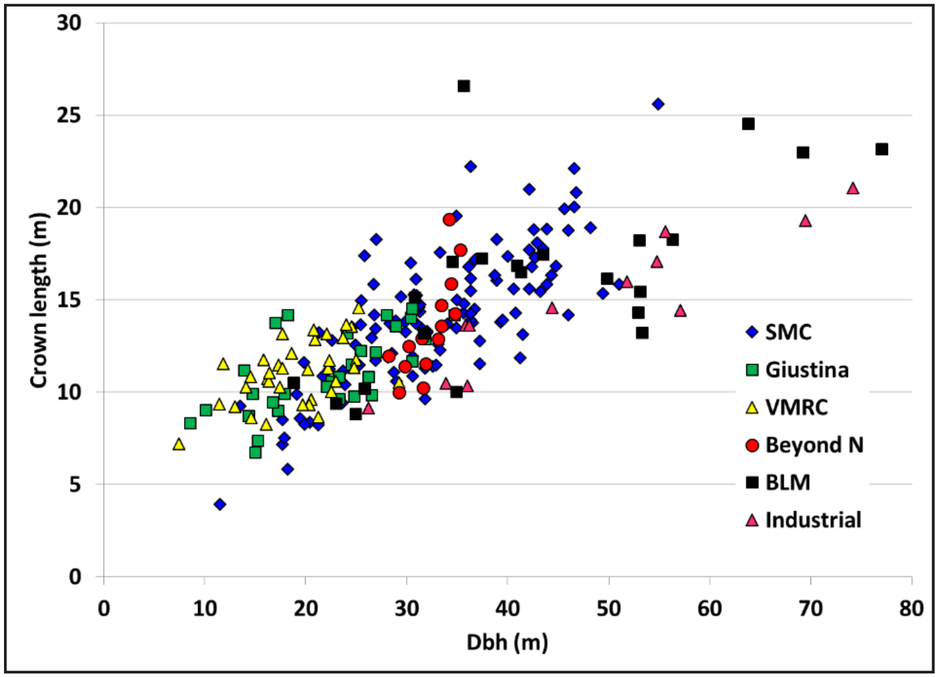

Figure PS-1.3. Relationship between DBH and CL for sample trees

Most of the trees (183) were sampled following the same protocol. Specifically, within a stand/treatment unit, three undamaged trees were chosen to correspond to the 10th, 50th, and 90th percentiles of the diameter distribution. After trees were felled, they were measured for diameter at breast height (DBH; nearest 0.1 cm), total height (Ht; nearest 0.01m), and height to the lowest live branch (HLLB; nearest 0.01m). The height (nearest 0.01 m) and diameter (nearest 0.1 mm) of all live branches were recorded. Eight live sample branches were randomly removed (flush with the bole), with probability proportional to frequency over two branch diameter strata and three crown position strata. In the top and middle third of the crown, two branches >15 mm diameter and one branch with diameter between 5 and 15 mm were sampled. In the bottom crown third, one branch >15 mm diameter, and one branch with diameter between 5 and 15 mm were sampled. If a branch of the specified size class was not available within the crown-third, a replacement was chosen regardless of size. All sampled branches were measured for total length and non-foliated length in field.

In addition to the eight sample branches removed from each tree, the southernmost branch in the whorl above crown mid-point (FB-foliage nutrient branch) was collected for determination of foliar chemistry, branch bark thickness, and branchwood density.

On all 90th percentile trees (and four 10th percentile trees)), the height (nearest 0.01 m) and diameter (nearest 0.1 mm) of all dead branches were recorded. Four dead branches were removed for biomass determination, two each from the lower and upper halves of the “clear” bole from breast height to live crown base. One dead branch was >15 mm diameter and one was between 5 and 15 mm. On the 9 plots of the Silver Creek SMC site, six dead branches were sampled from each 50th percentile tree, 2 branches > 15mm diameter and one between 5 and 15 mm in each half of the clear bole.

Four disks were cut from each tree at the following heights tree to sample heartwood, sapwood and bark density and chemistry: 1) Breast height (BH); 2) Mid-bole (mid-point between BH and live crown base); 3) Ten cm below crown base (CB) (lowest live branch contiguous with rest of live crown); and 4) Mid-crown (halfway between crown base and tree tip). All branches and disks were stored in a refrigerator until they could be processed.

Because the Beyond Nitrogen (BN) plots were from installations where fertilizer treatments were applied to individual tree plots, chosen sample trees were necessarily all dominant/co-dominant, and divided between N-fertlized trees and unfertilized trees. Otherwise, sampling procedures were unchanged.

Because the 30 Giustina trees were sampled as part of another study, they were subjected to a slightly different sampling procedure. For those trees, a total of six sample branches were collected, two from each crown third, with probability proportional to branch diameter basal area. In addition, only two stem disks were cut, one at BH and one at CB.

Lab work

All sample branches were cut into separate annual shoots and stored in paper bags. Bags containing foliage and twigs were then dried at 70° C for 3-5 days. After foliage and twigs were separated, samples were re-dried at 70° C for 24 hours, and then weights were recorded separately for foliage and wood by age class.

Disks were measured for outside bark diameter with a dbh tape. Inside bark diameter was measured twice (nearest mm) on two perpendicular axes, and sapwood width was measured four times (nearest mm) on the same axes. Disks were then split into wedges, and further into bark-sapwood and heartwood. Density of each was determined using the water displacement method (Olesen, 1971), with the volume of the bark determined from the difference between the volume of the bark-sapwood and the sapwood after removing the bark. The three separate wood samples were then dried at 70°C for 5 days and weighed.

Nutrient analysis

Nutrient analysis was performed on dried and ground tissues of the following six aboveground components: 1) Foliage (further separated into one, two, and three year old needles) from the largest four-yr-old secondary branch on the FB; 2) Live branchwood (wood+bark) from the largest of the middle crown-third branches; 3) Dead branchwood (wood+bark) from both the small sampled dead branch of the lower bole half and the large sampled dead branch of the upper bole half; and 4) Heartwood, sapwood, and bark from the mid-bole disk.

Calculations

Stem mass

Total tree volume and bark volume were estimated by applying an existing taper equation (Walters and Hann, 1986), a bark thickness equation (Maguire and Hann, 1990), and Smalian's formula to compute the component volumes of the four stem sections whose end points were delineated by the midpoints between the heights of the stem sample disks.

Heartwood volume was determined first by applying a heartwood taper equation (Maguire, 2014) that included estimated height of the heartwood core of the stem. Sapwood volume was calculated as (total stem volume inside bark) – (heartwood volume). To estimate mass, the volumes of heartwood, sapwood, and bark computed as described above were multiplied the density of the heatwood, sapwood, and bark of the disk cut from the center of each segment.

Foliar and Live branch mass

The branch-level regressions for foliage by age class (1 yr, 2 yr, and 3+ yr) and for total branchwood mass were fitted separately by site, using a regression equation with the following form:

$$[1] \quad \ln(X)=a_0 + a_1 \cdot \ln(BrD) + a_2 \cdot \ln(DINC) + a_3 \cdot \ln(RHACB)$$

where:

X	=	Foliage mass (g) or branchwood mass, wood + bark (g)
BrD	=	Branch diameter (mm)
$DINC$	=	Depth into crown (m)
$RHACB$	=	Relative height above crown base

Once fitted, these equations were applied to all recorded live branches within each tree and summed to estimate total foliage mass by age class and total branchwood mass (wood+bark).

Dead branch mass

The branch data regressions were fit separately by site, using a regression equation with the following form:

$$[2] \quad \ln(Deadmass)=b_0 + b_1\ln(BrD) + b_2\ln(RHAB)$$

where:

$Deadmass$	=	Dead branchwood mass, wood + bark (g)
BrD	=	Branch diameter (mm)
$RHAB$	=	Relative height above tree base

Once fitted, these equations were applied to all recorded dead branches within each tree.

Weighted regression equations predicting tree-level biomass by tree component were fitted using two methods, resulting in two sets of equations. In the first method, equations for directly predicting biomass were developed by applying least squares regression procedures to estimate the parameters of model forms limited to DBH, Ht, and crown length (CL) (equation [3]). These were selected to fully characterize the variability in tree allometrics resulting from intensive management. This simple model form was also the basis for testing whether silvicultural treatment was a significant factor accounting for additional variability in biomass not accounted for by treatment effects on these basic tree dimensions. Final models were selected using a combination of visual assessment of residual plots, and minimization of Furnival's (1961) index. The parameters of the entire system of biomass equations were also constrained to give estimates of total biomass that were consistent with the sum of the components (Parresol, 2001). Therefore, the parameter estimates of the component equations were not necessarily the least squares estimators if the equations had not been so constrained.

[3] $$Mass = c_0 \cdot DBH^{c_1} \cdot Ht^{c_2} \cdot \exp\,(Ht \cdot c_3) \cdot CL^{c_4}$$

where:

Mass	=	Predicted biomass (kg) for given component
DBH	=	Measured tree diameter at breast height (cm)
Ht	=	Measured tree height (m)
CL	=	Measured live crown length (m)

In the second method, equations were constructed without this constraint (equations [4]-[11]). The following system resulted from this second approach:

[4] $$FOL = a_1 \cdot \left(\frac{LCW}{10}\right)^2 \cdot \left(\frac{CL}{10}\right)$$

where:

[5] $$LBRW = a_1 \cdot \left[\left(\frac{LCW}{10}\right)^2 \cdot \left(\frac{FOL}{10}\right)^{a_2}\right]$$

[6] $$DBRW = a_1 \cdot \left[\left(\frac{DBH}{Ht}\right)^{a_2} \cdot \left(\frac{LCW}{10}\right)^2 \cdot \left(\frac{mBL}{10}\right)\right]$$

[7] $$Bark = a_0 + a_1 \cdot \left[\left(\frac{DBH}{10}\right)^2 \left(\frac{Ht}{10}\right) \cdot exp(a_2 \cdot CR)\right]$$

[8] $$TS_{ib} = a_0 + a_1 \cdot \left[\left(\frac{DBH}{10}\right)^2 \cdot \left(\frac{Ht}{10}\right) \cdot exp(a_2 \cdot CR)\right]$$

[9] $$If\ \left(\frac{DBH \cdot HT}{CR}\right) \le 60\ then$$

$$RSAP = a_1 \cdot (CR) + (1 - a_1 \cdot CR) \cdot exp\left(a_2 \cdot \left(\frac{DBH \cdot Ht - 60 \cdot CR}{1000}\right)^{a_3}\right)$$

$$If\ \left(\frac{DBH \cdot HT}{CR}\right) > 60\ then$$

$$RSAP = 1$$

[10] $$SPWD = TS_{ib} \cdot RSAP$$

[11] $$HTWD = TS_{ib} \cdot (1 - RSAP)$$

where

FOL	=	Predicted total foliage biomass of tree (kg)
LCW	=	Largest crown width of the tree estimated from Hann, (1997)
	=	$[4.6198 + 1.8426 - 0.011311 \cdot DBH^2] \cdot CR^{0.0043624 \cdot CL + 0.602002 \cdot \frac{DBH}{Ht}}$
CL	=	Measured live crown length of the tree (m)
LBRW	=	Predicted live branchwood (wood + bark) biomass of tree (kg)
DBRW	=	Predicted dead branchwood (wood + bark) biomass of tree (kg)
mBL	=	BL if BL ≤ c_2, and mBL= c_2 if BL > c_2 (m)
BL	=	Ht-CL (m)
Bark	=	Predicted total tree bark biomass (kg)
CR	=	Measured crown ratio (CL/Ht)
TS_{ib}	=	Predicted total stem biomass, inside bark (kg)
RSAP	=	Predicted % sapwood
SPWD	=	Predicted sapwood biomass (kg)
HTWD	=	Predicted heartwood biomass (kg)

Results

Final parameter estimates and standard errors are provided in Tables PS-1.1, PS-1.2 and PS-1.3. Using the unconstrained equations (equations [4]-[11]), trees with a dbh of 20-50 cm were estimated to have a bone dry biomass of 166-1553 kg, when based on the average height and crown length of trees corresponding to that di-ameter size class. Bark constituted approximately 16% of total stem biomass, and live branch biomass exceeded dead branch biomass by approximately 50% (Figure PS-1.4).

When tests were conducted to assess whether use of categorical variables as an additive function on the c_1 parameter in equation [3] could account for any of the silvicultural treatments applied at the five SMC sites (initial spacing, thinning, or fertilization), none of these treatments was a significant factor. From this result, it was concluded that treatment effects on the combination of DBH, Ht, and/or CL accounted for the variation in biomass attributable to various standard silvicultural treatments. It is possible that time since treatment may be a factor, given that most thinnings or fertilizations occurred at least eight years prior to sampling.

Conclusions

These equations produce unbiased estimates of biomass for each of 6 aboveground components from intensively managed stands. These equations have been incorporated into the post-processors associated with the ORGANON growth model (Hann, 2011), producing both tree and stand level estimates of biomass by compo-nent for projected stands.

Table PS-1.1. Site-level data for sample trees.

Name	Study	Lat	Long	Elev. (m)	Age	SI_{50} (m)	DBH range (cm)	Ht range (m)	CR range
Panther	BLM	45.28347	-123.367	244	90	36.5	18.8-77.0	18.1-57.4	0.29-0.74
TOL	SMC	44.69137	-123.944	113	28	44.1	18.2-51.0	18.1-25.7	0.32-0.72
RR	SMC	44.65228	-122.705	371	30	45.2	17.7-43.9	22.9-29.6	0.31-0.74
OR	SMC	46.21142	-122.848	143	38	44.1	13.5-46.6	23.0-34.5	0.31-0.66
ET	SMC	47.17681	-121.716	802	36	40	11.5-45.6	17.1-33.5	0.23-0.80
SC	SMC	44.87389	-122.565	645	39	42	17.9-54.9	21.4-33.0	0.33-0.75
WEY	Weyerhaueser	44.03198	-122.762	640	54	40	26.2-57.1	28.6-40.2	0.31-0.47
STR	Starker	44.43564	-123.486	579	75	42.9	35.8-74.2	37.6-53.6	0.28-0.39
WW	BN	45.8723	-123.283	259	35	36.2	29.2-35.3	26.6-30.0	0.37-0.69
CT	BN	44.5048	-122.688	457	29	41.8	28.2-34.8	26.4-30.4	0.37-0.52
H1S	VMRC	44.6434	-123.561	239	20	49.5	13-29.2	16.5-22.5	0.48-0.71
H1M	VMRC	44.1944	-122.77	274	20	47.4	15.8-24.5	16.9-21.4	0.49-0.69
CPT	VMRC	44.616	-123.575	250	12	53.2	7.4-17.7	8.2-13.4	0.83-0.98
HAN	Giustina	44.6589	-123.962	134	21	41.1	22.5-34.7	16.5-18.7	0.57-0.79
CTC	Giustina	44.4474	-122.621	450	21	45.4	16.7-31.8	17.3-21.1	0.47-0.64
OSU	Giustina	44.7202	-123.304	123	20	48	15-30.5	16.4-21.8	0.41-0.68
PC	Giustina	42.83768	-123.971	710	15	45.5	9.5-19.6	8.8-14.2	0.87-0.99
STT	Giustina	44.5775	-123.492	274	22	46	14.3-28.9	17-23.8	0.51-0.66

Table PS-1.2. Parameter estimates by component for equation [3]. Standard errors in parentheses.

	c0	c1	c2	c3	c4
Heartwood	0.00000258 (0.000000105)	1.779252 (0.03820)	4.122208 (0.16160)	-0.06919 (0.00463)	
Sapwood	2.880795 (0.73790)	1.674749 (0.0387)	-1.02311 (0.10650)	0.065507 (0.00286)	
Bark	0.002059 (0.000274)	2.037714 (0.06080)	0.973931 (0.07570)		
Live branch	0.008594 (0.00206)	1.934934 (0.09300)			0.727667 (0.12910)
Foliage	0.027047 (0.00562)	1.403022 (0.08120)			0.675327 (0.1128)
Dead branch	0.049454 (0.00941)	3.241204 (0.08670)	-1.46483 (0.1061)		

Table PS-1.3. Parameter estimates by component for equations [4]-[9]. Standard errors in parentheses.

	a_0	a_1	a_2	a_3
Foliage, equation [4]		38.83 (0.9973194)		
Live branch, equation [5]		7.93338518 (0.3471377)	0.804701137 (0.01903674)	
Dead branch, equation [6]		43.2444672 (6.92857)	20.89 (5.169313)	1.90718673 (0.3402741)
Bark, equation [7]	0.318564479 (0.1583753)	2.60600933 (0.1496987)	-0.385623122 (0.1097177)	
TS_{ib}, equation [8]	3.61578088 (0.58282)	14.1690124 (0.4942984)	-0.210021548 (0.0658482)	
RSAP, equation [9]		0.362790893 (0.0352123)	-0.804811836 (0.02849096)	0.538867365 (0.01619606)

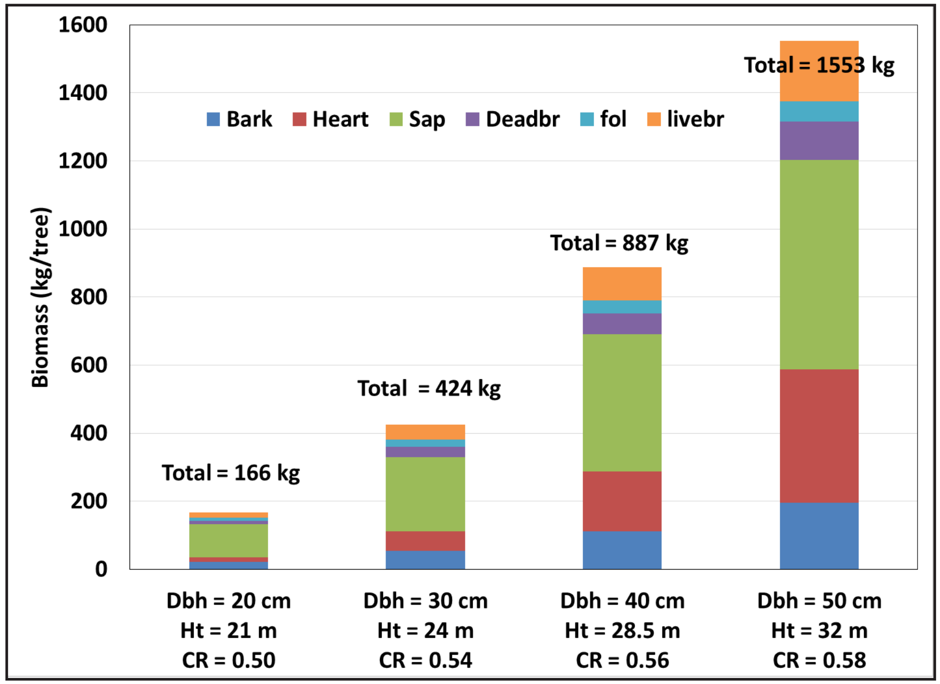

Figure PS-1.4. Estimates of biomass by components for individual trees, based on equations [4]-[11].

TASK 2: ESTIMATE NUTRIENT AND CARBON REMOVALS UNDER VARIOUS LEVELS OF BIOMASS HARVESTING

Task Objective

The ability to estimate the amount of site nutrient content removed during joint harvesting of timber and logging residuals has become important as the pressure on previously unutilized logging residues has increased due to its potential transformation into a domestic energy commodity, whether for combustion, conversion to liquid biofuels, or other uses.

In a recent effort to investigate the practicalities of converting post-harvest forest residuals into liquid biofuels, the Northwest Advanced Renewables Alliance has addressed many potential challenges currently associated with concentrating logging residuals into collection points for loading. One of the issues that requires consideration in assessing the ramifications of utilizing logging residuals for biofuel feedstock is distinction between material that is routinely yarded to the landing in the course of conventional timber harvest and any additional material that might be collected from the unit specifically for the purpose of biofuel feedstock, or a combination of biofuel feedstock and hog fuel. The marginal impact on site productivity can be viewed as limited to the additional materials collected from within the unit, because branches and cull wood that otherwise are left on the landing are removed from the site regardless of whether it is utilized.

With the recognition that soils cannot be assumed to remain perpetually productive despite significant nutrient removals, part of the objectives of this investigation was to determine the extent to which Douglas-fir forests are able to sustain increased removals of feedstock biomass and the nutrients contained therein.

To address this question, trees were sampled from within numerous intensively-managed stands and lab analyses were conducted to provide biomass and nutrient data on six different aboveground tree components and 11 separate nutrients (see Task 1: Develop allometric equations for managed stands). In combination with estimation of tree-level biomass, average nutrient concentrations from the collected samples was used to determine total nutrient contents of individual trees. Calculation of total nutrient content by tree component enables estimates to be made of the implied nutrient removal from a timber harvest of any intensity.

Methodology

Nutrient analysis was conducted by the Analytical Services Center at the University of Washington's College of the Environment. Analysis was performed on dried and ground tissues of six aboveground components: 1) Foliar nutrients from one, two, and three year old needles from the largest four-yr old lateral of the southernmost branch of the whorl above crown mid-point; 2) Live branchwood from the largest of the middle crown-third sample branches; 3) Dead branchwood from both the small sampled dead branch of the lower bole half and the large sampled dead branch of the upper bole half; 4) Heartwood, sapwood, and bark from the mid-bole disk. Wood and foliage samples were digested using a wet digestion procedure using nitric acid and hydrogen peroxide. Digested solutions were run through a Thermo Scientific Co. 61E inductively coupled plasma mass spectrometer to determine metals concentrations. Carbon and nitrogen were analyzed with a Perkin Elmer 2400.

Because simulations of harvest intensity were based primarily on the extent to which the crown components and top portions of the main stem were removed from the site following timber harvest, a method of estimating the proportion of crown component biomass above a given height or upper stem diameter needed to be determined. Applying the results from site-level fits of equation [1] and the entirety of the branch diameter/crown position dataset, equations were fit to estimate branch and foliar biomass proportion above a relative height in the crown. The final models describing these proportions were:

$$[12] \quad folp = 1 = exp(-3.8956 \cdot rdinc^{2.1405+0.7938 \cdot CR})$$

$$[13] \quad woodp = 1 = exp(-3.1011 \cdot rdinc^{3.1532+0.1964 \cdot CR})$$

where *folp* = foliar proportion above height *h* in the tree
woodp = wood proportion above height *h* in the tree
rdinc = relative depth into crown (*Ht-h*)
and *CR* is defined above.

Where utilization standards were based on a specific upper stem diameter, the height of this diameter was determined by applying a previously constructed taper equation (Walters and Hann, 1986), and then used to compute the variable *rdinc* in equations [12] and [13].

In order to estimate biomass and nutrient content removals, four separate harvest scenarios were applied to SMC-ORGANON projections of the untreated stands at the Roaring River and Toledo SMC sites. The initial tree lists were based on measurements made at age 31, and projected for 9 years. Average nutrient contents from each site were applied to the estimates of biomass. Four different harvest types were simulated: 1) Whole tree (WT), with the assumption that all branches, foliage, and tops were removed from the woods; 2) Bole only (BO), with the assumption that all branches and foliage remained in the woods;

3) Merchantable (Merch), with the assumption that everything above a 12.5 cm upper stem diameter remained in the woods, as did half the live crown below a 12.5 cm dib; and 4) NARA, with the assumption that 32.8% of the mass of the crown following a WT harvest is not recoverable and remains in the woods, based on data measured as part of the NARA project (Kevin Boston, pers. com).

Results

The result of chemical analysis of the component tissues on the different sites is presented in Table PS-2.1. Estimates of total tree-level nutrient content was produced by application of dataset average values for N, P, K, Ca, and Mg concentrations to the largest and smallest trees shown in Figure PS-1.4 (Figures PS-2.1 and PS-2.2). Of significance in the context of this task are the relatively high proportion of nutrients contained within the foliage, and, comparing Figures PS-2.1 and PS-2.2, the implied decrease in relative foliage biomass as a proportion of the total tree biomass as the tree gets larger (based on the decreased relative contribution of foliage biomass and hence nutrient content to the total). Although the biomass of the Toledo stand at age 40 is less than that of the RR stand, probably due to a lower SI_{50}, the nutrient yield is roughly similar as a result of the greater absolute quantity of high nutrient-concentration crown components at Toledo.

Table PS-2.1. Average nutrient concentration and standard deviation by component, nutrient, and site

Site	Study	Component	Count	Nitrogen (%)		Boron (mg/ Kg)		Calcium (mg/ Kg)		Copper (mg/ Kg)		Iron (mg/ Kg)		Potassium (mg/ K		Magnesium (mg/		Manganese (mg/		Phosphorus (mg/		Sulfur (mg/ Kg)		Zinc (mg/ Kg)	
				mean	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*
BLM	BLM	Bark	15	0.244	0.112	4.824	2.821	1697.4	558.74	3.737	0.727	75.833	93.697	972.8	471.52	238.93	93.2	87.87	57.01	253.4	110.41	163.8	29.7	12.501	4.949
		Heartwood	15	0.031	0.006	1.355	0.472	205.99	73.45	0.246	0.396	5.745	5.261	159.38	39.57	12.9	18.76	11.25	6.8	9.4	5.78	22.79	10.92	0.774	0.56
		Sapwood	15	0.041	0.009	1.294	0.525	857.18	792.19	0.653	0.484	21.58	27.813	191.78	91.63	74.3	24.82	32.06	20.7	56.98	16.42	42.78	14.28	2.126	0.369
		Foliage, 1 yr	14	1.173	0.15	14.948	3.664	2442.82	544.47	2.835	0.756	45.007	14.624	6493.17	1161.65	1148.95	193.53	387.04	256.93	1604.97	210.47	747.96	134.15	13.333	3.772
		Foliage, 2 yr	14	1.252	0.12	15.942	6.797	3713.02	718.23	3.176	1.029	56.692	15.04	5366.81	709.11	1147.59	277.99	519.39	307.21	1670.12	255.72	811.3	138.42	13.345	4.724
		Foliage, 3 yr	14	1.191	0.1	14.909	5.318	4317.05	930.4	3.634	1.211	62.177	15.493	5308.98	767.18	1059.03	246.56	608.87	403.71	1644.53	329.85	828.47	134.85	14.148	4.555
		Live branch, w+b	19	0.16	0.03	4.527	0.77	2317.13	617.52	2.516	0.312	34.401	19.502	1086.42	232.27	313.19	73.14	115.29	64.1	268.73	72.99	119.7	21.69	16.055	3.766
		Dead branches	18	0.143	0.076	3.131	1.21	1595.5	1419.01	1.592	0.683	70.343	34.964	188.8	150.37	226.66	145.86	75.34	64.68	102.7	64.06	135.39	59.75	11.332	7.782
CPT	VMRC	Bark	6	0.348	0.138	6.602	1.106	1795.83	398.86	3.842	0.271	46.05	34.918	2734.67	1057.15	333.67	79.89	154	35.81	573.5	130.76	224.33	27.47	27.65	8.816
		Heartwood	4	0.036	0.009	2.355	0.42	654.94	848.81	0.428	0.51	5.967	2.99	208.2	78.16	44.5	39.44	20.05	13.18	17.72	6.09	43.51	9.01	2.218	0.631
		Sapwood	6	0.043	0.01	2.301	0.309	1137.2	715.41	1.063	0.333	16.135	24.076	367.36	179.18	100.95	23.33	27.95	10.82	72.64	19.73	68.72	22.53	2.398	0.636
		Foliage, 1 yr	4	1.072	0.116	12.079	4.363	2636.8	951.19	2.378	0.652	78.412	48.95	5057.32	541.55	901.29	130.42	396.21	97.75	1360.85	179.88	736.13	135.58	8.672	1.649
		Foliage, 2 yr	4	1.187	0.075	8.023	3.886	3334.33	861.21	2.96	0.828	61.675	24.181	4555.99	280.67	636.07	119.84	402.12	156.89	1438.17	40.01	788.21	107.1	8.447	1.163
		Foliage, 3 yr	4	1.052	0.127	8.234	2.086	3745.73	1287.04	3.081	2.629	103.706	55.791	4340.25	816.67	645.86	169.18	424.34	125.71	1566.43	273.97	925.01	248.66	10.144	2.915
		Live branch, w+b	2	0.241	0.046	4.127	1.444	1506.38	310.35	2.623	0.399	17.915	5.93	1477.01	463.1	296.64	122.32	111.82	31.05	373.83	148.27	143.13	26.07	15.972	3.269
		Dead branches	2	0.238	0	4.781	1.087	3135.58	896.09	2.826	0.741	68.511	45.418	351.37	123.29	698.4	59.81	285.12	133.54	237.24	80.33	227.81	46.22	32.203	8.193
CT	BN	Bark	5	0.251	0.064	7.278	1.905	2275.2	821.23	4.662	0.979	40.12	21.12	1635.2	767.48	216.8	60.24	83.54	29.69	343	96.92	185.4	38.79	16.26	3.169
		Heartwood	5	0.026	0.004	1.748	0.429	216.98	30.59	0.518	0.72	4.961	1.887	134.75	50.26	13.3	12.47	9.49	4.04	9.26	6.4	26.18	5.19	1.286	0.719
		Sapwood	5	0.05	0.017	1.687	0.494	1317.95	978.61	1.214	0.369	9.133	5.326	328.78	76.13	81.6	15.15	23.79	8.69	73.13	22.57	56.42	8.46	2.608	0.702
		Foliage, 1 yr	6	1.256	0.18	12.779	2.915	3844.95	804.94	4.329	0.51	62.97	18.01	3712.35	167.37	1034.95	112.42	390.19	115.6	1124.59	190.33	798.83	109.88	15.217	3.136
		Foliage, 2 yr	6	1.336	0.155	9.524	1.505	5303.43	834.8	5.773	1.967	68.895	23.123	3688.95	249.63	990.72	226.75	549.15	139.86	1218.12	114.1	873.69	111.99	16.824	4.202
		Foliage, 3 yr	6	1.251	0.08	10.385	3.447	5420.46	1248.23	6.362	2.974	85.236	27.539	4041.57	445.66	849.59	296.94	543.3	165.35	1143.04	262.1	880.9	79.58	16.107	3.411
		Live branch, w+b	6	0.194	0.041	3.945	0.484	1829.2	487.17	2.811	0.514	24.398	10.492	1253.73	225.45	241.55	48.25	99.07	26.57	260.5	45.59	115.27	16.49	15.227	3.646
ET	SMC	Bark	21	0.252	0.043	5.086	1.148	1209.34	1203.48	3.962	1.767	829.649	1039.08	2372.41	504.06	335.85	100.59	79.46	44.35	511.7	92.11	205.07	32.4	18.865	6.503
		Heartwood	21	0.025	0.007	1.682	2.486	179.42	241.25	2.022	1.807	58.725	74.817	1.92	8.71	21.6	15.72	10.91	5.82	11.82	8.06	37.19	6.61	2.41	2.041
		Sapwood	21	0.032	0.008	0.572	0.862	193.09	188.09	1.863	1.809	158.124	160.336	301.13	61.14	70.62	16.95	17.23	8.87	56.72	10.87	39.35	5.46	2.64	1.596
		Foliage, 1 yr	14	1.248	0.109	6.702	3.547	2531.24	510.43	3.898	0.73	45.806	16.574	5815.76	1308.88	1097.98	197.36	241.21	95.12	1613.28	286.74	690.08	92.31	12.318	2.731
		Foliage, 2 yr	14	1.365	0.133	5.773	3.436	3521.42	528.72	4.512	4.411	71.413	51.302	4528	729.24	972.38	137.25	333.3	149.54	1415.39	364.05	723.06	121.24	11.072	3.056
		Foliage, 3 yr	14	1.312	0.169	5.021	2.394	3907.32	820.43	4.401	2.895	72.316	22.601	4085.33	479.05	854.94	160.46	355.2	158.51	1239.77	287.99	737.77	81.24	10.879	2.168
		Live branch, w+b	12	0.125	0.04	1.929	0.587	807.14	802.2	4	1.753	537.796	694.193	836.65	190.96	216.87	40.3	41.45	17.97	181.14	47.35	86.61	20.28	8.854	2.177
		Dead branches	14	0.147	0.091	1.775	1.49	1270.51	1391.98	3.512	1.976	639.926	798.077	263.63	292.81	232.11	106.45	89.12	56.49	151.88	114.74	178.33	131.88	14.373	8.526
H1M	VMRC	Bark	12	0.331	0.077	6.421	1.821	2305	411.26	5.092	0.767	61.917	34.163	1852.83	752.42	441.75	150.52	168.28	42.27	450.17	163.66	222.67	47.85	23.833	6.867
		Heartwood	12	0.041	0.013	2.852	2.414	289.31	150.74	1.504	3.444	7.008	3.583	150.97	40.99	28.21	14.45	19.59	11.19	17.24	3.53	34.97	4.94	1.993	0.601
		Sapwood	12	0.05	0.015	1.86	0.405	1321.51	1238.46	1.084	0.507	24.774	37.304	379.4	200.75	101	20.03	32.45	8.22	73.01	24.63	63.1	15.92	2.885	0.794
		Foliage, 1 yr	10	1.15	0.105	10.175	3.948	2571.01	1192.93	3.996	0.822	49.224	5.746	4392.17	678.31	1007.21	284.29	511.25	77.4	1164.76	116.99	780.19	99.13	11.211	2.567
		Foliage, 2 yr	10	1.14	0.072	7.694	3.571	2783.9	717.66	3.592	1.112	57.361	9.37	4591.49	663.66	756.94	232.33	561.86	150.13	1247.18	210.12	787.25	91.67	11.026	3.14
		Foliage, 3 yr	10	1.107	0.076	6.318	1.885	2833.16	1030.44	3.364	0.979	70.202	33.365	5100.87	1099.11	696.11	175.89	514.63	108.36	1197.28	220.25	815.03	52.59	10.234	2.189
		Live branch, w+b	14	0.199	0.048	4.151	0.711	1603.01	425.48	2.575	0.514	14.154	6.074	1194.66	334	324.38	67.82	122.81	36.72	286.56	86.4	135.47	42.63	14.83	4.232
		Dead branches	9	0.225	0.088	4.051	1.175	2284.86	386.77	2.368	0.704	83.663	52.775	229.4	103.3	550.98	165.83	220.42	79.14	141.07	62.09	159.21	71.84	28.298	6.87
H1S	VMRC	Bark	14	0.347	0.101	7.569	1.942	2147.86	695.79	4.955	1.034	47.114	22.841	3488.5	816.32	433.57	158.91	85.96	31.11	691.71	168.86	276.93	38.78	25.85	7.06
		Heartwood	13	0.039	0.009	1.703	0.209	257.2	111.57	0.797	1.057	10.878	22.356	204.34	53.68	33.05	19.31	9.81	3.49	18.14	11.09	34.31	9.4	1.992	0.801
		Sapwood	14	0.051	0.017	1.812	0.445	972.18	1268.25	1.174	1.246	24.369	34.411	324.29	165.4	88.25	27.96	19.34	7.07	74.08	33.81	56.26	20.11	2.809	1.457
		Foliage, 1 yr	10	1.327	0.174	9.449	2.718	1926.72	732.1	3.366	1.099	60.027	28.493	5524.33	1045.21	883.85	180.07	225.82	100.38	1480.44	140.26	680.11	54.49	10.398	3.115
		Foliage, 2 yr	10	1.327	0.127	7.476	3.458	2997.98	512.39	3.367	0.838	55.604	11.935	4900.27	1129.93	708.19	196.61	279.55	101.32	1506.27	265.29	739.18	78.02	10.3	2.333
		Foliage, 3 yr	10	1.224	0.12	6.291	1.757	3002.64	754.84	2.424	1.403	69.957	29.553	4888.09	878.71	571.67	191.85	231.85	71.04	1404.43	308.9	769.31	87.86	11.517	2.946
		Live branch, w+b	13	0.217	0.057	4.15	0.726	1647.58	461.76	2.787	0.631	13.244	10.945	1412.07	232.33	315.82	68.74	76.91	24.16	355.69	74.46	143.87	32.14	16.453	5.295
		Dead branches	12	0.289	0.092	4.094	1.092	2954.05	820.06	2.911	0.721	54.499	26.58	373.84	280.26	473.6	75.76	106.61	24.76	214.56	55.15	228.76	51.96	26.313	6.163

Table PS-2.1, cont'd Average nutrient concentration and standard deviation by component, nutrient, and site

Site	Study	Component	Count	Nitrogen (%)		Boron (mg/ Kg)		Calcium (mg/ Kg)		Copper (mg/ Kg)		Iron (mg/ Kg)		Potassium (mg/ K		Magnesium (mg/		Manganese (mg/		Phosphorus (mg/		Sulfur (mg/ Kg)		Zinc (mg/ Kg)	
				mean	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*	*mean*	*st. dev.*
OR	SMC	Bark	21	0.223	0.035	5.285	1.725	2004.4	1097.96	3.884	1.113	354.998	849.911	1877.51	431.24	330.39	94.5	58.72	18.39	390.19	99.63	197.76	24.03	13.693	5.04
		Heartwood	21	0.027	0.007	0.776	1.347	574.56	790.39	0.865	1.098	34.284	75.746	0.68	2.99	26.43	20.44	7.85	3.55	5.46	7.23	39.34	8.1	1.36	1.185
		Sapwood	21	0.027	0.007	0.786	1.525	612.35	565.67	1.375	1.087	47.058	110.623	272.08	101.73	81.41	22.87	16.48	6.22	43.97	9.8	38.28	8.28	1.947	0.884
		Foliage, 1 yr	14	1.435	0.152	7.051	1.573	2478.09	524.67	9.916	21.336	47.499	16.984	3796.88	1229.8	1032.61	135.45	200.29	64.61	1056.17	159.21	643.56	67.6	13.19	9.586
		Foliage, 2 yr	14	1.388	0.149	4.618	0.973	3347.48	630.96	3.737	0.468	63.038	17.241	3591.37	707.31	982.61	183.44	228.49	76.87	944.07	175.09	765.98	88.3	9.971	2.462
		Foliage, 3 yr	14	1.477	0.177	3.68	0.904	4273.38	862.88	4.344	0.65	81.439	24.281	3175.45	630.88	869.81	250.55	260.4	97.58	924.22	174.11	799.05	77.07	10.848	2.35
		Live branch, w+b	18	0.135	0.051	2.422	1.267	1243.84	423.07	3.115	1.093	12.101	12.395	826.82	208.63	188.95	46.68	44.51	11.4	153.78	49.73	94.16	24.27	7.06	2.356
		Dead branches	12	0.197	0.266	1.439	1.397	1601.88	905.59	3.106	2.426	128.297	242.367	139.48	160.85	192.58	64.77	62.22	46.68	117.89	126.82	199.55	185.27	12.181	8.296
TOL	SMC	Bark	22	0.22	0.033	6.094	1.446	1722.47	645.08	4.493	1.435	25.203	10.528	1824.67	446.94	381.38	138.54	56	35.7	476.18	120.75	195.89	27.01	14.792	4.538
		Heartwood	22	0.032	0.011	2.307	1.517	476.07	335.73	2.623	1.701	13.858	7.784	1.88	6.16	22.79	20.19	6.83	2.78	17.79	11.71	40.93	8.01	3.301	1.722
		Sapwood	22	0.037	0.007	2.134	1.18	530.47	322.51	2.329	1.619	14.56	9.977	298.09	135.03	71.53	19.08	11.94	4.55	71.26	16.29	52.65	9.79	3.172	1.466
		Foliage, 1 yr	16	1.399	0.081	9.768	3.21	1656.6	501.97	3.12	1.086	41.08	30.622	5534.01	995.57	824.78	136.56	127.8	42.66	1261.47	210.03	692.49	76.62	9.474	2.254
		Foliage, 2 yr	19	1.346	0.158	9.114	4.239	2311.91	629.81	3.576	4.081	47.071	43.244	5215.7	1277.71	818.91	240.33	149.69	63.11	1220.5	296.77	771.16	94.33	8.134	1.592
		Foliage, 3 yr	19	1.25	0.138	7.837	3.766	2639.58	837.19	2.755	0.562	73.961	96.785	4353.28	977.9	944.67	327.06	146.82	75.61	1146.31	376.52	776.1	110.24	10.374	8.422
		Live branch, w+b	14	0.171	0.043	4.472	1.375	1670.09	820.77	4.83	1.346	11.427	6.619	1012.55	386.8	306.16	124.92	45.09	21.58	278.89	105.16	130.49	37.7	12.977	4.335
		Dead branches	13	0.167	0.078	3.935	1.693	1763.76	697.88	3.654	1.78	37.16	30.814	239.91	290.1	375.88	106.04	46.9	30.77	136.61	58.47	176.39	89.19	15.426	7.903
RR	SMC	Bark	21	0.245	0.043	5.681	0.794	2352.93	816.65	3.858	1.656	43.798	31.446	1459.77	456.54	355.09	132.31	57.9	25.56	391.19	90.35	180.1	26.14	15.85	4.826
		Heartwood	21	0.026	0.008	1.808	1.197	334.57	503.48	0.468	0.633	25.913	76.554	4.94	12.83	10.36	15.23	4.88	2.11	5.25	8.62	32.83	18.09	1.095	1.086
		Sapwood	21	0.034	0.009	1.674	1.213	405.9	175.42	0.493	0.57	18.904	30.24	254.04	83.04	66.29	21.97	11.15	4.44	54.12	12.74	36.4	14.03	1.926	0.676
		Foliage, 1 yr	14	1.377	0.106	13.88	4.004	2952.86	774.77	3.947	0.473	57.813	16.563	4151.74	731.24	1172.13	221.74	178.32	53.01	1197.93	154.97	745.38	59.44	11.784	2.323
		Foliage, 2 yr	14	1.448	0.14	8.882	3.577	3830.59	939.47	4.093	0.526	85.036	42.308	4010.69	827.58	1042.52	294.45	195.45	60.84	1050.12	136.97	809.89	65.59	11.469	3.62
		Foliage, 3 yr	14	1.359	0.194	7.469	1.785	5208.27	1227	4.459	0.617	114.727	74.938	3620.14	737.82	1046.76	381.32	235.38	74.82	1021.65	136.1	826.01	78.75	11.56	2.323
		Live branch, w+b	17	0.163	0.058	2.458	1.037	1103.13	376.39	2.644	0.858	10.713	9.991	887.67	353.22	196.08	67.36	31.8	11.39	158.7	65.25	97.3	33.2	7.131	2.296
		Dead branches	12	0.158	0.12	2.721	2.269	1430.7	1351.8	1.73	0.702	67.579	103.614	286.61	336.22	204.92	65.07	47.61	50.19	104.62	75.67	120.14	79.02	11.123	7.753
STR	Industry	Bark	6	0.156	0.032	5.068	1.869	1573.5	535.25	3.422	0.418	39.15	12.773	679.5	263.09	186.83	65.97	85.17	15.23	207.83	56.09	152.5	27.13	10.115	4.6
		Heartwood	6	0.034	0.007	1.379	0.653	222.97	108.97	0.109	0.259	4.438	6.402	150.41	21.07	2.88	6.78	12.15	4.5	7.97	5.08	21.89	6.59	0.227	0.344
		Sapwood	6	0.038	0.007	1.595	0.586	1103.07	849.38	0.618	0.566	4.448	4.105	170.57	124.83	72.65	24.91	36.94	7.37	59.77	17.8	41.78	15.28	2.303	0.509
		Foliage, 1 yr	2	1.059	0.058	11.85	6.152	2471.1	507.2	6.446	4.121	54.657	20.065	4455.49	306.42	1117.27	63.12	513.5	32.93	1492.6	56.89	829.4	222.23	22.078	15.178
		Foliage, 2 yr	2	1.209	0.028	11.946	4.743	3501.28	123.71	7.566	5.037	59.327	3.414	4350.47	19.6	984.1	25.11	745.12	0.69	2065.34	194.17	930.96	159.86	20.41	14.528
		Foliage, 3 yr	2	1.158	0.028	14.263	7.406	3955.76	734.35	9.17	7.589	75.266	40.734	4693.91	46.4	939.73	76.94	754.09	32.61	2214.56	514.7	947.63	49.05	32.354	5.168
		Live branch, w+b	6	0.176	0.04	3.924	0.632	2424.33	674.71	2.253	0.376	37.546	12.663	1025.21	110.31	278.27	51.74	159.19	34.5	270.13	66.96	131.64	17.95	17.759	6.945
		Dead branches	1	0.222		2.079		1830.94		2.28		167.025		289.93		192.29		128.25		230.07		252.6		13.849	
WEY	Industry	Bark	6	0.265	0.077	5.13	2.093	2151.33	1042.71	3.888	0.724	42.817	29.864	1209.33	512.04	290.83	131.49	92.25	48.82	276.83	100.97	166.67	40.89	19.16	11.42
		Heartwood	6	0.033	0.004	1.999	0.38	357.07	419.39	0.304	0.466	6.959	4.387	139.93	62.73	7.54	12.65	8.42	3.12	13.33	2.69	28.38	8.32	0.575	0.474
		Sapwood	6	0.049	0.015	1.721	0.294	404.52	61.55	0.669	0.332	17.699	26.687	229.04	157.49	68.07	17.72	20.65	6.21	54.88	13.25	36.34	9.25	1.898	0.498
		Foliage, 1 yr	2	1.227	0.181	5.003	0.504	3172.5	201.67	3.811	0.593	44.326	0.414	4608.12	329.18	1173.27	181.06	503.68	44.55	1134.07	291.1	724.93	47.16	13.261	2.947
		Foliage, 2 yr	2	1.307	0.013	13.397	1.93	4333.25	785.42	6.474	0.732	64.113	9.763	4126.18	1025.51	1166.12	333.57	602.21	83.56	1047.68	189.31	742	8.72	15.366	3.89
		Foliage, 3 yr	2	1.233	0.043	8.127	0.454	5806.31	2159	5.52	1.131	72.937	3.972	3727.36	354.98	1069.27	494.34	671.51	212.45	914.12	86.25	807.22	63.64	15.161	6.985
		Live branch, w+b	4	0.219	0.061	4.45	1.846	2493.95	487.38	2.543	0.859	21.639	5.817	1232.65	399.4	292.18	62.39	119.74	49	277.54	114.71	145.16	42.89	16.497	5.21
		Dead branches	3	0.149	0.019	2.282	0.717	1950.12	1211.74	1.529	1.321	84.679	14.195	213.53	121.38	212.25	109.57	87.84	25.79	127.62	15.12	161.21	12.51	12.46	3.832
WW	BN	Bark	6	0.223	0.045	5.25	2.164	2006	640.81	3.692	0.678	20.583	7.023	1338.5	451.88	197.17	23.99	71.57	8.86	311.17	88.21	164.33	22.09	15.583	4.55
		Heartwood	6	0.042	0.013	1.814	0.381	227.2	172.76	0.002	0.001	5.547	3.766	149.66	30.67	12.93	10.31	7.88	5.03	16.09	11.74	31	5.01	0.671	0.609
		Sapwood	6	0.057	0.01	1.982	0.369	435.51	120.77	0.656	0.384	24.287	44.427	368.01	131.63	71.99	11.89	23.86	6.05	87.45	29.93	48.81	14.58	2.519	0.753
		Foliage, 1 yr	8	1.043	0.104	9.739	2.465	3346.88	721.07	5.103	3.876	177.66	321.818	3321.88	393.24	961.73	147.24	307.63	34.43	1480.84	253.27	720.12	106.27	14.688	3.708
		Foliage, 2 yr	8	1.063	0.101	8.002	2.353	4661.42	1012.41	5.214	2.18	164.28	238.153	3300.48	452.24	975.56	190.52	396.18	77.3	1641.13	454.93	788.27	97.9	15.29	6.192
		Foliage, 3 yr	8	1.015	0.078	6.955	1.539	5209.82	675.24	6.915	5.634	136.09	133.91	3170.32	314.36	951.04	202.5	415.25	59.82	1591.45	508.29	803.4	136.61	15.974	4.704
		Live branch, w+b	8	0.176	0.027	3.414	1.171	1995.58	1118.62	1.86	0.366	14.999	9	1301.37	159	268.69	54.54	90.12	28.16	275.06	21.17	121.37	17.21	13.22	2.46

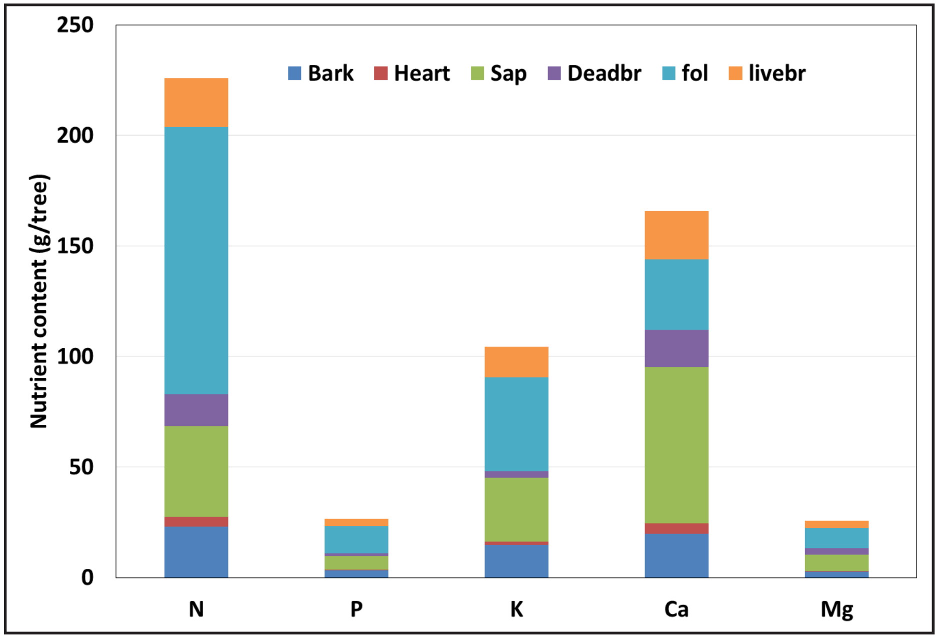

Figure PS-2.1. Content of five major macronutrients by biomass component for 20 cm dbh tree (based on tree in Figure PS-1.4)

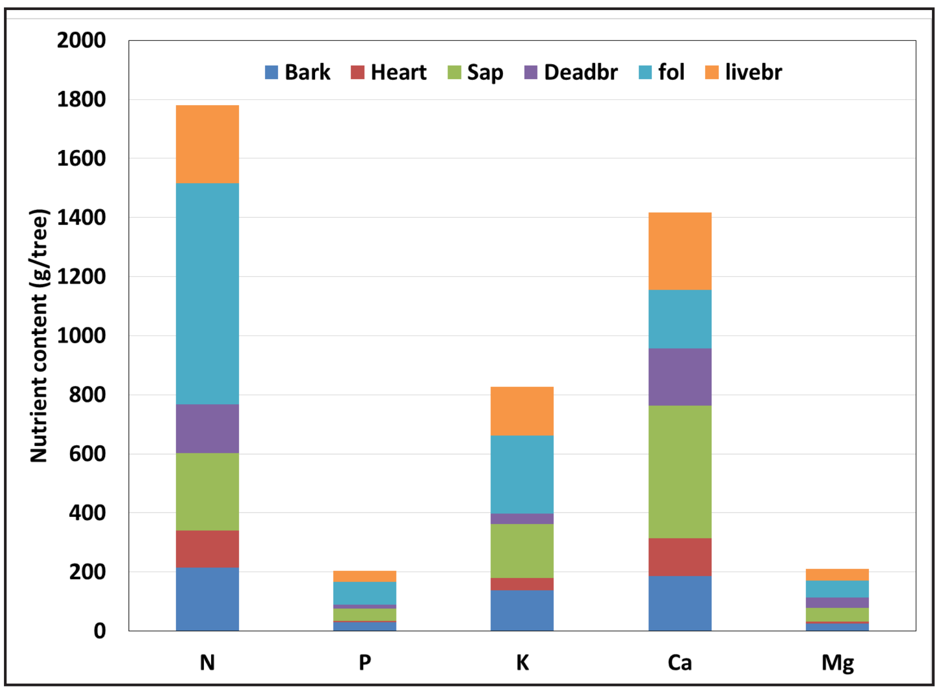

Figure PS-2.2. Content of five major macronutrients by biomass component for 50 cm dbh tree (based on tree in Figure PS-1.4)

Tables PS-2.2 and PS-2.3 demonstrate the large difference that harvest intensity can make in influencing the quantity of residual nutrients. On the Toledo site, a bole-only harvest leaves only about 15% of the total carbon biomass (Table PS-2.2), but results in leaving about half of the nutrients on site (Table PS-2.3). This is primarily due to the relatively high nutrient concentration of the foliage and relatively low nutrient concentration in heartwood and sapwood (Table PS-2.1). At the Roaring River site, approximately 10% of the carbon is left in the woods following a bole-only harvest, resulting in roughly a third of the nutrients left behind.

Table PS-2.2. Removed and residual carbon at 40 years for the Roaring River and Toledo SMC sites. Assumes 50% carbon in biomass (kg/ha)

		Removals						Residuals					
Roaring River		Heartwood	Sapwood	Bark	Live branches	Foliage	Dead branches	Heartwood	Sapwood	Bark	Live branches	Foliage	Dead branches
	WT	93826.43	85499.9	33713.42	7881.78	3958.24	7964.09	0	0	0	0	0	0
	BO	93826.43	85499.9	33713.42	0	0	0	0	0	0	7881.78	3958.24	7964.09
	Merch	93037.83	79105.82	32681.06	1883.2	555.31	3982.04	788.6	6394.08	1032.36	5998.58	3402.93	3982.04
	NARA	93826.43	85499.9	33713.42	5296.56	2659.94	5351.87	0	0	0	2585.23	1298.3	2612.22
Toledo		Heartwood	Sapwood	Bark	Live branches	Foliage	Dead branches	Heartwood	Sapwood	Bark	Live branches	Foliage	Dead branches
	WT	47430.21	103915.53	28584.29	11584.98	4962.21	14600.67	0	0	0	0	0	0
	BO	47430.21	103915.53	28584.29	0	0	0	0	0	0	11584.98	4962.21	14600.67
	Merch	46733.97	98377.88	27690.28	2676.36	706.4	7300.34	696.24	5537.65	894.01	8908.62	4255.82	7300.34
	NARA	47430.21	103915.53	28584.29	7785.11	3334.61	9811.65	0	0	0	3799.87	1627.61	4789.02

Table PS-2.3. Removed and residual nutrient amounts at 40 years for the Roaring River and Toledo SMC sites (kg/ha)

		Removals					Residuals				
Roaring River		N	P	K	Ca	Mg	N	P	K	Ca	Mg
	WT	432.35	51.75	198.52	364.12	55.28	0	0	0	0	0
	BO	271.74	39.03	148.33	290.84	40.36	160.62	12.72	50.19	73.27	14.92
	Merch	295.98	40.13	152.4	300.46	42.31	136.37	11.62	46.11	63.66	12.97
	NARA	379.67	47.58	182.06	340.08	50.39	52.68	4.17	16.46	24.03	4.89
Toledo		N	P	K	Ca	Mg	N	P	K	Ca	Mg
	WT	423.22	66.17	246.87	365.94	65.46	0	0	0	0	0
	BO	202.67	43.72	166.44	253.88	38.83	220.55	22.45	80.43	112.06	26.63
	Merch	246.99	47.25	175.91	282.07	45.67	176.23	18.92	70.96	83.87	19.79
	NARA	350.88	58.81	220.49	329.18	56.73	72.34	7.36	26.38	36.76	8.74

Conclusions

In practice, timber harvests are never as controlled as these hypothetical scenarios would indicate. Felling inevitably breaks branches, and some foliage and wood stay on site (as in the NARA scenario). In a regeneration harvest using cable yarding, limbing and topping is almost never done in the woods—for the sake of efficiency, whole-tree yarding is often practiced, and delimbed branches and foliage are often piled at the landing. These piles may be pushed off the landing or burned, or, if markets exist for biofuels, may be hauled away. On relatively flat ground, mech-anized harvesting does make it possible to distribute the crown components as residual material. Economics and logistical considerations currently dictate the post-harvest treatment of residual material. How an existing market for biofuel feedstock would alter the economics of this treatment is unknown.

TASK 3: DETERMINE SUSTAINABLE LEVELS OF BIOENERGY FEEDSTOCK UNDER RANGE OF SILVICULTURAL INTENSITIES

Task Objective

The use of allometric biomass equations in combination with estimates of nutrient concentrations of various tree tissues enables estimates to be made of nutrient removals from a timber harvest of any intensity. However, over the course of a rotation, other inputs and outputs act on the soil resource. A simple model of inputs and outputs is provided by the base cation model (Asskelson et al., Figure PS-3.1), which accounts for additions to the system from the weathering of parent material and deposition from the atmosphere (wet and dry) and losses in the form of leaching and accumulation or removal of organic matter. In this model, internal cycling is ignored. In determination of sustainable levels of bioenergy feedstock, published values of weathering, leaching and atmospheric deposition on the westside of the Cascades were combined with estimates of nutrient removal from different harvest types and utilization standards. The net change in nutrient content was compared to measured estimates of soil nutrient capital from four SMC sites.

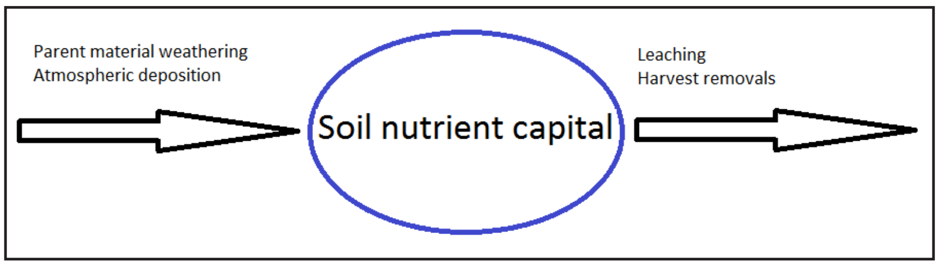

Figure PS-3.1. Diagram illustrating inputs and outputs of nutrients from the soil nutrient pool of a forest ecosystem.

In studies assessing the sustainability of different timber management systems, the proportional removal of the site nutrient capital per harvest, expressed as a ratio, has been considered an adequate measure of sustainability. Put forth by Evans (2009), the ratio has been used to identify the relative susceptibility of sites to nutrient depletion. The ratio is defined as the proportion of nutrients removed during a harvest rotation to the total site nutrient pool. As a determination of sustainability, a ratio of 0.1 and below was deemed to carry little or no risk to long-term site productivity. A ratio of 0.3 and above was judged a significant potential risk to long-term productivity. To address the objective of the NARA task of this section, stability ratios were calculated for four different harvest intensities at sites representative of the range of conditions found in Douglas-fir forests of western Oregon and Washington.

Methodology

Because no measurements of parent material weathering, atmospheric deposition, or leaching were made as part of this study, it was necessary to rely on published values. Furthermore, because these values vary regionally (Kimmins et al., 1985), it was decided to use published values from Douglas-fir stands of the coastal variety only. The complexity of the measurements, and the limited number of sites for which these calculations have been made necessarily limited the number of values used to estimate the components of the base cation model. The published values used to account for weathering, leaching, and deposition are shown in Table PS-3.1. For the purpose of this analysis, the values for weathering and atmospheric deposition were averaged for all sites. When accounting for leaching, values were applied separately for Cascades and Coast Range sites.

Table PS-3.1. Sources for measured estimates of soil inputs and outputs (kg/ha/yr) from forest soil nutrient pools.

Type	Location	N	P	K	Ca	Mg	Source
Atmospheric deposition							
	WA	1.7	2.3	2.5	0.3	0.5	Turner, Cole in Cole and Rapp 1980
	WA	2	0.3	1.2	3.1	1.2	Grier in Cole and Rapp 1980
Western Cascades (HJ Andrews)	OR	0.9	0.27	0.1	2.3	0.1	Fredriksen 1972
Western Cascades (HJ Andrews)	OR	1.1	0.27	0.3	7.6	0.7	Fredriksen 1972
Western Cascades (Cedar River watershed)	WA	1.1		0.8	2.8	0.7	Cole et al. 1967
Western Cascades (HJ Andrews)	OR		0.23	0.1	2.1	0.7	Abee and Lavendar 1972
Western Cascades (HJ Andrews)	OR	2	0.3	0.9	3.6	1.2	Sollins 1980
Coast Range	OR	1.16		0.5	0.8	1.35	Alsea, NADP
Western Cascades (HJ Andrews)	OR	1.7		0.25	0.66	0.42	HJ Andrews, NADP
Average		1.46	0.61	0.74	2.58	0.76	
Weathering							
Western Cascades (Cedar River watershed)	WA			15.2	17.4		Cole et al. 1967
Western Cascades (HJ Andrews)	OR		0.2	4.7	120	7.2	Sollins et al. 1980
Western Cascades (HJ Andrews)	OR			1.6	47	11.6	Fredriksen 1972
Average			0.2	7.17	61.47	9.4	
Leaching							
Western Cascades (HJ Andrews)	OR	1.5	0.8	9.6	123	9	Sollins et al. 1980
Western Cascades (Cedar River watershed)	WA	0.6	0.02	1	4.5		Cole et al. 1967
Western Cascades (Pack Forest)	WA	0.02	0.04	5	50	21	Bigger and Cole 1983
Western Cascades (Pack Forest)	WA	0.08	0.07	11	34	15	Bigger and Cole 1983
Coast Range	OR	5.94	0.02	6.43	8.24	7.83	Perakis et al. 2013
Average, Cascades		0.55	0.23	6.65	52.88	15	
Average, Coast		5.94	0.02	6.43	8.24	7.83	

Measuring deposition from the atmosphere is a relatively simple process, and the National Atmospheric Deposition Program (NADP) maintains nearly 400 wet deposition measurement sites and provides estimates of total atmospheric deposition (wet + dry) throughout the country. Estimating the weathering rates of parent material or the nutrient losses from leaching is more difficult and is usually limited to a watershed. Using a mass-balance method, which assumes conservation of mass, it is assumed that the nutrient flux has a net value of 0, such that inputs must balance outputs. This means that the factors within the model that are most difficult to measure are determined by difference, as has been shown in numerous nutrient budget studies (e.g. Vitousek, 1977; Sollins, 1980).

Soil nutrient capital contents were determined from data collected by staff members of the Stand Management Cooperative (SMC) at the University of Washington (Harrison et al., 2016). Data was collected at four of the five SMC sites sampled for construction of biomass equations (ET, OR, RR, and TOL). Three forest floor samples were collected per treatment plot in a 0.05 m^2 area. Mineral soil samples were collected from a 1.0-m deep soil pit at plot center with a horizontal core from the midpoint of each depth increment. Bulk density samples were dried at 105°C. Mineral soil pH was determined from a 2:1 distilled water:air dried soil mixture. Forest floor pH was determined from a wet slurry of forest floor with distilled water. A CHN analysis was performed on air-dried samples that were sieved to 2mm and then ground. A moisture correction factor was applied to the reported values. Total nutrient content of the soil to 1 meter of depth at each location was based on soil bulk density and nutrient concentration for each horizon. Estimates of nutrient removals were based on projections and harvest scenarios described under *Task 4: Estimate changes in long-term site productivity under different climate change scenarios*.

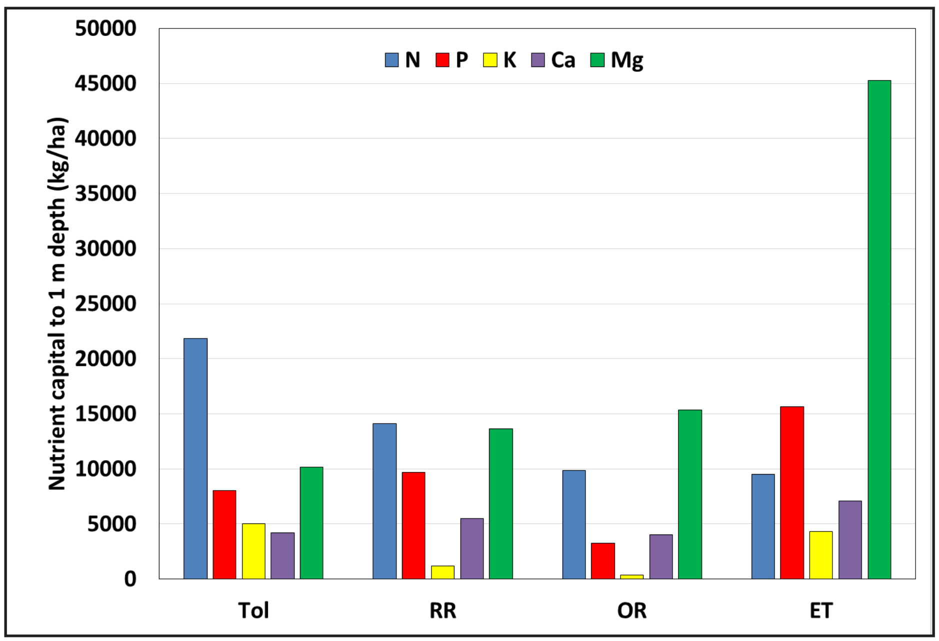

Figure PS-3.2. Total nutrient capital (kg/ha) to a 1.0-m depth on four SMC sites.

Results

The four sites varied significantly in soil nutrient content (Figure PS-3.2). When the net output for the Cascades RR site was compared to the soil nutrient capital at the same site (Table PS-3.2), with the exception of potassium under the most intensive harvest, all percentages were less than 10%. Based on the Evan's stability ratio, all scenarios must therefore be considered sustainable.

Table PS-2.2. Removed and residual carbon at 40 years for the Roaring River and Toledo SMC sites. Assumes 50% carbon in biomass (kg/ha)

	N	P	K	Ca	Mg
WT	-2.74	-0.29	-10.26	1.44	-1.82
BO	-0.52	-0.03	-2.12	3.98	-1.6
Merch	-0.85	-0.05	-2.78	3.65	-1.63
NARA	-2.01	-0.21	-7.59	2.27	-1.75

Coast Range harvests were considered under three scenarios. A recently published study from Oregon Coast Range sites found extremely low concentrations of calcium, particularly in sedimentary parent materials (Hynicka et al., 2016). In such conditions, Hynicka et al. (2016) declared that atmospheric deposition provided essentially all of the calcium inputs. On basaltic parent materials in the Oregon Coast Range, they found that atmospheric deposition made up from 31% to 66% of the calcium inputs. Given the measured values of atmospheric deposition in the Coast Range, calcium parent material can thus be expected to make up 0, 5.74, and 1.33 kg/ha, respectively. Using these estimates, Tables PS-3.3 through PS-3.5

Table PS-3.3. Change in nutrient capital over 40 year rotation at the Coast Range Toledo site assuming that atmospheric deposition contributes 100% of Ca inputs.

	N	P	K	Ca	Mg
WT	-2.7	-0.43	-3.25	-13.38	0.27
BO	-0.72	0.13	-0.1	-8.32	0.79
Merch	-1.12	0.04	-0.47	-9.59	0.66
NARA	-2.06	-0.25	-2.22	-11.72	0.44

Table PS-3.4. Change in nutrient capital over 40 year rotation at the Coast Range Toledo site assuming that atmospheric deposition contributes 31% of Ca inputs.

	N	P	K	Ca	Mg
WT	-2.7	-0.43	-1.5	-8.19	-0.59
BO	-0.72	0.13	1.65	-3.13	-0.07
Merch	-1.12	0.04	1.28	-4.4	-0.2
NARA	-2.06	-0.25	-0.46	-6.53	-0.42

Table PS-3.5. Change in nutrient capital over 40 year rotation at the Coast Range Toledo site assuming that atmospheric deposition contributes 66% of Ca inputs.

	N	P	K	Ca	Mg
WT	-2.7	-0.43	-1.5	-12.18	-0.59
BO	-0.72	0.13	1.65	-7.12	-0.07
Merch	-1.12	0.04	1.28	-8.39	-0.2
NARA	-2.06	-0.25	-0.46	-10.52	-0.42

show the percentage of the nutrient capital removed in a 40 year rotation. Where atmospheric deposition makes up a major portion of the inputs, the stability ratio just exceeds 0.1 (>10%) for calcium under the most intensive harvests (WT, NARA).

Conclusions

Other studies have identified significantly diminished soil calcium following whole tree harvesting (Zetterberg et al., 2013). Whole tree harvesting is estimated to double the depletion rate of the soil nutrient pool relative to a bole-only harvest, a difference that has been previously reported (Sverdrup and Rosen, 1998). Given the limited calcium content of some coastal sedimentary soils, the predicted stability ratio for calcium is indicative of some measure of depletion, though it still does not come close to the 0.3 threshold that would suggest a heightened risk of a decrease in soil productivity. Where previous research has identified significant calcium removals on sites with low soil calcium, trees continue to grow where little measurable soil calcium is detected, and where predictions of productivity decreases due to calcium limitations have not been realized (Rennie, 1955; Binns, 1962; Johnson and Todd, 1990). Biological stimulation of nutrient availability may be one mechanism that ameliorates this otherwise potential nutrient deficiency (Cromack et al., 1977; Vadeboncoeur et al., 2014).

While trees may continue to grow well where calcium availability is limited, it has been speculated that low calcium concentrations and relative high nitrogen concentrations may be contributing to the recent Swiss needle cast epidemic near the Oregon Pacific Coast (Maguire et al., 2000). Although the cause for the emergence of this otherwise innocuous endemic fungus as a significant problem in Douglas-fir remains unresolved, the correlation between limited calcium, a surplus of nitrogen and heightened disease may be another reason to retain as much crown biomass on the site as possible. Extending rotations does provide some relief, though limited. When the Toledo trees were grown to 80 years of age assuming a weathering rate of 0 kg/ha, the calculated stability ratio was 0.125, down from 0.134.

TASK 4: ESTIMATE CHANGES IN LONG-TERM SITE PRODUCTIVITY UNDER DIFFERENT CLIMATE CHANGE SCENARIOS

Task Objective

Determination of changes in long term site productivity due to change in climate required application of models which utilize climate for estimation of biomass production. There are existing temperature- and moisture-dependent tools for the estimation of tree growth, thereby enabling use of future climate scenarios that are provided with existing GCMs. However, although rising temperatures are an expected feature of future climate scenarios, different GCMs predict either increasing or decreasing precipitation to go with rising temperature. Changes in temperature and precipitation could be expected to have significant effects on tree growth through alterations in water availability, evaporative demand, and biogeochemical processes (Boisvenue and Running, 2006). How well the models account for these complex processes is unknown, but the complexity of the responses makes any attempt daunting.

Methodology

To gauge the long-term sustainability of Douglas-fir feedstock production under climate change, the first objective was to estimate the effect of predicted future climate scenarios on future Douglas-fir yields. This was done using two different models: 3-PG (Landsberg and Waring, 1997), a relatively coarse ecophyisological process model; and Climate-FVS (Crookston et al., 2010), a modified version of the USFS FVS empirical growth model. The effects of climate on biomass production are incorporated into 3-PG through changes in available soil water in the growing season, vapor pressure deficit, and the number of days with frost. Climate-FVS uses viability scores to estimate the ability of specific species to continue to grow and survive future climates, and functions that link climate and site productivity so that site productivity can be altered if necessary. Estimates of future yields under different GCM scenarios were used to speculate on the effects of predicted climate change on the sustainability of biomass harvesting.

Climate FVS and 3-PG were run using initial treelists from the most recent re-measurement of the control plots from the sampled SMC sites.These treelists were entered into each model and grown for 100 years using multiple GCM scenarios available within Climate WNA v. 5.10 for the years 2011-2100 (Wang, 2012). Examples of the predicted mean annual temperature (Figures PS-4.1 and PS-4.2) and precipitation (Figures PS-4.3 and PS-4.4) patterns are shown for the two extreme sites (TOL—coastal, 100 m elevation; and ET—Cascades, 784 m elevation).

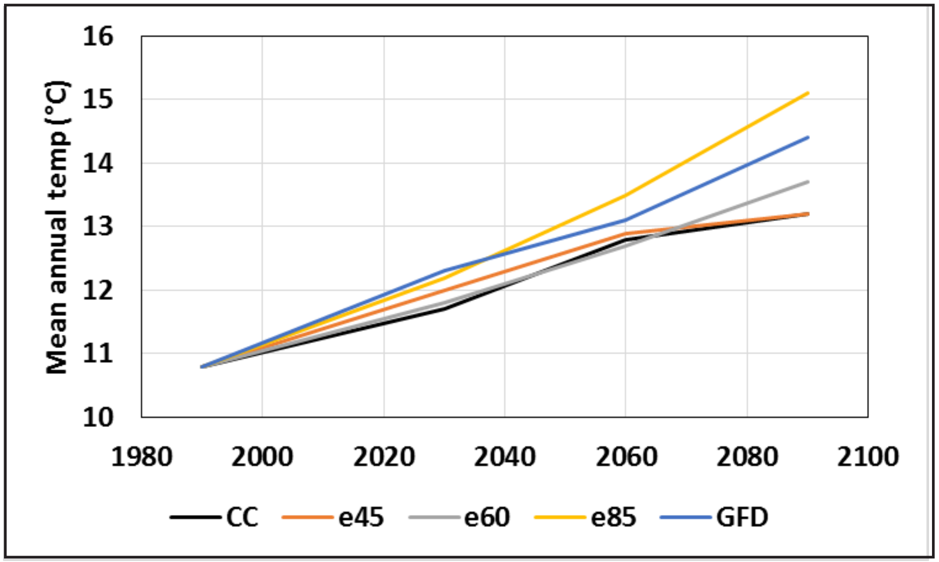

Figure PS-4.1. Predicted future annual temperature at the TOL site near the Oregon Pacific Coast.

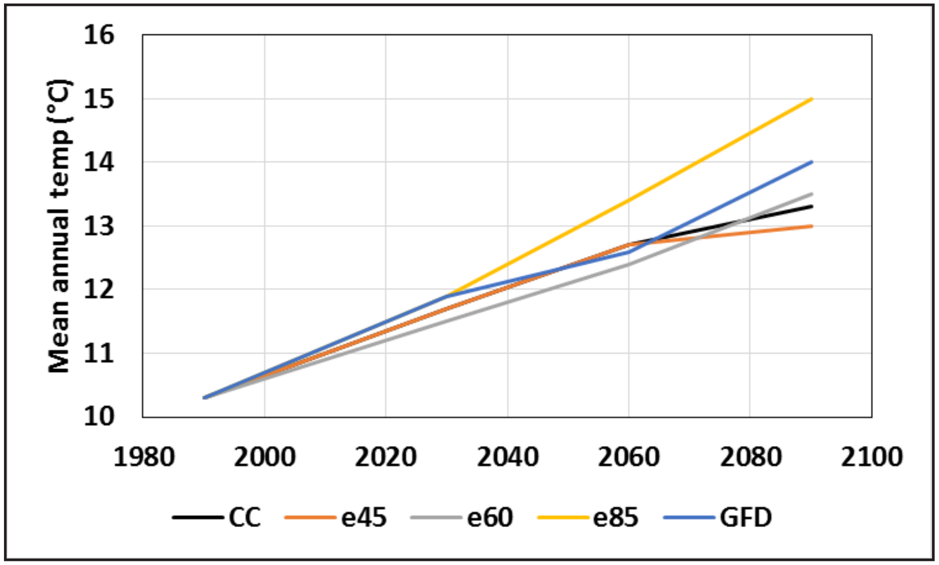

Figure PS-4.2. Predicted future annual temperature at the ET in the Washington Cascades.

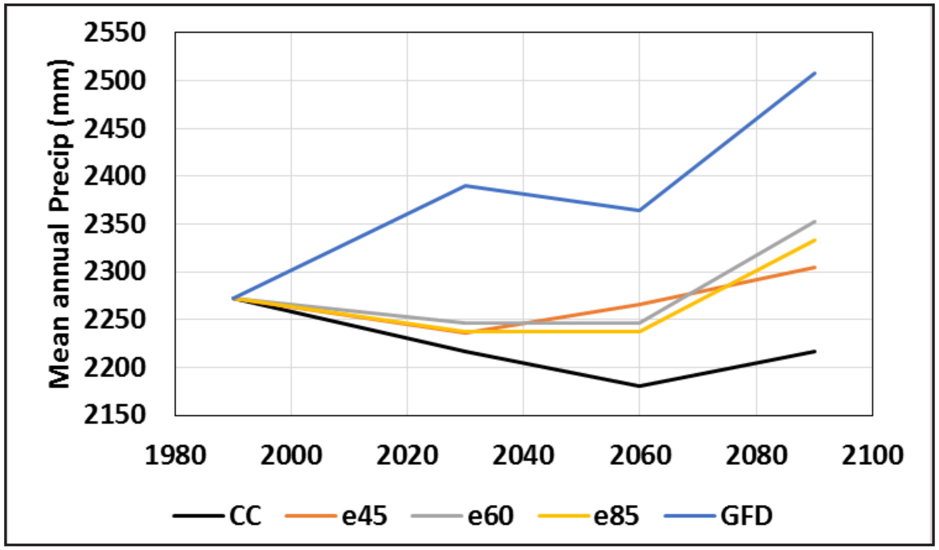

Figure PS-4.3. Predicted future annual precipitation at the TOL site near the Oregon Pacific Coast.

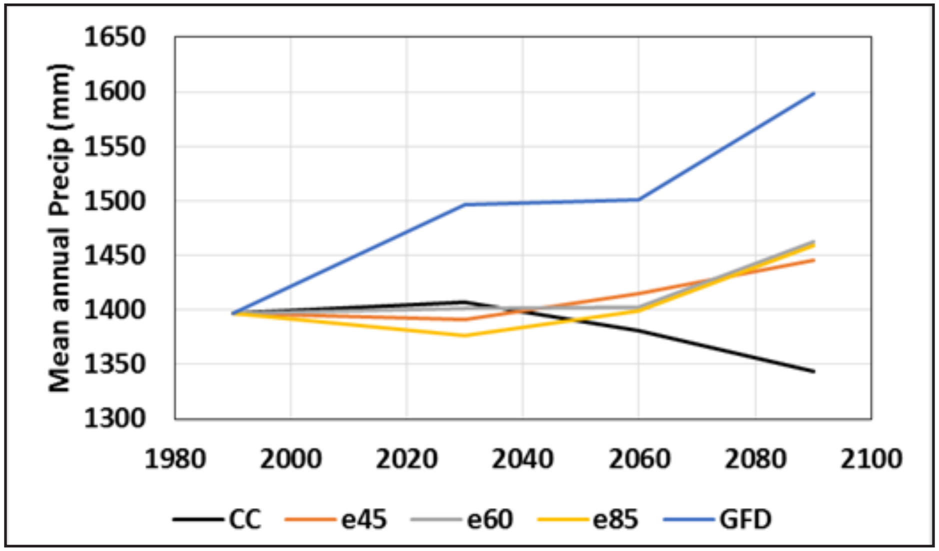

Figure PS-4.4. Predicted future annual precipitation at the ET in the Washington Cascades.

Average temperature values from the two sites are nearly identical in the baseline year of 1990, but different future trajectories result in maximum differences of ~2°C by 2090. Likewise, by 2090, large differences among the most extreme GCM scenarios result in future precipitation differences of ~300 mm.

The 3-PG model runs required soil and fertility data inputs. These were linked wherever possible to data available for the four sampled SMC-sites. The NRCS soil survey data was used to determine soil texture and maximum available soil water for each site. Initial stocking levels (TPH) for each run were chosen to conform to the maximum stocking of the control plot. The input fertility level at each site was then determined iteratively by matching the 3-PG predicted stand basal area to that of the most recent measurement at each site.

Results

The 3-PG model predicted minimal changes in biomass production over the 100 years of simulation, with predictions of reduced yields at three of the four sites (ET, OR, and TOL) and little to no increase at the other site (RR). Maximum reductions in cubic volume at 100 years of age at ET, OR, and TOL were 7, 9, and 5% respectively. Based on the results from 3-PG, Douglas-fir would be predicted to remain a sustainable source of biofuel feedstock.

Climate FVS predictions imply a more drastic change in biomass production, mostly due to decreasing values in species viability. When species viability values within Climate-FVS drop below 0.5, mortality increases to account for the increasingly inhospitable environment for the species of interest. By 2060, the average Douglas-fir viability value for the five different GCM scenarios at ET was 0.65, and at TOL it was 0.37. By 2090, these values were 0.50 and 0.36, respectively. This explains the steady increase in predicted mortality within the projected stands (Figures PS-4.5 and PS-4.6). At TOL, three of the five GCM scenarios predict that Douglas-fir will no longer be present by 2100. The prediction is slightly less drastic at ET, where only 2 of 5 scenarios predict 100% mortality. Climate FVS can be set to automatically establish regeneration when stocking falls below user-set levels, but the hardwoods that are predicted to replace the Douglas-fir (bigleaf maple, Pacific dogwood, and Pacific willow) do not provide compensatory volume for viable timber harvests and associated availability of biofuel feedstock. The choice of these replacement species is based on their relatively high viability scores. Better alternatives are

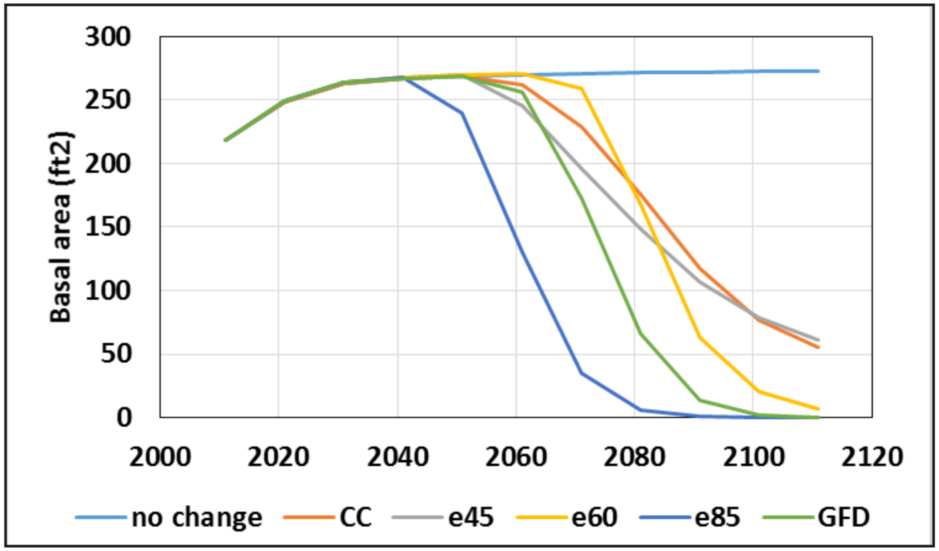

Figure PS-4.5. Climate-FVS predicted future basal area at the ET site in the Washington Cascades.

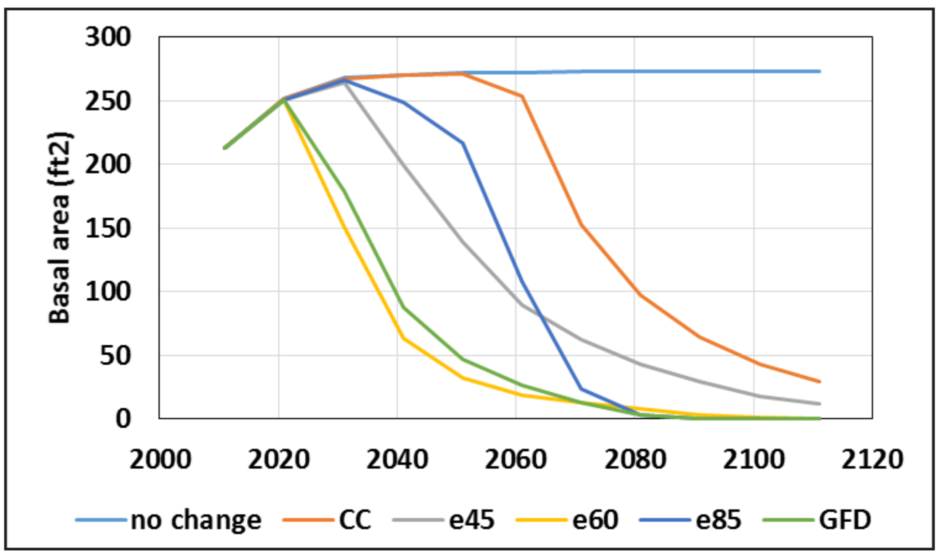

Figure PS-4.6. Climate-FVS predicted future basal area at the TOL site near the Oregon Pacific Coast.

Table PS-4.1. Climate-FVS viability scores for different species whose genus-species abbreviations are represented in the table columns (see Crookston et al. 2010); mortality ensues when score <0.50.

1990	*PRUNU*	*ALRU2*	*PSME*	*THPL*	*AMCA3*	*TSHE*	*SALIX*	*FRLA*	*ABGR*	*PISI*	*TABR2*	*ABAM*	*CONU4*	*CHNO*
	0.8075	0.792	0.77275	0.62675	0.5655	0.543	0.53	0.41625	0.314	0.28275	0.2425	0.218	0.19625	0.1035
2030	*ACMA3*	*PRUNU*	*ALRU2*	*PSME*	*SALIX*	*THPL*	*FRLA*	*TSHE*	*CONU4*	*QUGA4*	*PISI*	*TABR2*	*ABGR*	*ABAM*
	0.709479	0.629625	0.604271	0.583813	0.568771	0.526104	0.50525	0.392146	0.357625	0.331188	0.253208	0.242271	0.194708	0.147833
2060	*ACMA3*	*SALIX*	*ALRU2*	*FRLA*	*PSME*	*PRUNU*	*CONU4*	*THPL*	*QUGA4*	*TSHE*	*PISI*	*ARME*	*ABGR*	*TABR2*
	0.620208	0.568729	0.507438	0.481458	0.479917	0.475021	0.432354	0.371979	0.356125	0.292521	0.241438	0.215479	0.211438	0.206438
2090	*ACMA3*	*SALIX*	*ALRU2*	*FRLA*	*PRUNU*	*CONU4*	*QUGA4*	*PSME*	*THPL*	*PISI*	*TSHE*	*ARME*	*UMCA*	*ABGR*
	0.536833	0.51225	0.470354	0.465146	0.437021	0.433167	0.394521	0.387083	0.328438	0.317792	0.235667	0.229021	0.225125	0.223229

unavailable, as shown in Table PS-4.1. Regardless, based on the results from Climate FVS, Douglas-fir will not remain a sustainable source of feedstock.

Conclusion

Based on the drastically different results from applying the two models, it is difficult to confidently predict the fate of Douglas-fir productivity. Viability scores are based on species-specific likelihood of climate suitability based on the climates that the species are found inhabiting, and those where they aren't (Crookston et al., 2010). The low species viability scores for Douglas-fir occur despite the fact that Douglas-fir is found over a wide geographic and climate range in different varieties (Burns and Honkala 1990). Yet it is the low viability scores which result in Doug-las-fir's removal from the landscapes in the future.

The 3-PG estimates, being less drastic, present a more reasonable scenario. The slight decreases in production 100 years into the future, if treated like a decrease in site index, can be used to assess differences in the allocation of biomass production in stands of differing site index. Branches and foliage biomass tends to be relatively static with increasing stand age due to crown closure and recession. When projecting a treelist from age 30 to 70 with SI_{50} of 40m and 37 m (~9% difference), the stand with the lower SI was predicted to produce slightly greater crown biomass (live branches, dead branches, foliage) at older ages, suggesting greater potential supplies of forest residuals for a given harvest. The more important effect of a changing climate, and one that is not addressed with these models, is how changes in temperature, precipitation, and growing season length affect weathering, atmospheric deposition, and leaching.

NARA OUTPUTS

Publications:

Coons, K., Mainwaring, D., Bluhm, A., Maguire, D., Harrison, R., and Turnblom, E. 2012. Allometric relationships and above-ground nutrient pools under varying stand density and nitrogen fertilization regimes. CIPS Annual Report, 2011. Pp. 39-42.

Coons, K., Maguire, D., Mainwaring, D., Bluhm, A., Harrison, R., and Turnblom, E. 2013. Allometric relationships and above-ground Douglas-fir biomass and nutrient pools under varying stand density and nitrogen fertilization regimes. CIPS Annual Report, 2012. Pp. 28-32.

Coons, K., Maguire, D., Mainwaring, D., Bluhm, A., Harrison, R., Footen, P., Knight, E., and Turnblom, E. 2014. Estimating nutrient pools and nutrient removals under varying intensities of timber harvest and residue utilization in Douglas-fir plantations. CIPS Annual Report, 2013. Pp. 49-55.

Coons, K. 2014. Douglas-fir (*Pseudotsuga menziesii*) biomass and nutrient removal under varying harvest scenarios involving co-production of timber and feedstock for liquid biofuels. M.S. Thesis. Department of Forest Engineering, Resources, and Management. Oregon State University, Corvallis, Ore.

Hann, D., Mainwaring, D., and Maguire, D. 2015. Biomass equations for intensively managed Douglas-fir trees. CIPS Annual Report, 2014. Pp. 46-49.

Maguire, D.A. 2014. Models for the height and shape of the heartwood core on Douglas-fir. Pp. 37-41 in D.A. Maguire and D.B. Mainwaring (eds). CIPS 2013 Annual Report, Center for Intensive Planted-forest Silviculture, College of Forestry, Oregon State University, Corvallis, OR.

Mainwaring, D., Maguire, D., Bluhm, A., Footen, P., Harrison, R., Knight, E., Coons, K., and Turnblom, E. 2015. Estimating nutrient pools and fluxes under varying intensities of timber harvest and residue utilization in Douglas-fir plantations ecosystems. CIPS Annual Report, 2014. Pp. 50-53.

Mainwaring, D.B., Maguire, D.A., Bluhm, A., Harrison, R., and Turnblom, E. 2016. Macro and micro-nutrient concentrations of ten tree components from managed Douglas-fir in the Pacific Northwest. *In prep.*

Mainwaring, D.B., Maguire, D.A., and Hann, D.W. 2016. Silvicultural effects on biomass allometrics from managed Douglas-fir in the Pacific Northwest. *In prep.*

Mainwaring, D.B., Maguire, D.A., Hann, D.W., Bluhm, A., Harrison, R., and Turnblom, E. 2016. Biomass equations for intensively grown Douglas-fir in the Pacific Northwest. *In prep.*

Mainwaring, D.B., and Maguire, D.A., 2016. Forest productivity, feedstock removals, and implications for nutrient flux and sustainability. *In prep.*

Presentations:

Coons, K., Maguire, D., Mainwaring, D., Bluhm, A., Harrison, R., and Turnblom, E. 2012. Allometric relationships and above-ground nutrient pools under varying stand density and nitrogen fertilization regimes. CIPS Annual Meeting. Aurora, Ore.

Mainwaring, D., Maguire, D., and Bluhm, A. 2013. NARA biomass equations, full dataset. CIPS Annual meeting. Vancouver, WA.

Maguire, D., D. Mainwaring, A. Bluhm, and E. Turnblom. 2013. Sources of variation in wood density in Douglas-fir trees grown under varying combinations of stand density regime and nitrogen fertilization. MeMoWood Conference, Nancy, France. October 1-4, 2013.

Maguire, D. 2014. A model for estimating heartwood core in Douglas-fir. CIPS annual meeting. Vancouver, WA.

Maguire, D., D. Mainwaring, A. Bluhm, and K. Coons. 2014. Sustainability of biofuel feedstock production: Aboveground nutrient pools and removals. NARA Annual Meeting, Seattle, WA. September 15-17, 2014.

Hann, D. 2015. Douglas-fir Tree biomass equations. CIPS Technical review meeting. Vancouver, WA.

Mainwaring, D., and Maguire, D. 2015. NARA: Nutrient removals and flux. CIPS Annual meeting. Vancouver, WA.

Hann, D., Mainwaring, D., and Maguire, D. 2015. Biomass equations for intensively managed Douglas-fir trees. CIPS Annual meeting. Vancouver, WA.

Mainwaring, D., Maguire, D., and Harrison, R. 2015. Forest productivity, feedstock removals, and implications for nutrient flux and sustainability. Stand Management Cooperative Fall meeting, Victoria, B.C.

Mainwaring, D., Maguire, D. and Harrison, R. 2015. Forest productivity feedstock removals, and implications for nutrient flux and sustainability. NARA Annual Meeting, Spokane, WA. September 15-17, 2015.

NARA OUTPUTS (CONT.)

Mainwaring, D., Maguire, D., and Marshall, D. 2016. Biomass sampling at Silver Creek Mainline. Stand Management Cooperative Fall Meeting, Seattle, WA.

Posters:

Coons, K., Maguire, D., and Mainwaring, D. 2012. Sustainable biofuel production from forest biomass. Northwest Advanced Renewables Alliance Meeting, Seattle, WA.

Maguire, D., Mainwaring, D., Bluhm, A., Coons, K., Harrison R., and Turnblom, E. 2014. Sustainability of biofuel feedstock production: Above-ground nutrient pools and removals. Northwest Advanced Renewables Alliance Meeting, Seattle, WA.

Software Enhancements:

1) Biomass components added to ORGANON DLLs that control output from simulating Douglas-fir growth under intensive silviculture. ORGANON and DLL version developed by D. W. Hann, College of Forestry, Oregon State University, Corvallis, OR.

2) Biomass components and nutrient contents added to output from EXCEL application, XORG, that simulates Douglas-fir stand development under user specified silvicultural regimes. Developed by D. Mainwaring, Center for Intensive Planted-forest Silviculture (CIPS), College of Forestry, Oregon State University, Corvallis, OR.

NARA OUTCOMES

Previously published equations for Douglas-fir biomass have generally been constructed from combining disparate datasets (e.g. Gholz et al., 1979), and have included data from old growth stands (Means et al., 1994), uneven-aged stands (Marshall and Wang, 1995), young plantations (Helgerson et al., 1988; St. Clair, 1993), and Rocky Mountain stands (Brown, 1978). Furthermore, biomass has generally been predicted from diameter alone (Gholz et al., 1979; Jenkins et al., 2004). Because of the strength of the sampling dataset, the equations produced from this study constitute a powerful means of predicting biomass for the westside Douglas-fir stands producing most of the utilizable material: intensively managed stands subject to any number of silvicultural treatments or conditions.

FUTURE DEVELOPMENTS

Results from the NARA project have been applied directly in the growth models being developed the Center for Intensive Planted-forest Silviculture. Estimation of biomass components and corresponding nutrient contents have allowed simulation of Douglas-fir stand development to be interpreted with respect to periodic annual demand for nutrients, with implications for nutrient management through fertilization, retention of logging residuals, and consideration of natural nutrient cycling through the course of stand development. Future work will build on this basic NARA information, particularly in regard to refining models of nutrient cycling through litterfall, tree mortality, and harvesting residuals. Some basic insights into internal translocation of mobile nutrients have also helped refine estimates of uptake required to maintain productivity.

Patterns in nutrient use efficiency are also estimable from the NARA database, and will be pursued as an important part of controlling productivity through nutrient management.

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