AN ABSTRACT OF THE THESIS OF

Kristin L. Coons for the degree of Master of Science in Sustainable Forest Management presented on December 19, 2014

Title: Douglas–fir (*Psuedotsuga menziesii*) Biomass and Nutrient Removal under Varying Harvest Scenarios Involving Co-production of Timber and Feedstock for Liquid Biofuels

Abstract approved:

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Douglas A. Maguire

In this study an improved model of biomass and nutrient estimation of coastal Douglas-fir (*Psuedotsuga menziesii*) in the Pacific Northwest has been developed across a wide range of stand management regimes. This study quantifies and defines the type and intensity of biomass harvest and associated removal for actively managed stands on a scale applicable to biofuel production. This study provides a preliminary estimate of the implications of varying levels and intensity of harvest on long term site productivity that will require calibration with actual harvest and nutrient flux data. Of total tree mass over all sites, 1-yr-old, 2-yr-old, and ≥3-yr old foliage, live branches, bark, sapwood and heartwood comprised 2% (1.0-3.4% range), 1% (0.6-1.7% range), 1% (0.8-3.0% range), 3.3% (2.2-4.5% range), 13% (8-31% range), 44% (24-59% range) and 35% (24-44% range), respectively, of total aboveground tree biomass. Four scenarios for aboveground biomass removal from the site were considered: 1) BO: merchantable bole only; 2) BT: entire tree except for the top portion above a four-inch stem diameter; 3) VC: entire tree except for one vertical half of the crown; and 4) WT: whole tree with top and all

branches. The nutrient harvest and biomass removed under each scenario increased in the following order BO<BT<VC<WT. The mean relative total aboveground biomass removed by each of the scenarios was 70% for merchantable stem only (BO), 75% for loss of the top above the four inch stem diameter (BT), 97% if one vertical half of the crown was sheared off. Total foliage contained 20, 34 and 49% of Ca, Mn and N, respectively, despite comprising no more than an average of 9% of the total stand level aboveground biomass. The total aboveground nutrient pool contained no more than 2.2% (average of 0.4%) of the total pool (soil + aboveground biomass) of N, P, Ca, Mg and S, and contained no more than 8.6% (average of 1.4%) of the total site K pool. The maximum stability ratio among all nutrients and sites in this study was 0.089 (0.006 mean) and at a full rotation of 50 years would be no higher than 0.113 (0.0081mean), just over the static ratio threshold of slight risk to long term site productivity (0.1). These static stability ratios are limited in their estimates of potential adverse impacts on nutrient availability and supply because nutrient fluxes (e.g., mineralization, leaching and atmospheric deposition rates) are not taken into account. The quantification of nutrient fluxes is necessary to provide a more accurate representation of future impacts of increased harvesting intensity to long term site productivity.

Douglas–fir (*Psuedotsuga menziesii*) Biomass and Nutrient Removal under Varying Harvest Scenarios Involving Co-production of Timber and Feedstock for Liquid Biofuels.

by
Kristin L. Coons

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Kristin L. Coons, Author

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1 Introduction

The tripling of energy consumption in the U.S. from 1949 to 2010 (Perlack and Stokes, 2011) has increased the need for the utilization and development of alternative renewable energy sources for energy independence, stability and sustainability. Forest biomass is one potential source of liquid biofuels that could offer an economically viable and renewable alternative to fossil fuels**.** Biomass and nutrient distribution have not been adequately quantified for actively managed stands in the Pacific Northwest (PNW), limiting our knowledge about the sustainability of producing liquid biofuels from forest biomass. Actively managed timber stands will be the primary source of biomass utilized for biofuel production, at least initially, because residual biomass from timber production or from subsidized forest fuel reduction would not otherwise be economical to access. An increase in harvest utilization required for biofuel feedstock and associated removal of tree components that contain high concentrations of nutrients has the potential to cause declines in long term site productivity. The goal of the this project is to assess the ecological sustainability of producing biofuel feedstock from logging residues left after harvesting of intensively managed Douglas-fir forests. The three specific objectives of this analysis were; (1) to quantify and model the dynamics of tree biomass components in Douglas-fir ecosystems managed under a wide variety of silvicultural regimes; (2) to estimate the amount of all plant macro- and micro-nutrients removed under different utilization intensities of timber harvest residues; and (3) to estimate sustainable levels of biofuel feedstock production from logging residues in intensively managed Douglas-fir ecosystems.. Douglas-fir (*Psuedotsuga menziesii*) forests constitute the majority of

above-ground biomass in Oregon (Zhou and Hemstrom, 2009), but relatively little work has been done to develop tree allometric relationships and quantify nutrient concentrations specifically for intensively managed stands that have been subjected to a wide range of intensive silvicultural treatments (e.g., combinations of competing vegetation control, fertilization, and thinning). Accurate quantification of these responses is essential for understanding the potential for nutrient depletion under intensive utilization of forest biomass from stands already intensively managed for timber production. The four levels of biomass removal investigated in this analysis included: (1) WT: whole tree; (2) VC: whole tree minus one vertical half of crown assumed to be sheared off during felling and/or yarding; (3) BT; whole tree minus the top assumed to be broken off at a four-inch stem diameter (including stemwood, branchwood and foliage); and (4) BO: bole only. Because the effects of these four removal intensities will depend on the allometric relationships and nutrient concentrations described above, this analysis required understanding the interaction of specific management regimes and biomass removal intensities. Sustainable levels of biofuel feedstock production were inferred from organic matter removals, the full suite of contained tree nutrients, and assumptions about nutrient pools and replishment rates. Depending on the anticipated impact on various sites, the efficacy and viability of nutrient amendments were also discussed.

2 Literature Review

2.1 Biofuel as Alternative Energy

The production and development of liquid biofuel as an alternative renewable energy source will increase the diversification and stability of energy supplies in the United States. From 2004 to 2011, approximately 2 quadrillion BTUs of this renewable energy was supplied from woody biomass (Hojjati and Wade, 2012) In 2004 energy produced by forest biomass comprised 2% of primary energy consumption within the U.S. (50% of total energy derived from biomass), and this alternative energy source may have extensive capacity for increase (Graham et al., 2004). Douglas-fir is the tree species of greatest commercial importance in the Pacific Northwest (PNW) and in Oregon alone contributes about 51% of total above ground biomass of trees larger than 12.5 inches in diameter at breast height (dbh), approximately the current minimum merchantable size (Zhou and Hemstrom, 2009). Douglas-fir is a very important species in this region because it is adaptable to wide range of site conditions (wide ecological amplitude), maintains high growth rates (high net primary production), and produces high quality wood products (high modulus of elastisticity and module of rupture). Renewable energy consumption (excluding ethanol) is projected to increase to 8.4 quadrillion BTUs (8 % of energy consumption) by 2015 and to 9.7 quadrillion BTUs (9 %) by 2030 (White, 2010). The leading national level biomass assessment, The U.S. Billion-Ton Assessment, and ongoing subsequent analyses are exploring the possibility of displacing 30% of the nation's petroleum consumption with biofuels (Graham et al., 2004).

Assessment of the economic constraints of biomass harvesting and subsequent potential for biofuel production requires allometric equations which are applicable to a variety of stand conditions resulting from a range in intensive silvicultural regimes that are designed to optimize timber production, as well as other ecosystem services that vary from site to site. These stands are intensively managed for timber production are likely to be the source of most biofuel stock derived from forest biomass. Transportation is the single largest component cost (Ralevic et al., 2010) and therefore, constrains utilization of residual biomass as biofuel feedstocks to a limited distance from a processing facility. In the United States (US) and elsewhere, inventory data have been used for making current estimates of biomass and productivity at various scales from regional (Brown et al., 1997, 1999; Jenkins et al., 2001) to continental (Ni et al., 2001; Turner et al., 1995). The generalized equations used to estimate these regional supplies may be sufficient for a mix of forest types under low intensities of management, but lack the required accuracy for trees and stands managed under widely varying silvicultural regimes because of the latter's effects on allometric relationships. For site-specific applications, such as estimation of available biomass, the amounts in harvesting residuals, and potential impact of removals on nutrient capital, the equations must be sensitive to differences in biomass allocation imposed by stand density and nutrient availability (Jenkins et al., 2003).

2.2 Current Biomass Equation and Limitations

Current biomass equations for Douglas-fir were developed from unmanaged stands at or near maximum density, so height-diameter relationships did not vary tremendously, hence the allocation of biomass among components of a tree (i.e.,

allometric relationships among diameter, height, and foliage, stemwood, bark, root, and branch biomass) did not vary widely among trees with the same diameter. Generalized regional and national level equations such as those presented by Lambert et al. (2005), Jenkins et al. (2004), and Gholz et al. (1979) are estimates which use only diameter at breast height (dbh) and assume that allometric relationships are unaffected by current age, past management history, or environmental conditions. Among stands with varying management history, biomass and volume estimates calculated from diameter only do not account for the resulting variation in height and taper or the relative allocation of biomass among the foliage, branchwood and stem. Allometric relationships, as well as nutrient concentrations, vary considerably not only with species and management regime, but also by site quality as determined by soil attributes and climatic factors (Cannell, 1982; Bartelink, 1997; Poorter et al., 2012).

In summary, application of diameter-based equations can lead to extreme bias in estimates of biomass components (Harrison et al., 2009; Kantavichai et al., 2010). In softwood species like Douglas-fir, the mean differences among estimates from alternative biomass equations approaches 40% (Jenkins et al., 2003). At the Fall River long-term site productivity study in Washington, Harrison et al., (2009) found that equations developed by Gholz, (1979) overestimated stem wood dry weight of Douglas-fir by 17% in a 47-year-old coastal mixed conifer stand. In other 55-year-old Douglas-fir stands studied by Kantavichai et al., (2010) which received different combinations of thinning and biosolid applications, predictions from equations presented by Gholz et al. (1979) and Jenkins et al. (2003) varied from 52% to 103% of actual stemwood biomass.

When diameter can be supplemented with height as a predictor of aboveground biomass, the results are typically more accurate because a constant height-diameter relationship is not assumed and because a given dbh-height combination implies live crown size; hence, the variability in tree dimensions and the implications for biomass content are more accurately accounted for (Vallet et al., 2006). Although of less dramatic effect, correlated differences in tree stem taper can be also be accounted for (Case and Hall, 2008).

Increasing density can reduce dominant diameter growth, with relatively little effect on height growth except at extreme stand densities (Cremer et al., 1982; Knowe, 1994, 1991; Omule et al., 1987; Wagner and Radosevich, 1991). Exceptions have been documented; for example, height growth was substantially reduced at high stand densities ($\geq$ 275 trees ha^{-1}) in the Wind River spacing trials (Reukema, 1979, 1970). As implied in statistical analyses of other biomass equations, Lambert et al. (2005) found that the addition of height: 1) improved stem mass estimates; 2) did not improve accuracy of crown component estimates; and 3) was secondary to diameter in predicting stem biomass. The inefficacy of height in combination with diameter for estimating crown biomass contrasts sharply with other studies (e.g., Snell and Anholt, 1981).

Crown morphology and structure can be quite plastic in response to a tree's local growing environment (e.g. Fisher and Hibbs, 1982). Crown shape responds to both current and past competition in managed stands (e.g. Deluze et al., 1996), and for the reasons described above, crown biomass on a tree of given diameter can differ

substantially between stands (Bartelink, 1996). In particular, crown structure (particularly live crown length) has been shown to be influenced by age (Ishii and McDowell, 2002), crown class (Gilmore and Seymour, 1997), stand density (Curtis and Reukema, 1970), species composition (Garber and Maguire, 2005), stand density regime (Marshal and Curtis, 2002), and fertilization (Weiskittel et al., 2007). Crown development has been shown to respond strongly both to variations in initial spacing (Curtis and Reukema, 1970; Stiell, 1966) and to differences in thinning intensity (Briegleb, 1952); in fact, direct effects of spacing on branch size and branch distribution have been well documented (Grah, 1961; Kenk and Unfried, 1980).

The addition of crown length as a predictor is generally much greater than height for improving the accuracy of crown biomass compartments (Monserud and Marshall, 1999; Pulkkinen, 1991; Raulier et al., 1996). Crown length and width variables specifically have improved predictions of foliage biomass in interior Douglas-fir (Brown, 1978; Marshall and Wang, 1995). The size of the crown relative to stem diameter and height determines the ratio of foliage mass to branch mass (Bartelink, 1996). Branch diameter of Douglas-fir is highly sensitive to silvicultural treatments (e.g. Kenk and Unfried, 1980; Maguire et al., 1991), with significant differences even in an increase in initial densities from 100 to 200 trees per hectare (Hein et al., 2008). Crown closure is reached sooner at closer spacings, so maximum stand-level foliar biomass is also attained earlier than in more widely spaced stands (Tuner and Long, 1975). Wichmann (2002) found that tree size variables were very effective surrogates of past and present growing space; because they performed better than distance-dependent measures of growing space

for explaining individual branch growth, stand density measures are generally not needed in crown biomass equations. The efficacy of individual tree attributes for predicting crown structure has been assessed repeatedly in even aged, single species stands (Colin and Houllier, 1991; Mäkinen et al., 2003), but their efficacy in multi-cohort, mixed species stands is less well known (Weiskittel et al., 2010).

Direct growth response to N fertilization generally has been concluded to last less than ten years in Douglas-fir (Brix 1983), as well as in other species, but responses on some sites have been reported to last for a longer period (Binkley and Reid, 1985; Miller and Tarrant, 1983). The duration of stem growth responses to thinning and fertilization has been related to changes in foliar biomass and nutrient concentration (Brix, 1983). At the Shawnigan Lake installation on southeastern Vancouver Island, British Columbia, the direct and indirect stem growth response to N fertilization lasted at least 15 years in both thinned and unthinned stands (Gardner, 1990). On the same study site, Mitchell et al., (1996) found an increased total growth response in all aboveground tree components and changes in their distribution that lasted 18 years. The N fertilization increased production by 14% in unthinned stands and by 59% in thinned stands relative to their unfertilized counterparts, whereas thinning alone decreased production by 24% (Mitchell et al., 1996). Brix and Mitchell (1983) found that nitrogen fertilization of Douglas-fir increased the relative mass of foliage on the tree, thereby changing allometric relationships. Treatment effects (thinning and /or fertilization) were greatest on relative biomass allocation to live branches, and this relative shift in allocation increased over time (Mitchell et al., 1996).

2.3 Nutrients

Nutrient concentrations and distribution among tree components varies by site and species. Identifying patterns is difficult due to the wide variability in the range of nutrients examined, field and lab techniques, and silvicultural history. This variability between sites and studies has made assessment of nutrient concentrations across large scales very challenging. Inaccuracies and inconsistencies in estimating biomass components adds to the difficulty in drawing general conclusions about the quantity and distribution of nutrients in managed forests (Harrison et al., 2009; Hailemariam et al., 2007; Jenkins et al., 2003; Ponette et al., 2001).

Trees require thirteen essential elements (in addition to carbon, hydrogen, and oxygen) that are distributed in different patterns and concentrations throughout the tree. Macronutrients (those reaching highest concentrations) include nitrogen (N), phosphorous (P), and potassium (K), sulfur (S), magnesium (Mg), and calcium (Ca). The seven micronutrients include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), boron (B), and chlorine (Cl). The primary nutrients (N, P and K) have their highest concentrations in foliage, leading to high proportions of the total above-ground pool in foliage. Some nutrients, such as calcium, are contained in greater quantity in the stem wood. The trend of mean concentrations of most elements in Douglas-firs trees has been consistently found to increase from stemwood to stembark to branchwood to needles (Mitchell et al., 1996; Pang et al., 1987; Ranger et al., 1995). One exception is the relative concentrations between stem bark and branchwood, but this

comparison is confounded by the convention of including both bark and wood in the branchwood component.

In Douglas-fir stands ranging from 26-54 years in age in France, stem wood accounted for ≥70% of the aboveground biomass in Douglas-fir, but the contribution of stemwood to total aboveground nutrient content never exceeded 32% (Ponette et al., 2001). The proportion of several elements (N, P, K, Mg and Ca) in the branches (wood + bark + needles) ranged from 45% to 76%. In the same study, foliage contained from 20% to 53% of total nutrient content while comprising less than 10% of total aboveground biomass. In an earlier Canadian study of above-ground biomass in 21 young (15-20-yr-old) Douglas-fir trees, approximately 50% of the N, P and K and 40% of the Ca and Mg was contained in the foliage (Webber 1977). In a 36-year-old second growth plantation in western Washington, Douglas-fir foliage contained approximately 35% of the N, 48% of the P, 32% of the K and 25% of the Ca in the above ground biomass of 10 sample trees (Cole et al., 1967). Current foliage usually has higher concentrations and lower between tree variability than older age classes of foliage (Lowry and Avard, 1969; Mead and Will, 1976), although this trend can vary slightly for some elements among different locations in the crown. For most macronutrients and Cu, the precision obtained would be of the order of ± 5% to ±10%, but for Ca and the micronutrients it is usually much larger because between-tree variation of these elements is greater (Knight, 1978a) Some of the differences between trees is associated with crown class (Madgwick, 1964b).

As can be inferred from these studies of nutrient concentration and distribution within and among trees, different silvicultural treatments and harvest removals will differ with respect to their impact on site nutrient capital. Biomass removal for biofuel feedstock in the US Pacific Northwest (PNW) will potentially increase nutrient loss, depending on whether additional biomass is removed from the site or whether it will simply target slash piles that are otherwise left on landings. Regardless, forest residues left after conventional removal of the merchantable bole contain a disproportionately high proportion of the aboveground nutrient capital, so their location after harvesting operations is the first consideration when considering impacts of timber harvesting on nutrient removal and harvesting sustainability. Mann et al. (1988) found that whole-tree harvesting (removal of tree branches and tops along with the merchantable stem) removes about 16% more biomass than stem only harvesting from Douglas-fir stands, but 65%, 83%, 52%, and 169% more N,P, K, and Ca. Ralevic et al. (2010) estimated that the biomass that could be potentially available for bioenergy varied between 49% and 65% of total above-ground biomass. The technical harvestability of forest residuals depends on the profitability of the operation, season of harvest, and site conditions, especially moisture content (%). Site conditions include variables such as residual location (i.e., whether at the stump, at roadside, or at a landing), accessibility, tree size, species composition, age, spacing, density, area, terrain conditions, the condition and location of the road, season and ground characteristics and the subsequent type of harvest system and supply chain that has been adopted. The contamination of residues (i.e., fuel quality) and their moisture content are other important factors to consider in determining the value of

the delivered fuel. For instance, the high moisture content of harvest residues, combined with their low bulk density, makes the transport of biomass feedstock costly over long distances. The distance of the landings from the back of the stand will influence the handling and piling that is available at roadsides. Season of harvest has an impact on the productivity and duration of operations, primarily through effects on the moisture content of biomass, which then influences downstream transport operations, storage requirements and the overall value of the delivered fuel (Mederski, 2006; Cormier and Ryans, 2006). When these harvest limitations were considered Ralevic et al., (2010) found the technically harvestable biomass was reduced to between 2% to 25%. The potential quantity of forest residual removal varies by site and is dictated by economic and logistical constraints that are dependent upon stand characteristics, management strategies, and available equipment.

Whole-tree (WTH) harvesting can alter soil productivity under some site and stand conditions, such as P-limited sites (Ponder et al., 2012; Thiffault et al., 2011; Powers et al., 2005). However, results from 10 years after treatments in the Long Term Site Productivity (LTSP) study suggested that harvesting intensity had little consequence for soil productivity compared with forest floor removal (Ponder et al., 2012). Site sensitivity appears to be crucially linked to (1) climate and microclimate, (2) mineral soil texture and organic C content, (3) the capacity of the soil to provide base cations and P, (4) and tree species autoecology. Autoecology is defined as the interaction of Douglas-fir stands and trees with an ecosystem. Field trials that cover a range of conditions along a gradient of one of the four factors mentioned above would allow us to refine the

prioritization of these factors and facilitate the identification of threshold values or categories of vulnerable site or stand conditions, thereby identifying those sites with the greatest risk of impacts to long term site productivity from intensive biomass harvesting. Studies that measure and report such information would improve cross-site comparisons and aid in the examination of relationships between site conditions and potential impact of biomass harvesting on soil productivity (Thiffault et al., 2011).

In summary, variability in site conditions and silvicultural regime strongly influence allometric relationships and nutrient concentrations. In this study biomass and nutrient concentration of coastal Douglas-fir in the Pacific Northwest was sampled across a wide variety of tree diameter, height, and crown length (D/H/CL) combinations from plots that had been fertilized, thinned, and/or treated for competing vegetation. Sustainable deployment of bioenergy production systems requires developing site-specific ability to predict how intensive forest management and harvesting will affect long term site productivity (Smith, 1995). Defining and developing systems for predicting nutrient allocation and nutrient concentrations within Douglas-fir trees managed under differing silvicultural regimes will improve the ability of forest managers to assess the potential impacts of alternative biomass harvesting intensities. The objective of this project was to quantify tree biomass and nutrient pools and assess implications of varying biomass utilization intensities on total nutrient pools in managed Douglas-fir ecosystems. After developing a system for estimating biomass and nutrient content of tree components in intensively managed Douglas-fir stands, biomass and nutrient removals under the following four harvest scenarios were simulated: (1) whole

tree, (2) stem and all branchwood, (3) stem and clean chip components (top and large branches), and (4) stem-only. The prediction system and harvest systems were intended to represent as wide of a range of stand management regimes and removal intensities as possible and to encompass the operational regimes and removals that could potentially be put into practice for joint production of timber and biofuel feedstock.

3 Methods

3.1 Field

Four Stand Management Cooperative (SMC) Type I installations were selected for the Northwest Advanced Renewables Alliance (NARA) biomass and nutrient content sampling. All SMC Type I installations were established as one block of a regional randomized block design. Plot location within an installation was based on achieving uniformity and comparability across slope, aspect, ground vegetation, species composition and stocking Plots were arranged as contiguously as stand and site uniformity allowed to facilitate remeasurement and to protect the site from unscheduled management activities. These SMC Type I sites were established in juvenile stands of varying initial densities in order to: 1) assess the effects of wide early spacing on subsequent tree and stand growth, tree and stand yield, wood properties and product value; 2) to assess the effects of later thinning, applied to stands having early stocking control, on subsequent tree and stand growth, tree and stand yield, wood properties, and product value; 3) to assess the effects of pruning, fertilization, and tree selection during pre-commercial thinning on growth, yield, and value of stands that have received early and continued density control (Maguire et al., 1991).

Each SMC type I site has seven plots corresponding to the seven basic treatments. At plot establishment, the average number of stems per unit area (ISPA) was computed for a given installation, and four of the seven core plots were left at this ISPA, two were respaced to one half the ISPA (ISPA/2), and one was respaced to one quarter the ISPA (ISPA/4). Thinning regimes for the plots were designed to be triggered when stand

density reached a specific value; these thinning targets were specified by Curtis's (1982) relative density, defined as the ratio of stand basal area to the square root of the quadratic mean diameter. The following three stand density regimes were sampled for NARA biomass trees: (i) SD1A was an ISPA plot that received no thinnings; (ii) SD1B was an ISPA plot scheduled for repeated thinning, with the first thinning at a relative density of 55 and residual relative density of 35, the next thinning at a relative density of 55 to a residual relative density of 40, and all subsequent thinnings at a relative density of 60 and residual relative density of 40; (iii) SD2 was an ISPA/2 plot that had a minimal thinning regime starting when the relative density reached 55 and was thinned to a residual relative density of 35, but no further thinnings were implemented; and (iv) SD4 was the ISPA/4 plot, which received no thinnings (Sucre et al., 2008). The stand density treatments, SD1A, SD2 and SD4 represented the highest, medium, and lowest stand density regime for that installation. On nine installations that had sufficient room for additional plots, another set of three plots scheduled for the last three thinning regimes (SD1B, SD2, and SD4) were installed and scheduled for fertilization in addition to respacing/thinning. Three additional plots were fertilized with 220 kg/ha of nitrogen in the form of urea at every 4-year remeasurement, up to a maximum of five applications for a total of 1100 kg N/ha.

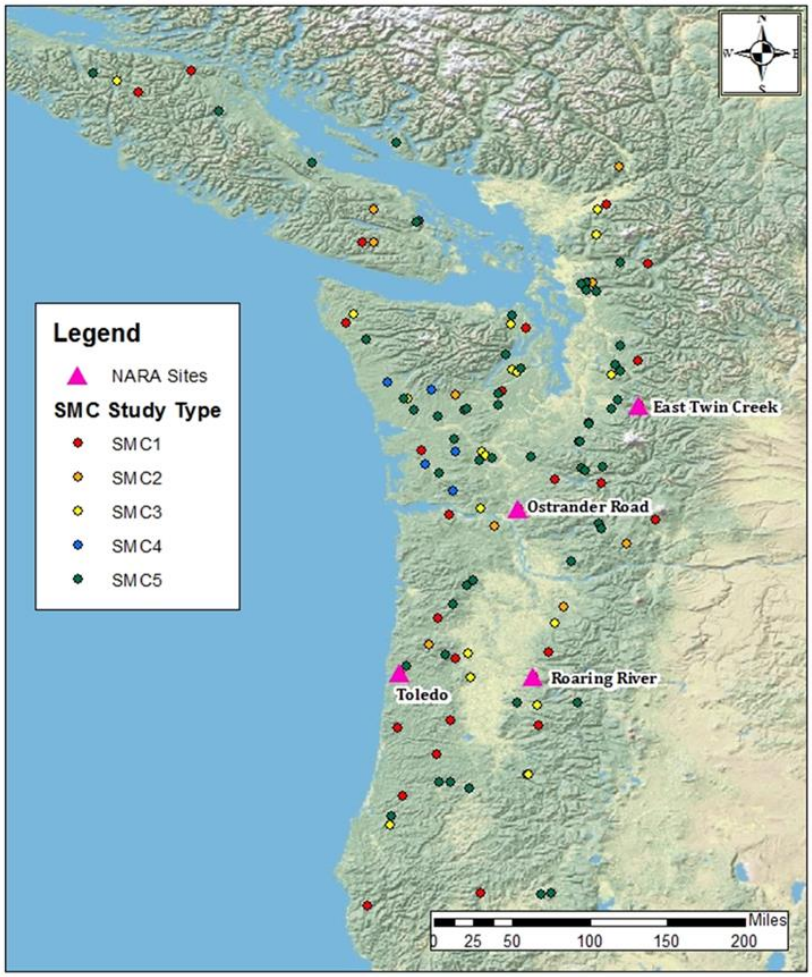


Figure 1. SMC sites with the four NARA SMC Type I sites sampled.

Four of the nine Stand Management Cooperative (SMC) Type I installations with supplementary fertilization treatments were selected for NARA sampling to represent the widest possible range in diameter, height, and crown length (D/H/CL) combinations (Fig. 2-6). These four sites were East Twin (ET), Ostrander Road (LF), Roaring River (RR), and Toledo (PC) (Fig. 1). The ET installation was the northern-most site sampled and is located on glacial outwash soils. The remaining installations (LF, RR and PC) occur on

soils with a more developed soil profile than the sites occurring on glacial outwash. The underlying material at these sites was either residuum (LF and RR) or alluvium (PC) (Sucre et al., 2008). The PC site has signs of Swiss Needle Cast (SNC), which is a foliage disease that is specific to Douglas-fir and is caused by the fungal pathogen *Phaeocryptopus gaeumannii*. More detailed site information is available in Table.1.

Table 1. Detailed descriptions of study sites with the SMC Type I study sites.

	Ostrander Rd. (LF)	East Twin Creek (ET)	Roaring River (RR)	Toledo (PC)
	(704)	(705)	(718)	(726)
Latitude	46 12'47.46"	47 10'35.97"	44 53'49.09"	44 41'29.99"
Longitude	122 50'48.91	121 43'4.22"	122 42'15.6"	123 56'34.4"
Elevation	600	823	335	69
SI 50 (m)	37	27	39	41
Douglas-fir site class	II	IV	II	I
Average slope (%)	20	30	10	15
Precipitation (mm-year-1)	1175	1449	1778	1726
Soil Texture	Fine-loamy	Loamy-skeletal	Fine	Fine-loamy
USDA soil suborder	Palehumult	Haplocryod	Palehumult	Dystrudept
Stand establishment	1976	1976	1982	1984
ISPA	575	700	400	362

1. Sucre et. al, 2008

Silvicultural treatments were implemented on seven 0.2-ha sample plots (47.2m x 47.2 m) surrounded by a 9.3 m wide buffer strip. Each plot has one additional 9.3 m buffer (double buffer) strip located on one side of the plot. Three trees were sampled from this double buffers at each of the seven selected treatments.

At each site, 21 trees were destructively sampled in the winter of 2011-2012 for estimating biomass components and nutrient concentrations. Three trees representing the 10^{th}, 50^{th} and 90^{th} percentiles of the diameter distribution were sampled from the

double buffer of each of the seven treatments. After trees were felled, they were measured for dbh (nearest 0.1 cm), height (nearest 0.01m), and height to the lowest live branch (nearest 0.01m). Total tree heights ranged from 17.11 – 34.50 m with an average of 26.16 m (Fig. 2). Diameters at breast height (1.37 m) and ranged from 11.5 cm to 51.0 cm and averaged of 32.4 cm (Fig. 3). Live crown length ranged from 3.94 m to 22.22 m with an average of 13.74 m (Fig.4). Crown lengths varied by up to 5 m for every 5 meter increment of height (range of 17-35 m) and total tree heights varied by up to 13 m for a every 5 cm increment of dbh. Specific parameter ranges and distribution are listed in Table 2 and Table 3.

Table 2. Variation in tree height (m) with each 5 (cm) diameter increment.

Diameter (cm)	Min (m)	Max (m)	Range (m)
10-14.99	17.11	24.62	7.51
15-19.99	18.05	26.7	8.65
20-24.99	19.4	27.13	7.73
25-29.99	21.58	30.1	8.52
30-34.99	20.43	32.01	11.58
35-39.99	21	33.1	12.1
40-44.99	21.7	34.5	12.8
45-49.99	23.05	33.5	10.45
50+	24.7	24.7	0

Table 3. Variation in crown length (m) with 5 (m) height increment.

Height (m)	Min (m)	Max (m)	Range (m)
15-19.99	17.11	19.4	2.29
20-24.99	20.43	24.92	4.49
25-29.99	25.25	29.6	4.35
30-35	30.1	34.5	4.4

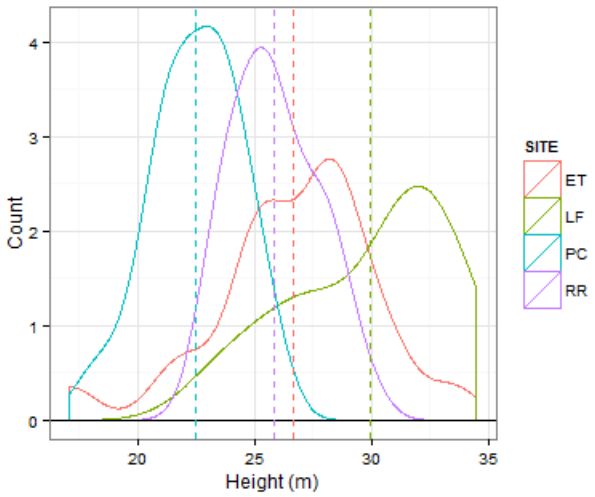


Figure 2. SMC Type I sampled tree height distribution. Mean height (m) for each site is indicated by the dashed lines color coded by site.

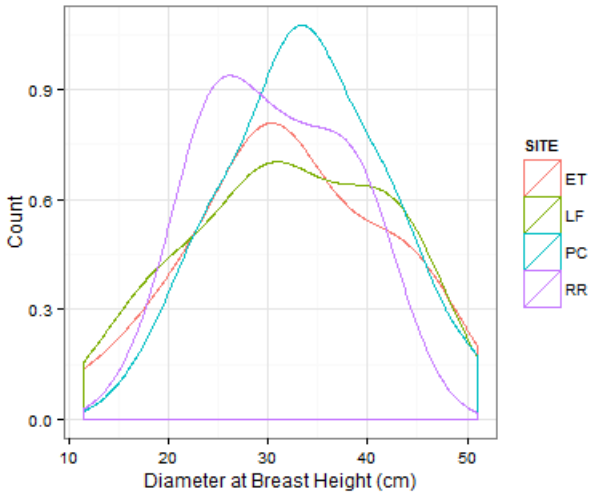


Figure 3.Type I sampled tree dbh distribution.

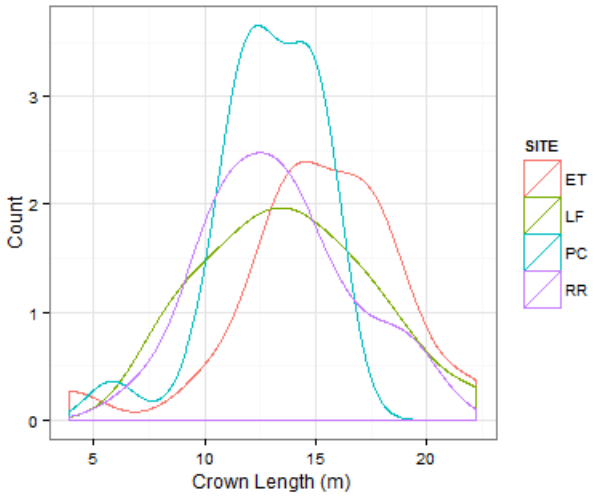


Figure 4. SMC Type I sampled tree crown length distribution.

The height (nearest 0.01 m) and diameter (nearest 0.1 mm) of all live branches were recorded (Fig.5-7). On the 90th percentile trees, the height (nearest 0.01 m) and diameter (nearest 0.1 mm) of all dead branches were also recorded (Fig. 8 and 9, Table 4).

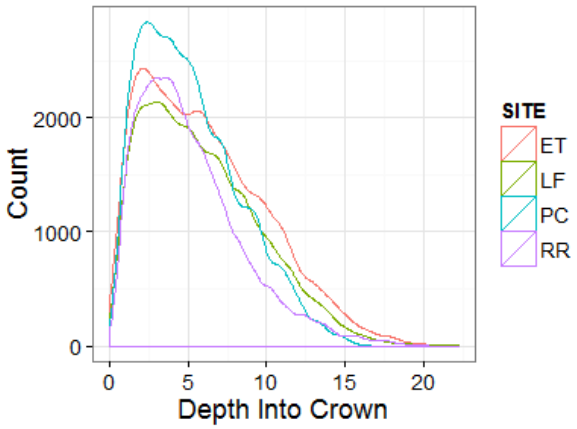


Figure 5. Number of live branches at specific depth into crown (DINC) by site.

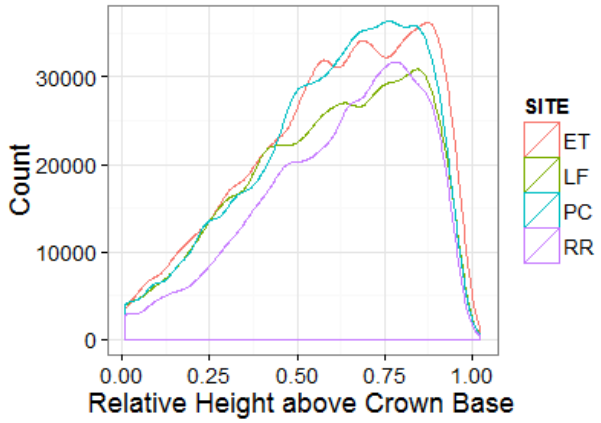


Figure 6. Number of live branches at specific relative height above crown base (RHCB) by site.

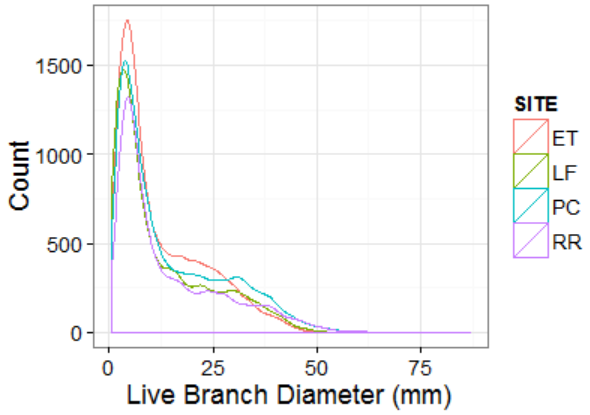


Figure 7. Number of live branches with specific diameter (mm) by site.

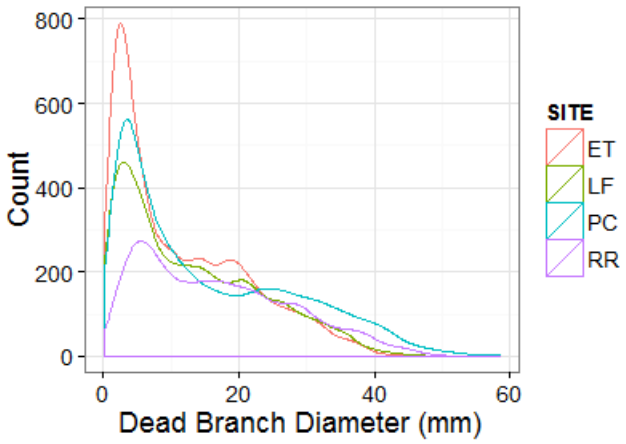


Figure 8. Number of dead branches with specific diameter (mm) by site.

Table 4. Single tree sampled branch frequency by 5 (cm) diameter class by site.

Diameter Class (cm)	Site			
	ET	LF	PC	RR
Live Branches				
10-14.99	544	440	-	-
15-19.99	1092	652	584	792
20-24.99	856	906	1047	719
25-29.99	998	907	872	737
30-34.99	981	825	977	841
35-39.99	1100	955	1065	845
40-44.99	1287	1117	866	1008
45-49.99	1304	1126	808	-
50+	-	-	900	-
Dead Branches				
25-29.99	964	-	-	-
30-34.99	1348	1292	724	1030
35-39.99	-	1128	1488	783
40-44.99	1416	1009	1142	874
45-49.99	1384	1110	712	-
50+	-	-	852	-

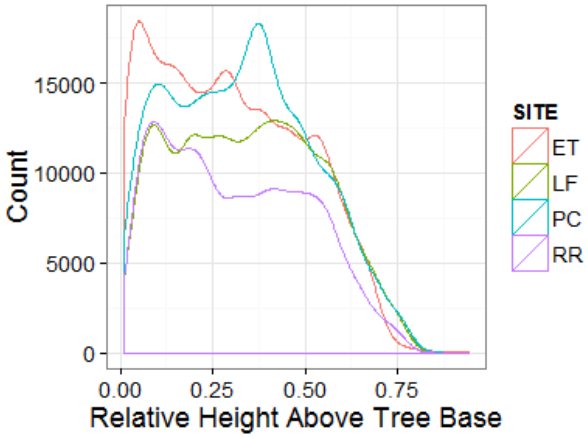


Figure 9. Number of dead branches at specific relative height above tree base (RHAB) by site.

Crown Base

Eight live sample branches were randomly chosen with probability proportional to frequency according to the following protocol: 1) Top crown-third: 2 branches >15 mm diameter, 1 branch with diameter between 5 and 15 mm; 2) Middle crown-third: 2 branches >15 mm diameter, 1 branch with diameter between 5 and 15 mm; 3) Bottom crown-third: 1 branch >15 mm diameter, 1 branch with diameter between 5 and 15 mm.

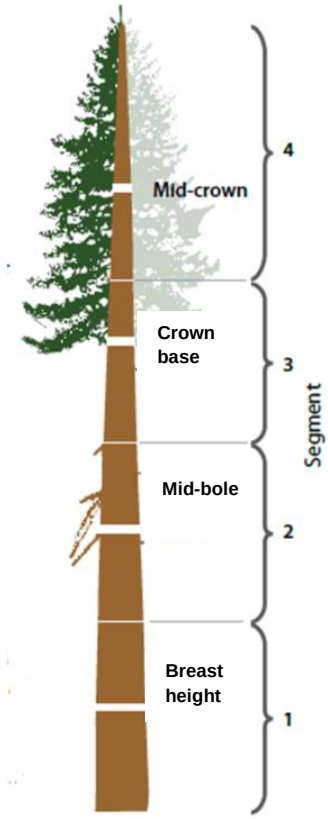


Figure 10. Sample tree disk location and segmentation.

Four dead branches were sampled according to the following procedure: 1) Between breast height and middle of the "clear" bole (halfway between breast height and crown base): 1 branch >15 mm diameter and 1 branch with diameter between 5 and 15 mm; 2) Between middle of "clear" bole and crown base: 1 branch >15 mm diameter and 1 branch with diameter between 5 and 15 mm. On the 10th and 90th percentile trees, an additional branch was taken ("Foliage" branch) to provide foliage for nutrient chemical analysis. This branch was the southernmost branch taken from the first whorl above the crown midpoint.

Four disks were cut from each tree at the following stem locations: 1) Breast height; 2) Midpoint between breast height and crown base; 3) Crown base; 4) Midpoint between crown base and tree tip (Fig.10). All branches and disks were stored in a refrigerator until they could be processed.

3.2 Soil Collection

Soil samples were collected from the control plots of each site by University of Washington collaborators (Paul Footen, Rob Harrison). Three forest floor samples were collected by hand per plot in a 0.05 m^2 area. Mineral soil samples were collected by from a 1.0 (m) soil pit at plot center with a horizontal core from the midpoint of each depth increment. Bulk density samples were dried at 105C. 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.

3.3 Chemical Analysis

Chemical analysis was performed on the following sampled components by the analytical lab at the School of Environmental and Forest Sciences at the University of Washington : 1) heartwood, sapwood, and bark components from the mid-bole disk; 2) the largest mid-bole branch; 3) the smallest dead branch from the lower half of the "clear" bole and the largest branch from the upper half of the "clear" bole; and 4) 1-, 2-, and 3-year-old foliage from the largest four-year old lateral of the above mentioned midbole sample branch. Prior to analysis at the lab samples were dried overnight in an oven at 75°C.

3.3.1 Digestion Method and Inductively Coupled Plasma (ICP) Analysis

A wet acid digestion procedure using nitric acid and 30% H_2O_2 was used to prepare plant tissue for determining concentrations of Ca, Cu, Fe, Mg, Mn, Mo, P, K, Se, Na, S and Zn using a (1:10) nitric-perchloric (HNO_3-HCL) acid digestion of organic matter in conjunction with external heating (Benton and Wolf, 1997). Digest analyte concentrations were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) (Munter and Grande, 1981). The metals in the soil (Mg and Al)

were extracted with a very similar method, EPA Method 3050. The method detection limit is approximately 0.02% for P, S, K, Ca, Mg and Na; and 0.5 mg/kg (sample dry basis) for Zn, Mn, Fe and Cu. Generally reproducibility is within ±7.0% (Kalra, 1998).

Digested samples (0.5 g) were then diluted to 25 mL or other appropriate volume and analyzed on an ICP atomic emission spectrometry (AES) in a Thermo Scientific ICAP-OES 61E. An ICP-AES has ideal qualities for the easy assay of plant tissue digests for all but a few of the elements essential for plant nutrition (B, Ca, Cu, Fe, Mg, Mn, P, K and Zn, but not N), plus those elements, at trace or ultra-trace levels that are found in plants but are not essential for phsyiological functions (Kalra, 1998).

3.3.2 Automated combustion method

Ground subsamples were analyzed for percent C and N using dry combustion on a Perkin-Elmer 2400 CHN analyzer. This method quantitatively determines the amount of N in all forms (NH_4, NO_3, protein, and heterocyclic N) in plant tissues using an induction furnace and a thermal conductivity detector. This method has a detection limit of 0.01% N on a dry sample basis (personal communication, Dongsen Xue, University of Washington) and is generally reproducible to within ±5% (Kalra, 1998).

3.4 Lab

All sample branches were cut into separate annual shoots and 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 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 on two perpendicular axes (nearest mm), and four sapwood widths were measured (nearest mm) on the same axes. Disks were then split into wedges, and then split again 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 volumes of the bark-sapwood and the sapwood after removing the bark (Fig. 11 and Fig. 12). The three separate wood samples were then dried at 70°C for 5 days and weighed. Three grams of each were then placed in separate Ziploc bags and submitted to the Analytical Services Center of University of Washington in Seattle, Washington for analysis. After drying, samples were ground to pass a 1.0-mm (20 mesh) screen using a WileyTM mill. Between processing of each sample, the grinder was cleaned with compressed air to prevent cross contamination.

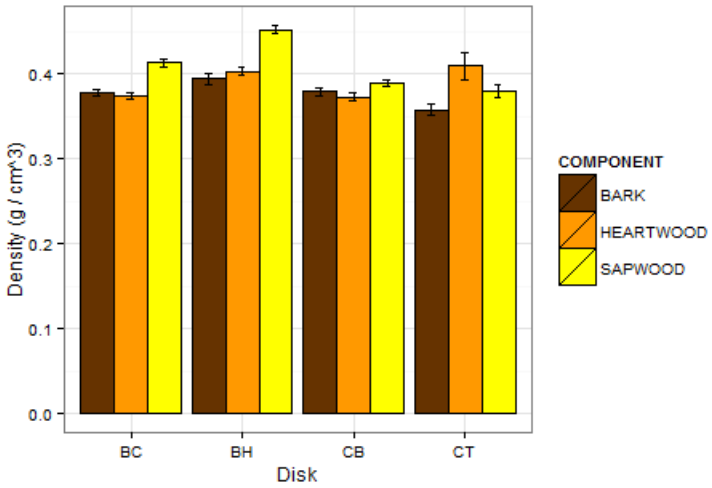


Figure 11. Sampled stem component density by disk.

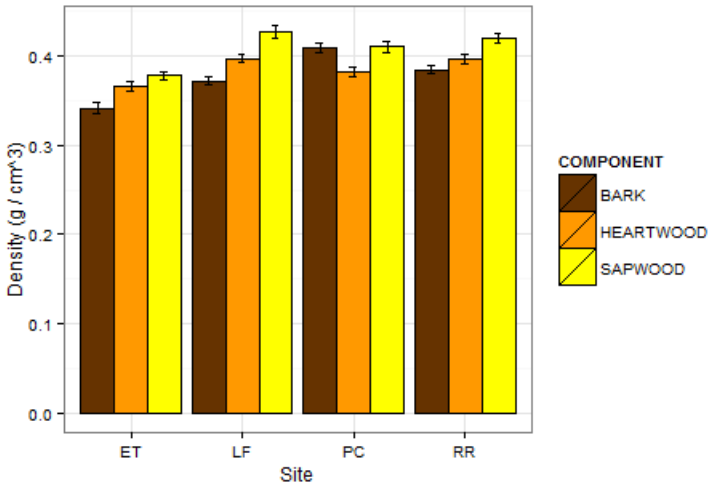


Figure 12. Sampled stem component density by site.

3.5 Data analysis: Stem mass calculations

To estimate stem mass, the stem was split into four segments, with heights corresponding to the midpoints between heights at which the four sample disks were cut (Fig. 10). The predicted DIB, sapwood area and double bark thickness for each of the four sections was calibrated with the disk measurements of the disk sampled in the center

of each section. Inside bark volume from breast height was calculated by numerically integrating the taper equation [14] from Walters and Hann (1986) with application of Smalian's formula, and assuming that the tip of the tree conformed to a cone. An equation for predicting heartwood height and a taper function for predicting heartwood diameter as a proportion of total diameter inside bark from Maguire et al. (Manuscript in preparation) was used to calculate volume of the heartwood core. Sapwood was calculated by subtracting heartwood volume from total stem volume inside bark. Bark volume was determined with estimates of double bark thickness from Maguire and Hann (1990) converting double bark thickness and DIB values to cross sectional area and assuming the frustum of a cone. Mean densities (Table 5) of each stem component were then applied to calculate stem mass for each of the sampled trees.

Table 5. Mean stem component density by disk.

Disk	Density (g / cm^3)		
	Bark	**Sapwood**	**Heartwood**
BH	0.393832	0.4522455	0.4026431
BC	0.37802	0.4132123	0.3741521
CB	0.379419	0.3887018	0.3724761
CT	0.357383	0.3795855	0.4096913

3.6 Statistical Methods

3.6.1 Model selection process

Biomass estimation for the tree components of interest required development of biomass equations for individual branches and for whole trees. Initial model selection

was based on the lowest Furnival's Index (FI) (1961) and residual plot assessment for heteroscedascticity. Residuals from unweighted linear and nonlinear models of all components indicated heteroscedasticity, as consistently documented throughout biomass literature. From the initial pool of models tested, a common model type (linear, log-linear, or nonlinear) was chosen that most frequently proved to be the best form or among the best forms for the various biomass components with more weight given to the largest biomass components, i.e., stem sapwood and heartwood. Log-linear equations have a prediction bias imposed by transforming back to the original scale, but would be appropriate if residuals were lognormally distributed and multiplicative on the original scale. Various methods have been proposed for correcting this bias (Baskerville, 1972). Simple correction factors (e.g., Baskerville, 1972) may be biased for small sample sizes (Flewelling and Pienaar, 1981) and tend to overestimate true bias (Hepp and Brister, 1982). More recently, (Zeng and Tang, 2011) have found no substantial difference in total tree biomass model estimates among four log bias correction factors, including Baskerville's and Snowdon's (1991), and likewise that the corrected models were similar to those fitted by weighted regression. For this study the Baskerville correction or "naive" estimator (Flewelling and Pienaar, 1981); i.e., a multiplier of exp(mse/2) on the back-transformed scale, was applied.

3.6.2 Branch Level Models

3.6.2.1 Live branch and foliage mass

The branch data from 84 trees (685 branches) were used to fit 28 plot-specific branch foliage and wood (wood+bark) models (Table 6) of one of the following general forms:

$$Ln(X) = b_0 + b_1 Ln(BrD) + b_2 Ln(RHCB) + b_3 Ln(DINC)$$

$$(X) = b_0 * (BrD)^{b1} \ (RHCB)^{b2} (DINC)^{b3}$$

All branch-level models forms included branch diameter (Brd), relative height above crown base (RHCB), and depth into crown (DINC) as predictor variables (Maguire and Bennett, 1991). Maguire and Bennett (1991) indicated these allometrics effectively captured the amount and vertical distribution of foliage across stands. Model parameter estimates for foliage by age class were developed for the form of the best equation for total foliage mass. The models for the crown components (live branch, dead branch and total foliage) with the lowest were selected, fit for each site, compared to the site independent model and used to estimate total foliage and live branch biomass on each of the 84 trees. Site specific models were utilized to estimate crown biomass for all live crown components (all foliage age classes and live branches). Residuals were assessed for major departures from homoscedasticity for the branch level models fitted to the composite data from all four sites. Statistical tests were generally performed at $\alpha=0.05$, but p-values between 0.05 and 0.10 were considered marginally significant, and p-values are provided throughout to portray the degree of statistical evidence in lieu of hypothesis test results based on arbitrary α-levels (R version 2.15.2).

3.6.2.2 Dead branch mass

Dead branch data from 28 trees (112 branches) were used to test 12 models. Branch level models included branch diameter (Brd) and relative height above tree base (RHAB) as predictor variables. From these models (Table 6) a final model with the following form was selected using FI:

$$Ln(X) = d_0 + d_1 Ln(BrD) + d_2 Ln(RHAB)$$

$$(X) = d_0 * (BrD)^{d1} * (RHACB)^{d2}$$

The best site model was selected by FI and was then fit at the installation level. An extra sums-of-squares test was performed to test whether the installation-level equations provided significantly greater predictive power than the composite model. The selected model was used to estimate total dead branch biomass on each of the 84 trees.

Table 6. Branch level models fitted to the comprehensive dataset (685 branches from 84 felled sample trees on four sites).

Model ID	Model	
	Linear Models	
model 1	$B = \beta_{10} + \beta_{11}BrD + \beta_{12}RH + \beta_{13}DINC$	
	Log Linear Models	
model 2	$\ln(B) = \beta_{20} + \beta_{21}\ln(BrD)$	
model 3	$\ln(B) = \beta_{30} + \beta_{31}\ln(RH)$	
model 4	$\ln(B) = \beta_{40} + \beta_{41}(DINC)$	
model 5	$\ln(B) = \beta_{50} + \beta_{51}\ln(BrD) + \beta_{52}\ln(RH)$	
model 6	$\ln(B) = \beta_{60} + \beta_{61}(BrD) + \beta_{62}\ln(RH)$	
model 7	$\ln(B) = \beta_{70} + \beta_{71}\ln(BrD) + \beta_{72}(DINC)$	
model 8	$\ln(B) = \beta_{80} + \beta_{81}\ln(RH) + \beta_{82}\ln(DINC)$	
model 9	$\ln(B) = \beta_{90} + \beta_{91}\ln(BrD) + \beta_{92}\ln(RH) + \beta_{93}\ln(DINC)$	
model 10	$\ln(B) = \beta_{100} + \beta_{10}BrD + \beta_{102}RH + \beta_{103}DINC$	
	Non-Linear Models	**Weight**
model 11	$B = \beta_{110}\, Brd^{\beta 111}$	-
model 11w1		$1 / brd$
model 11w2		$1 / brd^2$
model 12w1	$B = \beta_{120}\, RHB^{\beta 121}$	-
model 12w1		$1 / RHB$
model 12w1		$1 / RHB^2$
model 13	$B = \beta_{130}\, Brd^{\beta 131}\, RH^{\beta 132}$	-
model 13w1		$1 / (RH * BrD^2)$
model 13w2		$1 / (RH^2 * BrD^2)$
model 13w3		$1 / (RH * BrD^2)^2$
model 14	$B = \beta_{140}\, Brd^{\beta 141}\, RHB^{\beta 142}$	-
model 14w1		$1 / (RHB * BrD^2)$
model 14w2		$1 / (RHB^2 * BrD^2)$
model 14w3		$1 / (RHB * BrD^2)^2$
model 15	$B = \beta_{150}\, Brd^{\beta 151}\, DINC^{\beta 152}$	-
model 15w1		$1 / (DINC * brd^2)$
model 15w2		$1 / (DINC^2 * brd^2)$
model 15w3		$1 / (DINC * brd^2)^2$
model 16	$B = \beta_{160}\, brd^{\beta 161}\, RH^{\beta 162}\, DINC^{\beta 163}$	-
model 16w1		$1 / (DINC * brd^2)$
model 16w2		$1 / (DINC^2 * brd^2)$
model 16w3		$1 / (DINC * brd^2)^2$
model 16w4		$1 / (RH * brd^2)$
model 16w5		$1 / (RH^2 * brd^2)$
model 16w6		$1 / (RH * brd^2)^2$

The final branch level models and resulting branch level biomass estimates for the sampled tree data and 95% confidence intervals for each specific estimate were plotted with the R (version 2.15.2) package ggplot2() using the “loess” smoothing method.

3.6.3 Tree Level Models

The data from the 84 sample trees were pooled to fit 49 different models for each component except for dead branches for which 42 different models were tested. The regression models were fitted with the lm() and nls() packages in R version 2.15.2. Model forms for estimating tree-level biomass components at each site contained all or a subset of tree dbh (D), total height (H), crown length(CL) and/or clear bole length (CBL) as predictor variables (Table 7a and 7b). As described above, a model was chosen that most frequently proved to be the best form or one among several equivalent forms for the various biomass components, with more weight given to the largest biomass components, i.e., stem sapwood and heartwood. Once a common form of the best model was selected for the components three different methods of forced additivity were tested to determine the ideal way to predict whole tree biomass from the system of component equations. This model would then predict the total aboveground biomass of a whole tree biomass or one or more of the aboveground components from the forced additivity equation with the indicator variables while accounting for the different variance of each component.

Table 7a. Linear log-linear tree level models fitted to the comprehensive dataset (84 felled sample trees on four sites.

Model ID	Linear Models
Mod0	$B = \beta_0 + \beta_1 D + \beta_2 H + B_3 CL$
Mod1	$B = \beta_0 + \beta_1 D + \beta_2 H + B_3 CBL$
Mod2	$Ln(B) = \beta_0 + \beta_1 Ln(D)$
Mod3	$Ln(B) = \beta_0 + B_1 D$
Mod4	$Ln(B) = \beta_0 + \beta_1 Ln(H)$
Mod5	$Ln(B) = \beta 0 + \beta_1 H + \beta_2 CL$
Mod6	$Ln(B) = \beta 0 + \beta_1 H + \beta_2 CBL$
Mod7	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(H)$
Mod8	$Ln(B) = \beta 0 + \beta_1 Ln(D) + \beta_2 H + B_3 CL$
Mod9	$Ln(B) = \beta 0 + \beta_1 Ln(D) + \beta_2 H + B_3 CBL$
Mod10	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 Ln(H)$
Mod11	$Ln(B) = \beta 0 + \beta 1 D + \beta_2 H + B_3 CL$
Mod12	$Ln(B) = \beta 0 + \beta 1 D + \beta_2 H + B3 CBL$
Mod13	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(CL)$
Mod14	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(CBL)$
Mod15	$Ln(B) = \beta_0 + \beta_1 Ln(D) + B_2 CL$
Mod16	$Ln(B) = \beta_0 + \beta_1 Ln(D) + B_2 CBL$
Mod17	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 Ln(CL)$
Mod18	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 Ln(CBL)$
Mod19	$Ln(B) = \beta_0 + \beta_1 D + B_2 CL$
Mod20	$Ln(B) = \beta_0 + \beta_1 D + B_2 CBL$
Mod21	$Ln(B) = \beta_0 + \beta_1 Ln(H) + \beta_2 Ln(CL)$
Mod22	$Ln(B) = \beta_0 + \beta_1 Ln(H) + \beta_2 Ln(CBL)$
Mod23	$Ln(B) = \beta_0 + \beta_1 Ln(H) + B_2 CL$
Mod24	$Ln(B) = \beta_0 + \beta_1 Ln(H) + B_2 CBL$
Mod25	$Ln(B) = \beta_0 + \beta_1 H + B_2 CL$
Mod26	$Ln(B) = \beta_0 + \beta_1 H + B_2 CBL$
Mod27	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(H) + \beta_3 Ln(CL)$
Mod28	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(H) + \beta_3 Ln(CBL)$
Mod29	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(H) + B_3 CL$
Mod30	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(H) + B_3 CBL$
Mod31	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 H + \beta_3 CL$
Mod32	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 H + \beta_3 CBL$
Mod33	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 Ln(H) + B_3 CL$
Mod34	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 Ln(H) + B_3 CBL$
Mod35	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 H + \beta_3 CL$
Mod36	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 H + \beta_3 CBL$

Table 7b. Non-linear tree level models fitted to the comprehensive dataset (84 felled sample trees on four sites).

Model ID	Non-Linear Models	Weights
model1	$B = \beta_o D^{\beta 1}$	
model1w1		$1 / D$
model1w2		$1 / D^2$
model2	$B = \beta o D^{\beta 1} * H^{\beta 2}$	
model2w1		$1 / (H * D^2)$
model2w2		$1 / (H^2 * D^2)$
model2w3		$1/ (H * D^2)^2$
model3	$B = \beta_o D^{\beta 1} * CL^{\beta 3}$	
model3w1		$1 / (CL * D^2)$
model3w2		$1 / (CL^2 * D^2)$
model3w3		$1/ (CL * D^2)^2$
model4	$B = \beta_o D^{\beta 1} * CBL^{\beta 3}$	
model4w1		$1 / (CBL * D^2)$
model4w2		$1 / (CBL^2 * D^2)$
model4w3		$1/ (CBL * D^2)^2$
model5	$B = \beta_o D^{\beta 1} * H^{\beta 2} * CL^{\beta 3}$	
model5w1		$1 / (H * D^2)$
model5w2		$1 / (H^2 * D^2)$
model5w3		$1/ (H * D^2)^2$
model5w4		$1 / (CL * D^2)$
model5w5		$1 / (CL^2 * D^2)$
model5w6		$1/ (CL * D^2)^2$
model6	$B = \beta_o D^{\beta 1} * H^{\beta 2} * CBL^{\beta 3}$	
model6w1		$1 / (H * D^2)$
model6w2		$1 / (H^2 * D^2)$
model6w3		$1/ (H * D^2)^2$
model6w4		$1 / (CBL * D^2)$
model6w5		$1 / (CBL^2 * D^2)$
model6w6		$1/ (CBL * D^2)^2$
model7	$B = \beta_o D^{\beta 1} * H^{\beta 2} * e^{\beta 3 * CL}$	
model7w1		$1 / (H * D^2)$
model7w2		$1 / (H^2 * D^2)$
model7w3		$1/ (H * D^2)^2$
model7w4		1 / (CL * D2)
model7w5		1 / (CL2 * D2)
model7w6		1/ (CL * D2)2

Table 7b. Continued…

Model ID	Non-Linear Models	Weights
model8	$B = \beta_o D^{\beta 1} * H^{\beta 2} * e^{\beta 3 * CBL}$	
model8w1		$1 / (H * D^2)$
model8w2		$1 / (H^2 * D^2)$
model8w3		$1/ (H * D^2)^2$
model8w4		$1 / (CBL * D^2)$
model8w5		$1 / (CBL^2 * D^2)$
model8w6		$1/ (CBL * D^2)^2$
model9	$B = \beta_o D^{\beta 1} * e^{\beta 2 * CL}$	
model9w1		$1 / (CL * D^2)$
model9w2		$1 / (CL^2 * D^2)$
model9w3		$1/ (CL * D^2)^2$
model10	$B = \beta_o D^{\beta 1} * e^{\beta 2 * CBL}$	
model10w1		$1 / (CBL * D^2)$
model10w2		$1 / (CBL^2 * D^2)$
model10w3		$1/ (CBL * D^2)^2$
model11	$B = \beta_o D^{\beta 1} * e^{\beta 2 * H}$	
model11w1		$1 / (H * D^2)$
model11w2		$1 / (H^2 * D^2)$
model11w3		$1/ (H * D^2)^2$

In the first procedure the whole tree biomass regression function is defined as the sum of the individually calculated best regression functions of the aboveground tree components (Burkhart and Tome, 2012; Parresol, 2001; Reed and Green, 1985). The set of equations was fitted with the nls() package in R (version 2.15.2). The disadvantage of this approach is that optimal estimates of total biomass are not considered because the sum of squared errors around total biomass are not considered. The second approach therefore fitted a large regression equation using indicator variables for individual

components to force total biomass to be equal to the sum of the individual component equations (Reed and Green, 1985).

Once the best model form was selected by fitting alternative models to the pooled data set, installation-level models of the same form were fitted and compared.

3.6.4 Whole tree equation comparison

The fitted whole tree equations were compared to those of six other studies including those by: Harrison et al. (2009), Ung et al. (2008), Jenkins et al. (2004), Bartelink (1996), Feller (1992), and Gholz et al. (1979). Equations were compared across the range in diameter, height and crown length of the SMC Type I site data (Table 8).

Table 8. Site characteristics and sample data variation of compared biomass equations.

Author	Location	Site Index (at 50 years)	Sample Size	Stand Age	Density (stems/ha)	Basal Area (m2/ha)	Height (m)	Diameter (cm)
Harrison et al. (2009)	Pacific County, Washington	41-43 (m) (King 1966)	31	47	615	32.5	32.8 (23.6-39.8)	39.1 (15-80.1)
Ung et al. (2008)	British Colombia, Canada	_	14	-	-	-	10.8 (4.1-31.2)	15.6 (4.5-50.8)
Jenkins et al. (2004)	North America	_	165	-	-	-	_	3-215
Bartelink (1996)	central Neatherlands	_	23	-	406-2133	9-27.2	6.7-27.2 (Dominant stand height)	6.9-28.5 (range in average dbh)
Feller (1992)	Near Port Alberni, Vancouver Island	_	49	31 (9-86)	-	-	15.1 (4.1-44.0)	21.2 (4.5-66.0)
Gholz (1979)	Western OR and western WA	-	99-126	-	-	-	-	1.8-162

2 Numbers in parenthesis under height column represent the range in height of the study.

3.7 Site Application

The fitted equations were applied to the tree list of the most recent remeasurement (2009-2011) of the plots at each site to estimate total above-ground biomass per hectare by tree component. Species, dbh (nearest 0.1 in), total height (nearest 0.1 ft), height to live crown (nearest 0.1ft), tree number, plot and condition code were recorded for all trees > 1.55 in. in dbh. Live crown base on Douglas-fir was defined as the lowest whorl with live branches in at least three of the four quadrants around the stem circumference (Curtis, 1983).

3.7.1 Nutrients

Nutrient concentrations were averaged for a given plot to convert biomass estimates into above-ground nutrient pools. More specifically, nutrient concentrations applied to the SMC Type I lists for stand level nutrient content estimates were calculated with a weighted average nutrient concentration from the sampled trees by component, treatment (fertilized or unfertilized) and site for each nutrient. The nutrient concentrations from the disk components at bole center (BC) were applied to the entire stem. In addition, the proportion of foliar mass by age class throughout the crown was assumed to be equivalent to the summed proportions, by age class, present on all sampled branches.

3.7.2 Harvest Scenarios

The four harvest scenarios simulated involved removal of: (1) merchantable stem (0.3048-m stump to 10.16-cm merchantable top) (BO); (2) whole tree (0.3048-m stump to tree tip) minus 50% of the branches by assuming one (vertical) side of the crown is sheared off during yarding (VC); (3) whole tree minus all tree components above a 10.16-cm top stem diameter, assuming this portion of the tree was broken off during yarding (BT): and (4) whole tree (ground level to tree tip) (WT). These four scenarios were chosen to represent typical quantities of biomass that will be relocated to a slash pile from which forest residuals will be removed for liquid biofuel production. The 10.16 cm merchantable top is a typical merchantable log top diameter. The branch and stem data from 84 trees were used to fit regression equations the following general form:

$$CUM\% = 1 / (1 + \exp (b_0 + b_1 RDINC + b_2 H + b_3 CL + b_4 D)$$

where CUM% is the cumulative % of the branch wood or cumulative % of the foliage as a function of relative depth into crown (RDINC) and other covariates like D, HT or CL. Each harvest scenario was assessed with equations fitted to the entire pooled dataset. The final model form was selected based on Furnival's (1961) index. Total nutrients removed of each component was estimated by multiplying the resulting relative biomass (%) by the SMC site-specific biomass estimates and mean nutrient concentrations specific to

each site, component and treatment for each essential plant nutrient (N, P, K, S, Ca, Fe, Mg, B, Cu, Mn and Zn).

3.7.3 Soil Nutrients

Total nutrient and relative (%) nutrient content of Ca, K, Mg, N, P and S at depth were calculated on a per hectare basis to a depth of 1 (m).

3.7.4 Stability Ratio

In order to address objective (3) about estimating sustainable levels of biomass utilization the Evans (1999) stability ratio was computed by calculating the proportion of a given nutrient removed in a single forest regeneration harvest (total aboveground stand nutrient content), relative to the corresponding total site nutrient capital (total soil nutrient content to 1 m in depth + total aboveground nutrient content of pre-harvest live trees) for each of the SMC Type I sites.

4 Results

4.1 Biomass estimation

4.1.1 Branch component mass estimates

The best model form for the six branch-level models (live branch, dead branch, 1-yr foliage, 2-yr foliage, ≥3-yr foliage, total live branch) differed among the biomass components (Table 9).

Table 9. Indices of fit (Furnival 1961) for alternative branch level models fitted to the comprehensive dataset (685 branches from 84 felled sample trees on four sites). The best model for each biomass component is indicated by a bold index of fit (Furnival 1961).

Model ID	Model		Foliage				Live Branch	Dead Branch
	Linear Models		Total	1-yr	2-yr	≥3-yr		
model 1	$B = \beta_{10} + \beta_{11}BrD + \beta_{12}RH + \beta_{13}DINC$		>1000	>1000	>1000	>1000	>1000	>1000
	Log Linear Models							
model 2	$\ln(B) = \beta_{20} + \beta_{21}\ln(BrD)$		60.58	25.97	15.84	31.95	46.39	33.28
model 3	$\ln(B) = \beta_{30} + \beta_{31}\ln(RH)$		94.27	30.04	21.49	38.67	72.44	100.17
model 4	$\ln(B) = \beta_{40} + \beta_{41}(DINC)$		89.66	31.11	21.46	33.19	70.50	-
model 5	$\ln(B) = \beta_{50} + \beta_{51}\ln(BrD) + \beta_{52}\ln(RH)$		50.99	18.90	12.74	31.94	38.71	**30.84**
model 6	$\ln(B) = \beta_{60} + \beta_{61}(BrD) + \beta_{62}\ln(RH)$		-	-	-	-	-	36.06
model 7	$\ln(B) = \beta_{70} + \beta_{71}\ln(BrD) + \beta_{72}(DINC)$		59.90	21.78	14.90	29.25	44.29	-
model 8	$\ln(B) = \beta_{80} + \beta_{81}\ln(RH) + \beta_{82}\ln(DINC)$		84.86	29.63	20.50	32.13	68.47	-
model 9	$\ln(B) = \beta_{90} + \beta_{91}\ln(BrD) + \beta_{92}\ln(RH) + \beta_{93}\ln(DINC)$		48.62	**18.55**	**12.71**	27.53	**38.58**	-
model 10	$\ln(B) = \beta_{100} + \beta_{101}BrD + \beta_{102}RH + \beta_{103}DINC$		60.76	19.09	13.83	31.00	46.80	-
	Non-Linear Models	**Weight**						
model 11	$B = \beta_{110}\ Brd^{\beta111}$	-	111.49	50.38	32.50	55.28	217.61	90.19
model 11w1		$1 / BrD$	79.52	38.49	23.92	41.19	154.95	59.96
model 11w2		$1 / BrD^2$	60.68	31.10	18.74	33.30	115.77	42.19
model 12w1	$B = \beta_{120}\ RHB^{\beta121}$	-	-	-	-	-	-	401.69
model 12w1		$1 / RHB$	-	-	-	-	-	399.06
model 12w1		$1 / RHB^2$	-	-	-	-	-	452.78
model 13	$B = \beta_{130}\ Brd^{\beta131}\ RH^{\beta132}$	-	75.29	33.35	21.72	48.87	181.03	-
model 13w1		$1 / (RH * BrD^2)$	58.10	27.64	14.83	37.54	137.03	-
model 13w2		$1 / (RH^2 * BrD^2)$	161.37	-	26.80	69.70	288.95	-
model 13w3		$1 / (RH * BrD^2)^2$	96.69	-	19.85	50.69	128.47	-
model 14	$B = \beta_{140}\ Brd^{\beta141}\ RHB^{\beta142}$	-	-	-	-	-	-	88.69
model 14w1		$1 / (RHB * BrD^2)$	-	-	-	-	-	42.39
model 14w2		$1 / (RHB^2 * BrD^2)$	-	-	-	-	-	49.47
model 14w3		$1 / (RHB * BrD^2)^2$	-	-	-	-	-	36.33
model 15	$B = \beta_{150}\ Brd^{\beta151}\ DINC^{\beta152}$	-	96.56	39.94	26.89	54.74	182.73	-
model 15w1		$1 / (DINC * BrD^2)$	50.82	25.91	15.90	29.23	66.14	-
model 15w2		$1 / (DINC^2 * BrD^2)$	51.61	29.01	16.89	29.89	61.58	-
model 15w3		$1 / (DINC * BrD^2)^2$	85.55	39.36	23.78	45.59	75.71	-
model 16	$B = \beta_{160}\ BrD^{\beta161}\ RH^{\beta162}\ DINC^{\beta163}$	-	74.53	33.31	21.72	45.75	180.79	-
model 16w1		$1 / (DINC * BrD^2)$	**41.61**	20.80	13.16	**26.66**	64.95	-
model 16w2		$1 / (DINC^2 * BrD^2)$	43.95	23.53	14.24	28.72	60.28	-
model 16w3		$1 / (DINC * BrD^2)^2$	84.18	36.49	22.91	45.33	74.61	-
model 16w4		$1 / (RH * BrD^2)$	58.07	27.52	14.83	35.23	137.01	-
model 16w5		$1 / (RH^2 * BrD^2)$	133.66	45.90	23.81	69.72	288.09	-
model 16w6		$1 / (RH * BrD^2)^2$	96.67	37.33	19.76	48.32	128.48	-

The best model for each component was fitted to the data from each site independently to arrive at a site-specific branch-level biomass equation for each component. The final models for each component took the following forms:

[1] $(B_{FT}) = a_0 (BrD)^{a1} (RH)^{a2} (DINC)^{a3}$

[2] $\ln(B_{F1}) = b_{10} + b_{11} \ln (BrD) + b_{12} \ln (RH) + b_{13} \ln (DINC)$

[3] $\ln(B_{F2}) = b_{20} + b_{21} \ln (BrD) + b_{22} \ln (RH) + b_{23} \ln (DINC)$

[4] $(B_{F3}) = b_{30} (BrD)^{b31} (RH)^{b32} (DINC)^{b33}$

[5] $\ln(B_{LIVEBR}) = c_0 + c_1 \text{Ln} (BrD) + c_2 \ln (RH) + c_3 \ln (DINC)$

[6] $\text{Ln}(B_{DEADBR}) = d_0 + d_1 \ln(BrD) + d_2 \ln(RHB)$

where B was the biomass component indicated by the subscript (FT=total foliage, F1=1-yr-old foliage, F2=2-yr-old foliage, F3=≥3-yr-old foliage, LIVEBR-live branch wood + bark, DEADBR=dead branch wood + bark) (g), BrD was branch diameter (mm), DINC was depth into crown (m), RHACB was relative height above crown base, RH was relative height on the tree between ground line and tree tip, and a_0, a_1, a_2, a_3, b_{10}, . . . , d_2 were parameters estimated from the data. Parameter estimates and their standard errors and p-values are provided in Tables 10-16. Dead branch data from 28 trees (112 branches) were used to test 16 models. No major departures from homoscedasticity were indicated in the standardized residuals on the model scale (scale of the response variable) for the branch level models fitted to the composite data from all four sites (Fig. 13).

Table 10. Parameter estimates, standard errors, and p-values for model [1] predicting total foliage biomass for individual branches.

Parameter	Estimate	Std. Error	P-value
a0 (ET)	0.06041	0.01857	0.001204
a0 (LF)	0.1529	0.03878	<0.001
a0 (PC)	0.04112	0.012	<0.001
a0 (RR)	0.23564	0.04761	<0.001
a1 (ET)	2.44836	0.12433	<0.001
a1 (LF)	2.04837	0.11092	<0.001
a1 (PC)	2.45634	0.11231	<0.001
a1 (RR)	1.86789	0.08374	<0.001
a2 (ET)	0.69246	0.17361	<0.001
a2 (LF)	0.77853	0.12699	<0.001
a2 (PC)	0.98538	0.14434	<0.001
a2 (RR)	0.88674	0.13464	<0.001
a3 (ET)	0.37554	0.11058	<0.001
a3 (LF)	0.68575	0.10559	<0.001
a3 (PC)	0.68873	0.11933	<0.001
a3 (RR)	0.81912	0.09993	<0.001
MSE = 0.4662		DF = 635	

Table 11. Parameter estimates, standard errors, and p-values for model [2] predicting 1-yr-old foliage biomass for individual branches.

Parameter	Estimate	Std. Error	P-value
b10 (ET)	-4.59528	0.51311	<0.001
b10 (LF)	1.21427	0.68294	0.0759
b10 (PC)	0.08486	0.69466	0.90281
b10 (RR)	2.06831	0.6843	<0.001
b11 (ET)	3.17856	0.20281	<0.001
b11 (LF)	2.73964	0.18564	<0.001
b11 (PC)	3.23637	0.17961	<0.001
b11 (RR)	2.7786	0.17621	<0.001
b12 (ET)	1.44514	0.19629	<0.001
b12 (LF)	1.56328	0.19075	<0.001
b12 (PC)	2.11936	0.20539	<0.001
b12 (RR)	1.15904	0.15917	<0.001
b13 (ET)	-0.64704	0.19935	0.00124
b13 (LF)	-0.11707	0.2116	0.5803
b13 (PC)	-0.25406	0.23135	0.27257
b13 (RR)	-0.90477	0.22519	<0.001
MSE = 1.103		DF=612	

Table 13. Parameter estimates, standard errors, and p-values for model [3] predicting 2-yr-old foliage biomass for individual branches.

Parameter	Estimate	Std. Error	P-value
b20 (ET)	-4.8609	0.409	<0.001
b20 (LF)	1.0404	0.5681	0.06752
b20 (PC)	-0.6047	0.5931	0.30828
b20 (RR)	1.6196	0.573	0.00485
b21 (ET)	3.0041	0.158	<0.001
b21 (LF)	2.2071	0.1606	<0.001
b21 (PC)	2.9151	0.1528	<0.001
b21 (RR)	2.3023	0.1525	<0.001
b22 (ET)	0.9987	0.1437	<0.001
b22 (LF)	1.3556	0.1664	<0.001
b22 (PC)	2.0812	0.1832	<0.001
b22 (RR)	1.0758	0.1395	<0.001
b23 (ET)	-0.3582	0.1571	0.02292
b23 (LF)	0.8273	0.1878	<0.001
b23 (PC)	0.6203	0.2258	0.00618
b23 (RR)	0.1881	0.2026	0.35359
MSE = 0.954		DF=627	

Table 14. Parameter estimates, standard errors, and p-values for model [4] predicting ≥3-yr-old foliage biomass for individual branches.

Parameter	Estimate	Std. Error	P-value
b30 (ET)	0.046453	0.0158668	0.00354
b30 (LF)	0.037127	0.0152295	0.01506
b30 (PC)	0.000433	0.0003802	0.25478
b30 (RR)	0.09632	0.0312207	0.00213
b31 (ET)	1.908343	0.1207068	<0.001
b31 (LF)	1.870587	0.1494067	<0.001
b31 (PC)	2.957685	0.2587936	<0.001
b31 (RR)	1.514252	0.1195599	<0.001
b32 (ET)	0.537626	0.125674	<0.001
b32 (LF)	0.494396	0.1253102	<0.001
b32 (PC)	1.075546	0.2200607	<0.001
b32 (RR)	0.602558	0.147334	<0.001
b33 (ET)	0.9883	0.1422079	<0.001
b33 (LF)	1.083456	0.1731816	<0.001
b33 (PC)	1.599846	0.3300204	<0.001
b33 (RR)	1.207776	0.1787195	<0.001
MSE= 0.6033		DF=604	

Table 15. Parameter estimates, standard errors, and p-values for model [5] predicting wood + bark biomass for individual live branches.

Parameter	Estimate	Std. Error	P-value
c0 (ET)	-2.8057	0.32184	<0.001
c0 (LF)	0.50951	0.44561	0.2533
c0 (PC)	-0.64517	0.452	0.154
c0 (RR)	1.03197	0.44658	0.0212
c1 (ET)	2.47379	0.12381	<0.001
c1 (LF)	2.3471	0.12695	<0.001
c1 (PC)	2.73492	0.12062	<0.001
c1 (RR)	2.22277	0.1205	<0.001
c2 (ET)	0.61284	0.11339	<0.001
c2 (LF)	0.78746	0.13044	<0.001
c2 (PC)	1.27758	0.13807	<0.001
c2 (RR)	1.01988	0.10885	<0.001
c3 (ET)	0.03962	0.12376	0.749
c3 (LF)	0.27995	0.1447	0.0535
c3 (PC)	0.13094	0.15646	0.403
c3 (RR)	0.09148	0.154	0.5527
MSE= 0.7541		DF=635	

Table 16. Parameter estimates, standard errors, and p-values for model [6] predicting wood + bark biomass for individual dead branches.

Parameter	Estimate	Std. Error	P-value
d0	-3.71694	0.32345	<0.001
d1	3.071	0.10077	<0.001
d2	0.35871	0.08913	<0.001
MSE = 0.6363528		DF = 97	

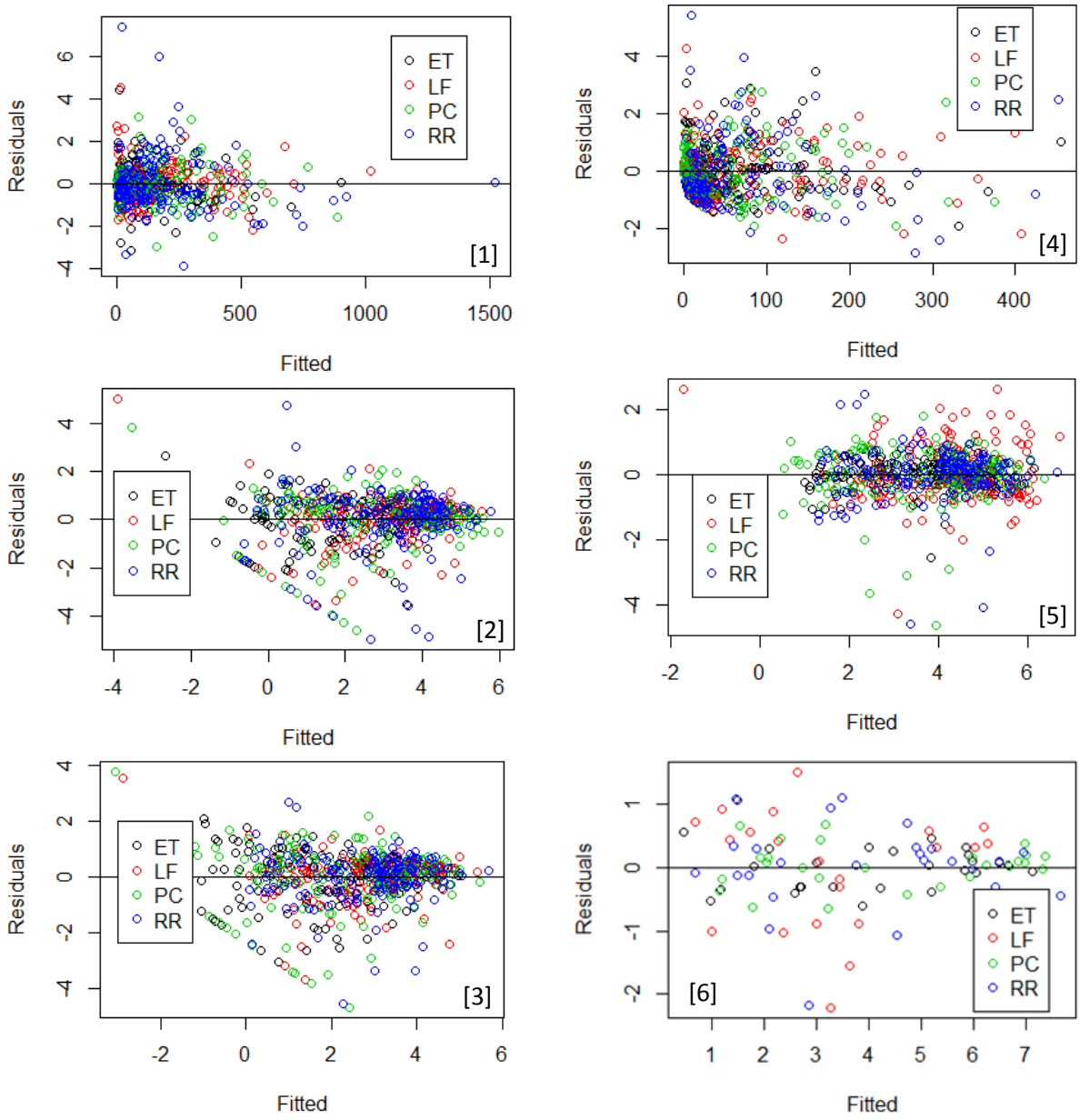


Figure 13. Residuals plotted on predicted values for model [1] fitted to total foliage mass, model [2] fitted to 1-yr-old foliage mass, for model [3] fitted to 2-yr-old, for model [4] fitted to ≥3-yr-old foliage mass foliage, mass, model [5] fitted to total live branch biomass (wood + bark), model [6] fitted to total dead branch biomass (wood + bark), color coded by site. Model numbers of are indicated in brackets '[ ]' on each plot.

The relative distribution of crown biomass components differed among sites (Fig. 14). Over all sites, 1-yr-old, 2-yr-old, and ≥3-yr old foliage comprised 23% (12-34% range), 14% (10-16% range), and 21% (6-35% range) of total crown mass. Live branches (wood + bark) comprised 41% (35-49% range) of the live crown biomass. Of total tree mass over all sites, 1-yr-old, 2-yr-old, and ≥3-yr old foliage comprised 2% (1.0-3.4% range), 1% (0.6-1.7% range), and 1% (0.8-3.0% range). Live branches (wood + bark) comprised 3.3% (2.2-4.5% range) of total tree biomass (Fig. 15). The PC site had the highest proportion of 1-yr-old foliage and the lowest proportion of all other age classes of foliage. The ET site had the highest average of ≥3-yr old foliage, but it along with the LF site retained the oldest foliage (up to 10 years in contrast to 7 and 8 years at the other sites; Appendix Table A-1).

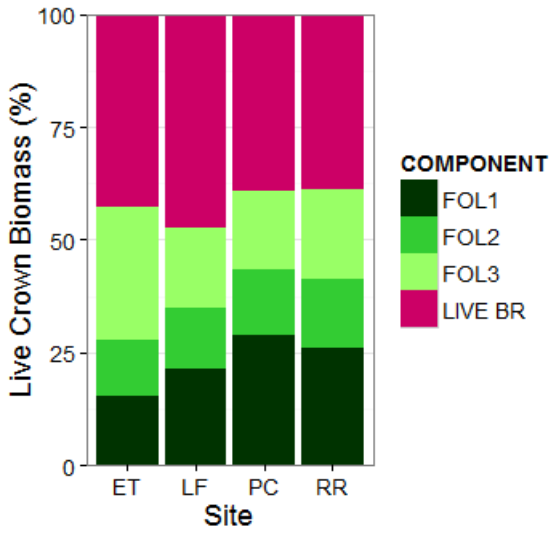
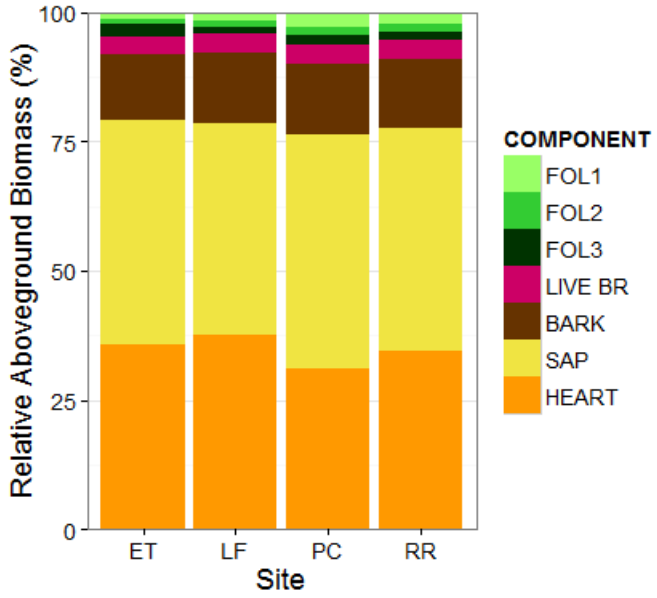


Figure 14. Relative distribution of live crown biomass components by site.

4.1.2 Whole tree component mass estimates

Figure 15. Average proportions of aboveground biomass components by site.



The relative distribution of biomass components in the sampled Douglas-fir trees was more similar than might be expected across a wider range of sites if they differed more in stand age and tree size (Fig. 15). On average, sapwood mass comprised 44% (24-59% range) of total mass, heartwood comprised 35% (24-44% range) and bark 13% (8-31% range). Live crown biomass on the PC site was 17% greater on average than all other sites and sapwood mass also averaged slightly higher than all other sites. The proportion of bark mass (13%) was relatively consistent among sites. The LF site had the greatest proportion of heartwood (38%) and the lowest proportion of sapwood (41%). The PC site had the lowest proportion of heartwood (31%) and the highest proportion of sapwood (46%). The ET and RR proportions were more similar to those of the LF site than the PC site.

4.1.3 Site differences in branch-level biomass

Differences in branch-level biomass estimates among sites was verified by applying equations [2]-[6] to estimate biomass of live branch wood + bark, dead branch

wood + bark, and foliage by age class for a branch of average size and position; i.e., BrD of 13.4 mm, DINC of 5.62 m, RHCB of 0.6, and a RHAB of 0.32. For this average branch, the PC site had the lowest predicted 3 year and older foliage, decreased the most proportionally by age class of foliage, and had the largest dead branch mass (Table 17). ET had the most unusual pattern of predicted foliage distribution by age class, but all sites differed substantially from each other with respect to distribution of foliage mass by age class. Differences in total foliage amount, total live woody biomass, and the age-class distribution of foliage mass for the same average branch underscored the need to develop site-specific equations for branch-level biomass estimates.

Table 17. Differences in estimates of branch biomass components among the four sample sites for a branch with BrD=13.4 mm, DINC=5.62 m, RHCB=0.6, and RHAB=0.32.

Site	Live Branch	Dead Branch	1-yr	2-yr	≥ 3-yr	Total Foliage	Total Live Branch (wood + bark + fol)
ET	22.24	15.73	11.12	7.78	27.52	46.42	68.66
LF	42.54	13.75	33.04	25.62	24.03	82.69	125.23
PC	29.14	18.83	30.58	21.30	8.54	60.41	89.55
RR	44.55	13.24	22.95	19.83	28.99	71.78	116.33

Generally the biomass of crown components peaked at a RHCB of approximately 0.5, except for biomass of ≥3-yr-old foliage that tended to peak much lower in the crown (Fig. 16). Conversely, branch-level 1-yr-old and 2-yr-old foliage peaked higher in the crown, near a RHCB of 0.65. Live branch mass, not surprisingly, behaved more like ≥3-yr-old foliage by peaking at a RHCB of approximately 0.35 (Fig. 16). Estimates of 1-yr-old and 2-yr-old foliage biomass were very similar for each site across the range in branch diameter (Fig. 17).

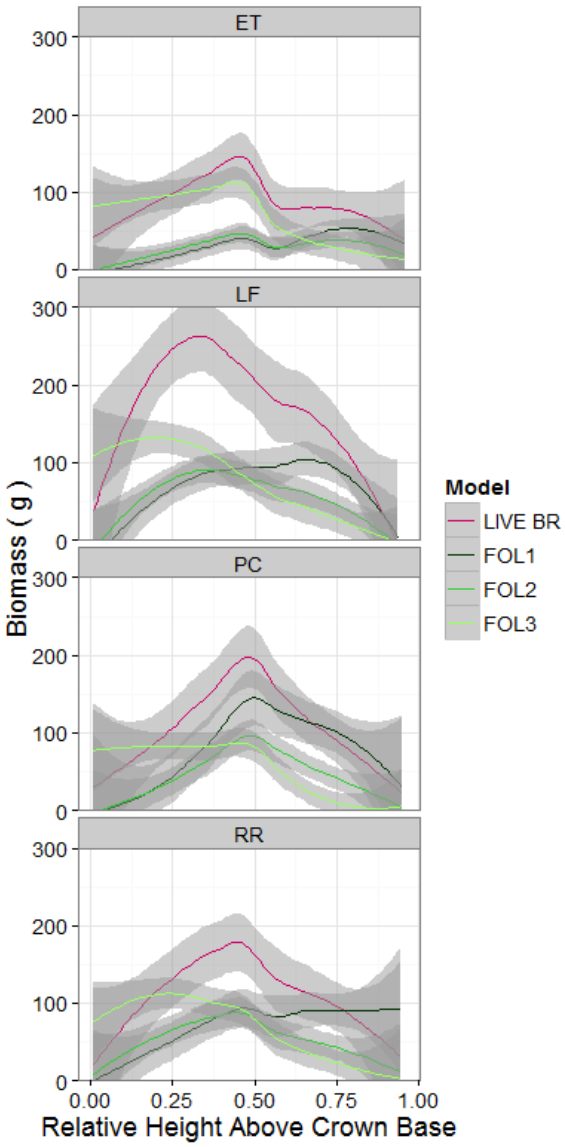


Figure 16. Trends in predicted branch-level biomass components over relative height above crown base (m) by site. The 95% confidence intervals are indicated in grey shading.

The branch level biomass models (Fig.16-18) show smoothed line plots and grey bands indicating the 95% confidence intervals of estimates with the input variables of each actual sampled branch. The PC site showed the greatest difference among all sites between maximum ≥3-yr-old foliage and maximum 1-yr-old foliage at the branch level (654 g), with over 4 times difference between maximum foliage estimates along variation in DINC (Fig. 18).

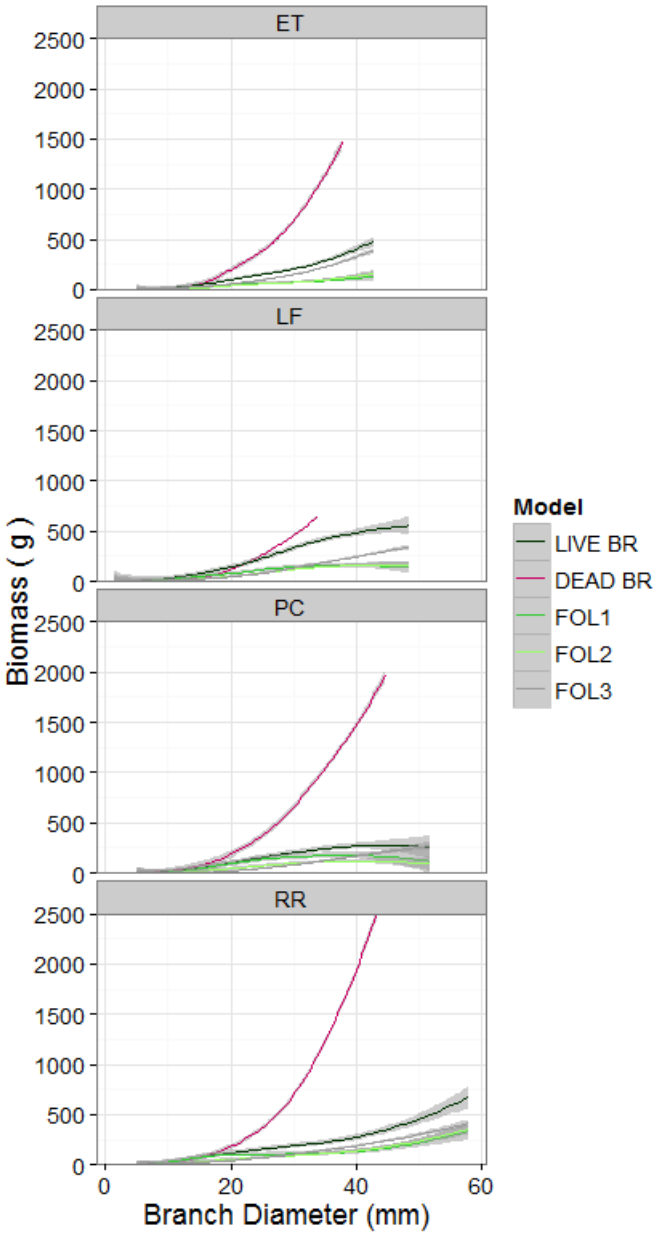


Figure 17. Trends in predicted branch-level biomass components over branch diameter (mm) by site. The 95% confidence intervals are indicated in grey shading.

Across all sites the amount of ≥3-yr-old foliage biomass on a given branch increased as DINC increased up to a depth of approximately 18 m (Fig. 18).

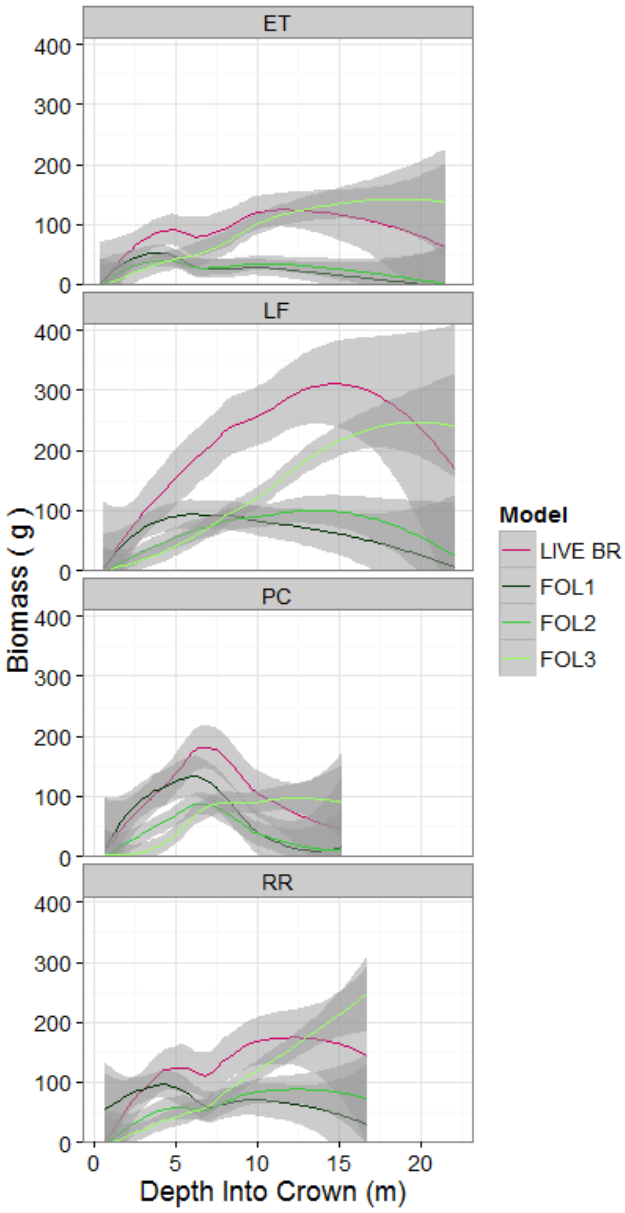


Figure 18. Trends in predicted branch-level biomass components over depth into crown (m) by site. The 95% confidence intervals are indicated in grey shading.

The pattern in predicted biomass of dead branches (wood + bark) is strongly influenced by early brush competition, early stand density, early stand density control, and the pattern of mortality from ground line up, particularly in regard to mortality of interwhorl versus whorl branches. The ET and RR sites, as well as the LF site to a large degree, followed a pattern with height on tree that would be most typical of trees that withstood early competition from brush or other trees (hardwood and conifer), but then had more space to grow and develop larger branches going up the stem (Fig. 19).

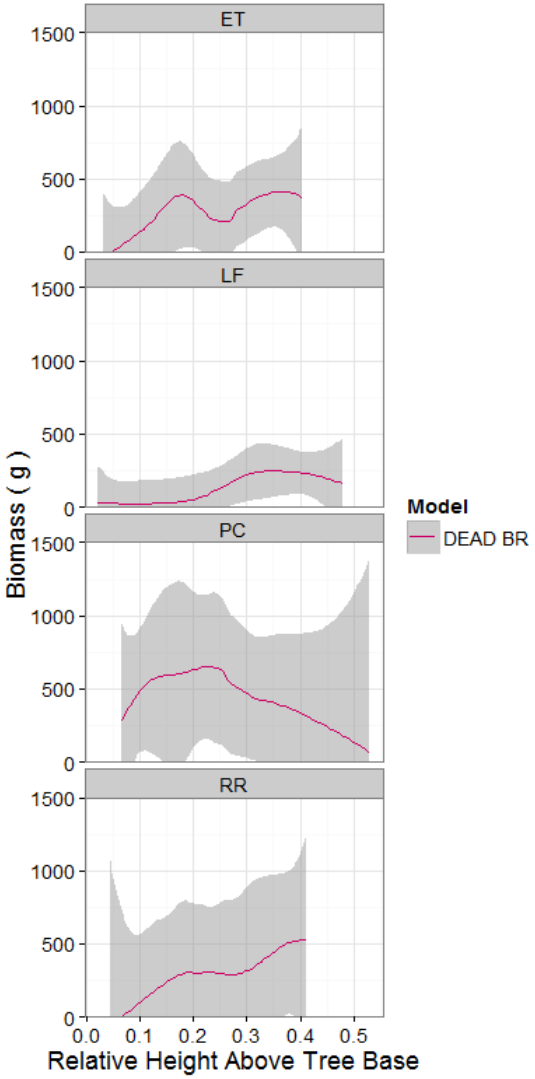


Figure 19. Trends in predicted biomass of dead branches (wood + bark) over relative height on tree by site. The 95% confidence intervals are indicated in grey shading.

This increase, however, is a balance between size attained by the branch before it died and how much it has deteriorated and lost biomass since mortality. The progression of interwhorl branch mortality is much more rapid than whorl mortality, so the highest dead branches will always be relatively small interwhorl branches. It is important to note that these graphical depictions of biomass trends (Figs. 16-19) are not smooth because the average level of other covariates over intervals of the X-variable are computed and used in the prediction by the algorithm in R. The pattern of decreasing dead branch biomass with height at PC probably reflects a smaller branch size associated with mortality of many interwhorl branches further up the stem.

4.1.4 Bole component volume estimates

Volumes for the three main stem or bole biomass components (bark, heartwood and sapwood) were calculated in the following three different ways: 1) entire bole from ground line to tree tip; 2) bole from a stump height of 0.3048 m (1 ft) to tree tip; and 3) bole from a stump height of 0.3048 m (1 ft) to a top diameter of 10 cm (4 inch). Over all sites sapwood volume averaged 0.4801 m^3 per tree (0.0561 – 1.2231 m^3), heartwood averaged 0.4474 m^3 (0.0286 – 1.1509 m^3), bark averaged 0.1558 m^3 (0.0122 – 0.3916 m^3), and total volume inside bark averaged 1.0832 m^3 (0.0969- 2.505m^3). The PC site had the lowest average total bole volume (0.949 m^3 average) and smallest range of all bole volume components, with the RR site as a close second (Table 18). The LF site

consistently had the largest average total bole volumes and the widest size range of bole volume components.

Table 18. Individual-tree bole volume data averaged by site

Component	Site	Volume (m^3)			
		Mean	Min	Max	Stdv.
BARK	ET	0.1583	0.0122	0.3409	0.0887
BARK	LF	0.1934	0.0310	0.3916	0.1070
BARK	PC	0.1272	0.0374	0.1922	0.0469
BARK	RR	0.1442	0.0413	0.2861	0.0663
SAP	ET	0.4983	0.0561	1.0397	0.2887
SAP	LF	0.5274	0.0783	1.0114	0.2883
SAP	PC	0.4722	0.1307	1.2231	0.2552
SAP	RR	0.4223	0.1536	0.7117	0.1737
HRT	ET	0.4757	0.0286	1.1267	0.3066
HRT	LF	0.5770	0.0505	1.1509	0.3666
HRT	PC	0.3492	0.0776	0.7802	0.1755
HRT	RR	0.3877	0.1010	0.6542	0.1883
Total	ET	1.1324	0.0969	2.4537	0.6640
Total	LF	1.2979	0.1598	2.5053	0.7554
Total	PC	0.9487	0.2457	2.1602	0.4640
Total	RR	0.9542	0.2959	1.6039	0.4220

4.1.5 Developing tree-level biomass equations

As described above, estimates of tree-level bark, sapwood, and heartwood biomass were computed from the combined estimates of volumes of these components and estimates of their density measured from field samples specific to each section of the felled sampled trees. Tree level estimates of the following biomass components were computed by applying the branch-level equations to each live or dead branch measured for diameter and height on the felled sampled trees: live branch wood (wood + bark), 1-yr-old foliage, 2-yr-old foliage, ≥3-yr-old foliage, and dead branch wood (wood + bark). Estimates of all eight biomass components were available for each of the 84 felled

sample trees. These 84 sample trees formed the dataset for developing tree-level biomass equations that could be applied to all of the trees on the plot based on their dbh, total height, and crown length.

Alternative models were explored for each biomass component separately, but the data for all four sites were combined during model exploration, with the intent to fit site-specific models after selection of the best model form. The best nonlinear model was selected from one of 50 model forms for dead branch biomass and from one of 54 model forms for all other components (Table 19).

Table 19. Indices of fit (Furnival 1961) for alternative tree level models fitted to the comprehensive dataset (84 felled sample trees on four sites). The best model for each biomass component is indicated by a bold index of fit (Furnival 1961).

Model ID	Linear Models	Funival's Index								
		Sap-wood	Heart-wood	Bark	Live Branches	Dead Branches	Foliage (yr. 1)	Foliage (yr. 2)	Foliage (yr. >=3)	Total Tree
Mod0	$B = \beta_0 + \beta_1 D + \beta_2 H + B_3 CL$	>1000	>1000	>1000	>1000	-	>1000	>1000	>1000	>1000
Mod1	$B = \beta_0 + \beta_1 D + \beta_2 H + B_3 CBL$	-	-	-	-	>1000	-	-	-	-
Mod2	$Ln(B) = \beta_0 + \beta_1 Ln(D)$	33.7305	33.73052	24.6361	3.9794	28.0939	2.8636	1.5118	2.6986	62.7771
Mod3	$Ln(B) = \beta_0 + B_1 D$	40.5064	40.50639	30.4348	4.8648	28.1560	3.2771	1.8286	3.1231	83.6489
Mod4	$Ln(B) = \beta_0 + \beta_1 Ln(H)$	65.7026	65.70257	72.6760	9.9272	30.1404	5.8573	3.6516	5.4077	180.3314
Mod5	$Ln(B) = \beta 0 + \beta_1 H + \beta_2 CL$	66.0826	66.08263	73.2240	1.00E+01	-	5.891007	3.683453	5.5012	181.6259
Mod6	$Ln(B) = \beta 0 + \beta_1 H + \beta_2 CBL$	-	-	-	-	30.3214	-	-	-	-
Mod7	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(H)$	16.3177	16.31770	20.3901	3.8102	25.2991	2.8113	1.5181	2.5797	33.4703
Mod8	$Ln(B) = \beta 0 + \beta_1 Ln(D) + \beta_2 H + B_3 CL$	15.9605	15.96047	20.4914	3.83E+00	-	2.7996	1.5198	2.6137	33.4137
Mod9	$Ln(B) = \beta 0 + \beta_1 Ln(D) + \beta_2 H + B_3 CBL$	-	-	-	-	25.3356	-	-	-	-
Mod10	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 Ln(H)$	24.1516	24.15156	25.6490	4.6106	25.3268	3.2754	1.8227	2.9522	57.5763
Mod11	$Ln(B) = \beta 0 + \beta 1 D + \beta_2 H + B_3 CL$	24.7599	24.75990	26.1883	4.6586	-	3.2620	1.8307	3.0055	59.4061
Mod12	$Ln(B) = \beta 0 + \beta 1 D + \beta_2 H + B3CBL$	-	-	-	-	25.3700	-	-	-	-
Mod13	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(CL)$	33.3335	33.33345	24.6510	3.2560	-	2.8810	1.3489	1.4360	61.3951
Mod14	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(CBL)$	-	-	-	-	27.9984	-	-	-	-
Mod15	$Ln(B) = \beta_0 + \beta_1 Ln(D) + B_2 CL$	33.3283	33.32832	24.6634	3.46E+00	-	2.8699	1.4085	1.7446	61.7194
Mod16	$Ln(B) = \beta_0 + \beta_1 Ln(D) + B_2 CBL$	-	-	-	-	28.1985	-	-	-	-
Mod17	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 Ln(CL)$	38.0362	38.03621	28.9816	3.6660	-	3.2368	1.5140	1.5382	76.2709
Mod18	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 Ln(CBL)$	-	-	-	-	28.0486	-	-	-	-
Mod19	$Ln(B) = \beta_0 + \beta_1 D + B_2 CL$	39.3680	39.36800	30.1219	4.1898	-	3.2964	1.6715	2.0734	80.8475
Mod20	$Ln(B) = \beta_0 + \beta_1 D + B_2 CBL$	-	-	-	-	28.2495	-	-	-	-
Mod21	$Ln(B) = \beta_0 + \beta_1 Ln(H) + \beta_2 Ln(CL)$	51.2349	51.23487	55.7740	6.0066	-	4.50E+00	2.3241	2.4098	134.5526
Mod22	$Ln(B) = \beta_0 + \beta_1 Ln(H) + \beta_2 Ln(CBL)$	-	-	-	-	30.5630	-	-	-	-

Table 19. Continued…

Model ID	Linear Models	Funival's Index								
		Sap-wood	Heart-wood	Bark	Live Branches	Dead Branches	Foliage (yr. 1)	Foliage (yr. 2)	Foliage (yr. >=3)	Total Tree
Mod23	$Ln(B) = \beta_0 + \beta_1 Ln(H) + B_2 CL$	52.7837	52.78368	57.7056	6.5955	-	4.8091	2.5415	2.8921	140.3270
Mod24	$Ln(B) = \beta_0 + \beta_1 Ln(H) + B_2 CBL$	-	-	-	-	30.6592	-	-	-	-
Mod25	$Ln(B) = \beta_0 + \beta_1 H + B_2 CL$	52.7031	52.70310	57.7957	6.6038	-	4.81E+00	2.5440	2.9082	140.4061
Mod26	$Ln(B) = \beta_0 + \beta_1 H + B_2 CBL$	-	-	-	-	30.8022	-	-	-	-
Mod27	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(H) + \beta_3 Ln(CL)$	15.8988	15.89880	20.3770	3.2435	-	2.8165	1.3483	1.4437	33.4657
Mod28	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(H) + \beta_3 Ln(CBL)$	-	-	-	-	23.6270	-	-	-	-
Mod29	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(H) + B_3 CL$	15.9907	15.99069	20.3813	3.4284	-	2.8284	1.4136	1.7476	33.3518
Mod30	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 Ln(H) + B_3 CBL$	-	-	-	-	22.8487	-	-	-	-
Mod31	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 H + \beta_3 CL$	**15.6693**	15.66927	20.5041	3.4351	-	2.8168	1.4110	1.7542	33.3574
Mod32	$Ln(B) = \beta_0 + \beta_1 Ln(D) + \beta_2 H + \beta_3 CBL$	-	-	-	-	22.7430	-	-	-	-
Mod33	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 Ln(H) + B_3 CL$	24.2754	24.27542	25.8052	4.1390	-	3.2879	1.6817	2.0700	57.9062
Mod34	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 Ln(H) + B3CBL$	-	-	-	-	22.8415	-	-	-	-
Mod35	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 H + \beta_3 CL$	24.9112	24.91119	26.3509	4.1592	-	3.2723	1.6799	2.0822	59.6716
Mod36	$Ln(B) = \beta_0 + \beta_1 D + \beta_2 H + \beta_3 CBL$	-	-	-	-	22.7596	-	-	-	-

Table 19. Continued....

Model ID	Non-Linear Models	Weights	Funival's Index								
			Sap-wood	Heart-wood	Bark	Live Branches	Dead Branches	Foliage (yr. 1)	Foliage (yr. 2)	Foliage (yr. >=3)	Total Tree
model1	$B = \beta_o D^{\beta 1}$		29.1851	5.23E+01	18.68244	6.1066	22.6917	4.4753	2.5762	3.3787	90.8858
model1w1		$1 / D$	26.8900	4.60E+01	16.76452	5.4778	22.7222	3.9739	2.2888	3.0768	80.5127
model1w2		$1 / D^2$	25.2856	4.12E+01	15.39539	4.9839	22.8800	3.5880	2.0602	2.8432	72.5600
model2	$B = \beta o D^{\beta 1} * H^{\beta 2}$		22.9779	1.92E+01	15.17645	5.8186	17.7102	4.2435	2.5865	3.2413	42.6374
model2w1		$1 / (H * D^2)$	19.4575	15.5810	12.44209	4.6884	18.4035	3.3710	2.0101	2.7052	34.5262
model2w2		$1 / (H^2 * D^2)$	18.9235	1.53E+01	12.08862	4.6305	18.2329	3.3319	1.9641	2.6747	33.8369
model2w3		$1/ (H * D^2)^2$	18.7521	15.5588	11.66480	4.1500	19.5966	2.9912	1.7105	2.5102	33.0836
model3	$B = \beta_o D^{\beta 1} * CL^{\beta 3}$		27.9607	47.7995	18.60156	5.5736	-	4.4192	2.5011	2.3278	82.1487
model3w1		$1 / (CL * D^2)$	24.3099	38.1188	14.84838	4.0612	-	3.3100	1.7379	1.6437	66.3805
model3w2		$1 / (CL^2 * D^2)$	24.1998	37.4009	14.72935	3.7549	-	3.1131	1.5673	1.5158	65.1477
model3w3		$1/ (CL * D^2)^2$	26.3288	34.9240	15.63924	3.3985	-	2.8833	1.3544	**1.3277**	64.6505
model4	$B = \beta_o D^{\beta 1} * CBL^{\beta 3}$		-	-	-	-	20.8404	-	-	-	-
model4w1		$1 / (CBL * D^2)$	-	-	-	-	22.0984	-	-	-	-
model4w2		$1 / (CBL^2 * D^2)$	-	-	-	-	23.5849	-	-	-	-
model4w3		$1/ (CBL * D^2)^2$	-	-	-	-	24.5663	-	-	-	-
model5	$B = \beta_o D^{\beta 1} * H^{\beta 2} * CL^{\beta 3}$		23.1210	19.1232	14.99870	5.5541	-	4.2698	2.5075	2.3208	42.90031
model5w1		$1 / (H * D^2)$	19.5122	1.53E+01	12.28736	4.3401	-	3.3848	1.8953	1.7747	34.6853
model5w2		$1 / (H^2 * D^2)$	18.9588	15.0408	11.98328	4.2549	-	3.3429	1.8451	1.7478	34.0112
model5w3		$1/ (H * D^2)^2$	**18.7104**	15.0325	**11.6644**	3.67E+00	-	2.9745	1.5494	1.4709	33.0861
model5w4		$1 / (CL * D^2)$	19.4457	14.8599	12.20378	3.2785	-	3.1501	1.7330	1.6447	33.1730
model5w5		$1 / (CL^2 * D^2)$	19.0991	**1.45E+01**	12.10027	2.99E+00	-	2.9430	1.5571	1.5181	**31.6491**
model5w6		$1/ (CL * D^2)^2$	20.2705	1.54E+01	12.94506	**2.6977**	-	**2.769434**	**1.34788**	1.335504	32.7304
model6	$B = \beta_o D^{\beta 1} * H^{\beta 2} * CBL^{\beta 3}$		-	-	-	-	17.7596	-	-	-	-
model6w1		$1 / (H * D^2)$	-	-	-	-	18.4549	-	-	-	-
model6w2		$1 / (H^2 * D^2)$	-	-	-	-	18.4504	-	-	-	-
model6w3		$1/ (H * D^2)^2$	-	-	-	-	19.5836	-	-	-	-
model6w4		$1 / (CBL * D^2)$	-	-	-	-	18.4906	-	-	-	-
model6w5		$1 / (CBL^2 * D^2)$	-	-	-	-	18.8255	-	-	-	-
model6w6		$1/ (CBL * D^2)^2$	-	-	-	-	19.7306	-	-	-	-

Table 19. Continued....

Model ID	Non-Linear Models	Weights	Funival's Index								
			Sap-wood	Heart-wood	Bark	Live Branches	Dead Branches	Foliage (yr. 1)	Foliage (yr. 2)	Foliage (yr. >=3)	Total Tree
model7	$B = \beta_o D^{\beta 1} * H^{\beta 2} * e^{\beta 3 * CL}$		23.1210	19.1218	15.09998	5.6435	-	4.2652	2.5395	2.5251	42.9003
model7w1		$1 / (H * D^2)$	19.5101	15.3277	12.37758	4.4435	-	3.3917	1.9334	1.9732	34.6861
model7w2		$1 / (H^2 * D^2)$	18.9573	1.51E+01	12.04883	4.3668	-	3.3522	1.8860	1.9469	34.0117
model7w3		$1/ (H * D^2)^2$	18.7264	15.0895	11.69187	3.8038	-	3.0039	1.5998	1.6899	33.0983
model7w4		1 / (CL * D2)	19.4459	14.9527	12.28930	3.40E+00	-	3.1633	1.7764	1.8512	33.1769
model7w5		1 / (CL2 * D2)	19.1044	1.46E+01	12.14804	3.14E+00	-	2.9718	1.6128	1.7443	31.6598
model7w6		1/ (CL * D2)2	20.2862	15.7077	12.94762	2.9206	-	2.8419	1.4225	1.6216	32.7865
model8	$B = \beta_o D^{\beta 1} * H^{\beta 2} * e^{\beta 3 * CBL}$		-	-	-	-	**17.1456**	-	-	-	-
model8w1		$1 / (H * D^2)$	-	-	-	-	17.7190	-	-	-	-
model8w2		$1 / (H^2 * D^2)$	-	-	-	-	17.8485	-	-	-	-
model8w3		$1/ (H * D^2)^2$	-	-	-	-	18.6479	-	-	-	-
model8w4		$1 / (CBL * D^2)$	-	-	-	-	17.8993	-	-	-	-
model8w5		$1 / (CBL^2 * D^2)$	-	-	-	-	18.5398	-	-	-	-
model8w6		$1/ (CBL * D^2)^2$	-	-	-	-	19.1700	-	-	-	-
model9	$B = \beta_o D^{\beta 1} * e^{\beta 2 * CL}$		27.9347	47.8244	18.60444	5.6895	-	4.3951	2.5273	2.5141	82.1733
model9w1		$1 / (CL * D^2)$	24.3016	3.81E+01	14.72888	4.1854	-	3.2929	1.7740	1.8416	66.6462
model9w2		$1 / (CL^2 * D^2)$	23.8060	36.7599	14.11960	3.9071	-	3.0950	1.6128	1.7341	64.5366
model9w3		$1/ (CL * D^2)^2$	23.8434	3.30E+01	13.54615	3.63E+00	-	2.8980	1.4193	1.6122	60.2321
model10	$B = \beta_o D^{\beta 1} * e^{\beta 2 * CBL}$		-	-	-	-	21.2678	-	-	-	-
model10w1		$1 / (CBL * D^2)$	-	-	-	-	22.6150	-	-	-	-
model10w2		$1 / (CBL^2 * D^2)$	-	-	-	-	24.1851	-	-	-	-
model10w3		$1/ (CBL * D^2)^2$	-	-	-	-	25.1843	-	-	-	-
model11	$B = \beta_o D^{\beta 1} * e^{\beta 2 * H}$		23.0986	1.99E+01	15.00861	5.8079	-	4.2500	2.5869	3.2665	43.04533
model11w1		$1 / (H * D^2)$	19.5376	1.59E+01	12.34804	4.6837	-	3.3709	2.0108	2.7279	34.6300
model11w2		$1 / (H^2 * D^2)$	19.0163	1.55E+01	12.00231	4.6249	-	3.3305	1.9651	2.7005	33.8758
model11w3		$1/ (H * D^2)^2$	18.9387	15.3426	11.70032	4.1548	-	2.9811	1.7120	2.5337	33.0617

The following site specific models were selected as best for each specific component (Table 20) and were fitted to each site separately:

[6] $B_s = g_{0s} * D^{g1s} * HT^{g2s} * CL^{g3s}$ Weight = $1 / (D^2*HT)^2$

[7] $B_h = g_{0h} * D^{g1h} * HT^{g2h} * CL^{g3h}$ Weight = $1 / (D^2*CL^2)$

[8] $B_k = g_{0k} * D^{g1k} * HT^{g2k} * CL^{g3k}$ Weight = $1 / (D^2*HT)^2$

[9] $B_L = g_{0L} * D^{g1L} * HT^{g2L} * CL^{g3L}$ Weight = $1 / (D^2*CL)^2$

[10] $B_D = g_{0D} * D^{g1D} * HT^{g2D} * e^{g3kD*CBL}$ Weight = $1 / (D^2*HT)^2$

[11] $B_{F1} = g_{10F} * D^{g11F} * HT^{g12F} * CL^{g13F}$ Weight = $1 / (D^2*CL)^2$

[12] $B_{F2} = g_{20F} * D^{g21F} * HT^{g22F} * CL^{g23F}$ Weight = $1 / (D^2*CL)^2$

[13] $B_{F3} = g_{30F} * D^{g31F} * CL^{g32F}$ Weight = $1 / (D^2*CL)^2$

[14] $B_T = g_{0T} * D^{g1T} * HT^{g2T} * CL^{g3T}$ Weight = $1 / (D^2*CL^2)$

where B_s represents stem sapwood biomass (kg), B_h represents stem heartwood biomass (kg), B_k represents stem bark biomass (kg), B_L represents total live branch biomass, wood + bark (kg), B_D represents total live branch biomass, wood + bark (kg), B_{F1} represents 1-yr-old foliage biomass (kg), B_{F2} represents 2-yr-old foliage biomass (kg), B_{F3} represents ≥3-yr foliage biomass (kg), D was diameter at breast height (cm), H was total tree height (m), CL was crown length (m), CBL was clear bole length (m), and g_{0s}-g_{3T} were parameters estimated from the data (Table 20-28).

Preliminary checks on the normality of the standardized residuals for the branch level models were made by evaluating kurtosis and symmetry, and homogeneity of variance was checked with plots of standardized residuals on predicted values.

Table 20. Parameter estimates for site-specific and site-independent biomass equations.

Parameter	Site				Site Independent
	ET	LF	PC	RR	
Sapwood					
gos	0.17026	0.03979	0.03264	0.03607	0.05528
g1s	1.9819	1.64647	1.51044	1.42454	1.69802
g2s	0.07013	0.89048	1.1341	0.98809	0.73856
g3s	-0.07144	-0.07443	-0.09091	0.14027	-0.07997
Heartwood					
g0h	0.0016516	0.0005695	0.0006001	0.000539	0.00050304
g1h	2.2991548	2.1332	1.4590924	1.7872308	1.9425853
g2h	1.307384	1.80976	2.4622734	1.8902672	1.97591816
g3h	-0.3305046	-0.3134107	-0.2241916	0.0659763	-0.23226721
Bark					
g0k	0.0000112	0.019603	0.0489222	0.0413246	0.003262
g1k	0.7485556	2.1821607	1.5753794	2.0328027	1.819518
g2k	3.8484414	0.5167874	0.4326724	0.0578775	1.170269
g3k	0.0077332	-0.4425913	0.0434729	0.0039393	-0.144976
Live branches					
g0L	0.0010697574	0.0109292402	0.0023101951	0.0002365301	0.00040089
g1L	1.9771752732	1.9711580798	2.0446149982	1.8769258081	1.96268638
g2L	0.0657310185	-0.8503311648	-0.4585362350	0.1343372956	0.40630105
g3L	0.8878879806	1.3409715549	1.2037709572	1.5851200810	0.92952603
Dead branches					
god	1.48E-03	3.51E+06	3.50E+01	3.27E-07	33.16185
g1d	4.22E+00	4.51E+00	1.10E+00	4.20E+00	2.61518
g2d	-4.46E+00	-1.02E+01	-5.44E-01	3.11E-01	-3.1148
g3d	3.91E+00	2.74E+00	-6.88E-01	1.10E+00	0.10037
Foliage yr 1					
g0f1	0.001235	0.005804	0.001019	0.003183	0.00503906
g1f1	2.266372	1.769794	2.310149	2.278652	2.62856547
g2f1	-0.276932	-0.741070	-0.412341	-0.527122	-0.92651206
g3f1	0.504465	1.400152	0.990005	0.719997	0.51667447
Foliage yr 2					
g0f2	0.0003254143	0.0014022119	0.0001090671	0.0000334270	0.00038492
g1f2	2.2230447642	1.8519760765	2.0961195359	1.9316369068	2.27173619
g2f2	-0.0097941325	-0.9144917944	-0.2247235010	0.2721465943	-0.35537488
g3f2	0.6505829530	1.8903640746	1.6625235499	1.7418778923	1.07401013
Foliage yr 3					
g0f3	0.00032076170	0.00020958140	0.00001101943	0.00011764820	0.0001485
g1f3	1.77455100000	1.79842600000	2.17783100000	1.46815000000	1.69728947
g3f3	1.53620600000	1.60968800000	2.22196600000	2.30591900000	1.89447656

Table 21. Parameter estimates, standard errors, and p-values for model [6] predicting sapwood biomass for individual trees, all sites combined.

Parameter	Estimate	Std. Error	P-value
gos	0.05528	0.01504	>0.001
g1s	1.69802	0.06382	>0.001
g2s	0.73856	0.10216	>0.001
g3s	-0.07997	0.06913	0.25085
MSE = 0.0007601		DF = 80	

Table 22. Parameter estimates, standard errors, and p-values for model [7] predicting heartwood biomass for individual trees, all sites combined.

Parameter	Estimate	Std. Error	P-value
goh	0.000503	0.000134	>0.001
g1h	1.942585	0.072066	>0.001
g2h	1.975918	0.092387	>0.001
g3h	-0.23227	0.080304	0.00492
MSE = 0.03551		DF = 80	

Table 23. Parameter estimates, standard errors, and p-values for model [8] predicting bark biomass for individual trees, all sites combined.

Parameter	Estimate	Std. Error	P-value
gok	0.003262	0.00182	0.0769
g1k	1.819518	0.134382	>0.001
g2k	1.170269	0.207794	>0.001
g3k	-0.14498	0.148247	0.3311
MSE = 0.0004738		DF = 80	

Table 24. Parameter estimates, standard errors, and p-values for model [9] predicting total live branch biomass for individual trees, all sites combined.

Parameter	Estimate	Std. Error	P-value
gof2	0.000401	0.000238	0.0962
g1f2	1.962686	0.145675	>0.001
g2f2	0.406301	0.218303	0.0664
g3f2	0.929526	0.164032	>0.001
MSE = 0.0002606		DF = 80	

Table 25. Parameter estimates, standard errors, and p-values for model [9] predicting total dead branch biomass for individual trees, all sites combined.

Parameter	Estimate	Std. Error	P-value
god3	33.16185	71.69052	0.647839
g1d3	2.61518	0.51414	3.34E-05
g2d3	-3.1148	0.7907	0.000614
g3d3	0.10037	0.03755	0.013304
MSE = 0.0004008		DF = 24	

Table 26. Parameter estimates, standard errors, and p-values for model [10] predicting 1-yr-old foliage biomass for individual trees, all sites combined.

Parameter	Estimate	Std. Error	P-value
gof1	0.005039	0.004532	0.2695
g1f1	2.628565	0.207079	>0.001
g2f1	-0.92651	0.328588	0.00606
g3f1	0.516674	0.238188	0.03304
MSE = 0.0002204		DF = 80	

Table 27. Parameter estimates, standard errors, and p-values for model [11] predicting 2-yr-old foliage biomass for individual trees, all sites combined.

Parameter	Estimate	Std. Error	P-value
gof2	0.000385	0.000281	0.175
g1f2	2.271736	0.172582	>0.001
g2f2	-0.35537	0.26513	0.184
g3f2	1.07401	0.201173	>0.001
MSE =	0.000107	DF = 80	

Table 28. Parameter estimates, standard errors, and p-values for model [12] predicting ≥3-yr-old foliage biomass for individual trees, all sites combined.

Parameter	Estimate	Std. Error	P-value
gof3	1.49E-04	4.14E-05	>0.001
g1f3	1.70E+00	1.17E-01	>0.001
g2f3	1.89E+00	1.35E-01	>0.001
MSE = 0.0001057			

4.1.6 Forced additivity tree-level biomass equations

Parameter estimates from the SMC general model (site independent) fit to the data were entered as starting values for a set of forced additivity models for the sampled

Douglas-fir trees. Forced additivity was imposed by indicator variables as formulated below:

$$[15]\ MSWT_i = (f_{10}\ D^{f11}\ H^{f12}\ CL^{f13}) * I_{f1} / (((D^2\ CL)^2)^{0.5}\ MSE_{f1}^{0.5}) +$$
$$(f_{20}\ D^{f21}\ H^{f22}\ CL^{f23}) * I_{f2} / (((D^2\ CL)^2)^{0.5}\ MSE_{f2}^{0.5}) +$$
$$(f_{30}\ D^{f31}\ CL^{f32}) * I_{f3} / (((D^2\ CL)^2)^{0.5}\ MSE_{f3}^{0.5}) +$$
$$(lb_0\ D^{lb1}\ H^{lb2}\ CL^{lb3}) * I_{br} / (((D^2\ CL)^2)^{0.5}\ MSE_{lb}^{0.5}) +$$
$$(bk_0 * D^{bk1}\ H^{bk2}\ CL^{bk3}) * I_{bk} / (((D^2\ H)^2)^{0.5}\ MSE_{bk}^{0.5}) +$$
$$(s_0\ D^{s1}\ H^{s2}\ CL^{s3}) * I_s / (((D^2\ H)^2)^{0.5}\ MSE_s^{0.5}) +$$
$$(h_0\ D^{h1}\ H^{h2}\ CL^{h3}) * I_h / ((D^2\ CL^2)^{0.5}\ MSE_h^{0.5})$$

where $MSWT_i$ is the weighted biomass of biomass component i (kg), parameters estimated from the data were f_{10}-f_{13} for 1-yr-old foliage biomass (kg), f_{20}-f_{23} for 2-yr-old foliage biomass (kg), f_{30}-f_{32} for ≥3-yr-old foliage biomass (kg), lb_0-lb_3 for live branch biomass including wood + bark (kg), bk_0-bk_3 for stem bark biomass (kg), s_0-s_3 for sapwood biomass (kg) and h_0-h_3 for heartwood biomass (kg); $I_{f1}$was the indicator variable for total biomass or 1-yr-old foliage, $I_{f2}$was the indicator variable for total biomass or 2-yr-old foliage, $I_{f3}$was the indicator variable for total biomass or ≥3-yr-old foliage, I_{lb} was the indicator variable for total biomass or bark, I_s was the indictor variable for total biomass or sapwood, and I_h was the indictor variable for total biomass or heartwood; MSE_k was the mean squared error for biomass component *k*; and all other variables are as defined above. This system weighted each observation of a given biomass component by the square root of the reciprocal of its MSE to address the fact that the variances around the regression for each component are of differing magnitude. In addition, a weight equal

to a function of the reciprocal of tree dimensions specific to each component (e.g., $1/(D^2CL)^2)^{½}$ for 1-yr-old foliage) was applied to homogenize the increasing variance with increasing trees size. Variance homogeneity was verified with plots of standardized residuals on the model scale (scale of the response variable) predicted values (Fig. 20 and 21).

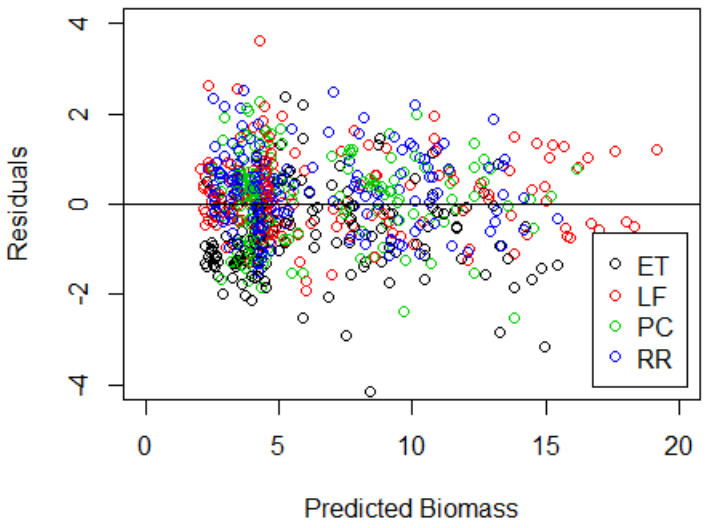


Figure20. Residuals plotted on estimated total aboveground biomass from site-independent model [15], color coded by site.

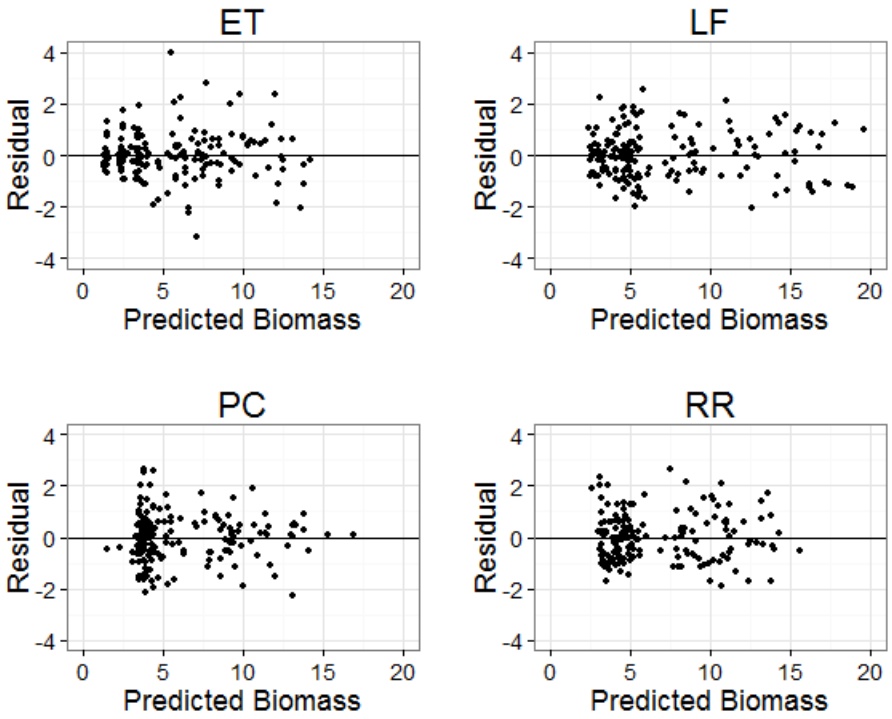


Figure 21. Residuals plotted on estimated total aboveground biomass from site-specific model [15] for ET, LF, PC and RR sites, color coded by site.

The SMC site-specific models were fitted to only the data from one of the four specific sites (Fig. 23-26, Table 29 and Table 31-34). The SMC general model was fitted to the entire 84 tree dataset (Table 29 and 30, Fig.22). As an indicator of the need for site-specific equations, the total biomass of a tree with a 50 (cm) dbh, 31 m height and a crown ratio of 0.5225 was computed from both site-independent and site-specific forced additivity equations. The comprehensive model gave a total tree biomass of 1144 (kg), and the site specific models gave total tree biomass estimates of 1083 (kg), 987 (kg), 1144 (kg) and 1143 (kg) for ET, LF, PC and RR, respectively.

Table 29. Parameter estimates from forced additivity model [15] for the four SMC site-specific models and the SMC general model.

Parameter	Site				Site Independent
	ET	LF	PC	RR	
Sapwood					
s0	0.1867200000	0.0412853841	0.03275363	0.0336828400	0.057654631
s1	1.9897190000	1.6214356549	1.49449	1.4047990000	1.681884296
s2	0.0233394300	0.8904777425	1.148204	1.0145070000	0.732864472
s3	-0.0594421600	-0.0578708797	-0.0893187	0.1588008000	-0.06904682
Heartwood					
h0	0.0018881560	0.0005313908	0.00057898	0.0005116438	0.000513241
h1	2.2980400000	2.0808666230	1.450022	1.7734560000	1.928251951
h2	1.2567210000	1.8633677218	2.488576	1.9098230000	1.987887185
h3	-0.3169838000	-0.2879689273	-0.2312254	0.0791161600	-0.23678622
Bark					
bk0	0.00001479792	0.0206018448	0.05025193	0.0403305000	0.003425404
bk1	0.7807156000	2.1267832430	1.556981	2.0047690000	1.794750523
bk2	3.7291840000	0.5272730464	0.4394676	0.0687243400	1.172035736
bk3	0.0077031930	-0.4051535685	0.0476755	0.0357883700	-0.1350382
Live branches					
lb0	0.0011848190	0.0114308625	0.00238144	0.0002445168	0.000419649
lb1	1.9877060000	1.9515827792	2.032777	1.8710800000	1.947019004
lb2	0.0224040400	-0.8583221754	-0.4490402	0.1234135000	0.405229223
lb3	0.8888151000	1.3592147027	1.195556	1.5934670000	0.933299641
Foliage yr 1					
f10	0.0014415580	0.0062227564	0.00104567	0.003260814	0.005406247
f11	2.2775140000	1.7447246339	2.299803	2.269182000	2.604666481
f12	-0.3442746000	-0.7565407718	-0.402686	-0.534843400	-0.93341843
f13	0.5139377000	1.4253988520	0.9815008	0.732628200	0.52912161
Foliage yr 2					
f20	0.0003442235	0.0014452218	0.00011131	0.000033953790	0.00039703
f21	2.2274000000	1.8378385413	2.089879	1.929357000	2.262284684
f22	-0.0333644100	-0.9194871026	-0.2183769	0.267090300	-0.35720382
f23	0.6526071000	1.9034799061	1.654975	1.745092000	1.076590241
Foliage yr 3					
f30	0.0003229100	0.0002124140	1.1483E-05	0.000117773	0.000151232
f31	1.7744530000	1.7879994699	2.172603	1.466679000	1.691338261
f32	1.5337550000	1.6179905073	2.2128	2.307360000	1.895137312
MSE	0.8957	0.8411	0.8186	0.7786	0.9993
DF	141	141	141	141	645

Table 30. Parameter estimates, standard errors, and p-values from the forced additivity model [15] fitted to the pooled data from all four sites together (SMC general).

Parameter	Estimate	Std. Error	P-value
f10	5.406000E-03	4.85E-03	0.265707
f11	2.605000E+00	2.07E-01	>0.001
f12	-9.334000E-01	3.28E-01	0.004613
f13	5.291000E-01	2.37E-01	0.026049
f20	3.970000E-04	2.90E-04	0.171136
f21	2.262000E+00	1.72E-01	>0.001
f22	-3.572000E-01	2.65E-01	0.178267
f23	1.077000E+00	2.01E-01	>0.001
f30	1.512000E-04	4.21E-05	>0.001
f31	1.691000E+00	1.17E-01	>0.001
f32	1.895000E+00	1.35E-01	>0.001
lb0	4.196000E-04	2.49E-04	0.091784
lb1	1.947000E+00	1.45E-01	>0.001
lb2	4.052000E-01	2.18E-01	0.063245
lb3	9.333000E-01	1.63E-01	>0.001
bk0	0.00342500000	1.83E-03	0.06192
bk1	1.7950000	1.29E-01	>0.001
bk2	1.1720000	1.99E-01	>0.001
bk3	-0.1350000	1.43E-01	0.344803
s0	5.765000E-02	1.39E-02	>0.001
s1	1.682000E+00	5.75E-02	>0.001
s2	7.329000E-01	9.05E-02	>0.001
s3	-6.905000E-02	6.27E-02	0.271302
h0	5.132000E-04	1.28E-04	>0.001
h1	1.928000E+00	6.73E-02	>0.001
h2	1.988000E+00	8.67E-02	>0.001
h3	-2.368000E-01	7.48E-02	1.62E-03
MSE = 0.9993		DF = 645	

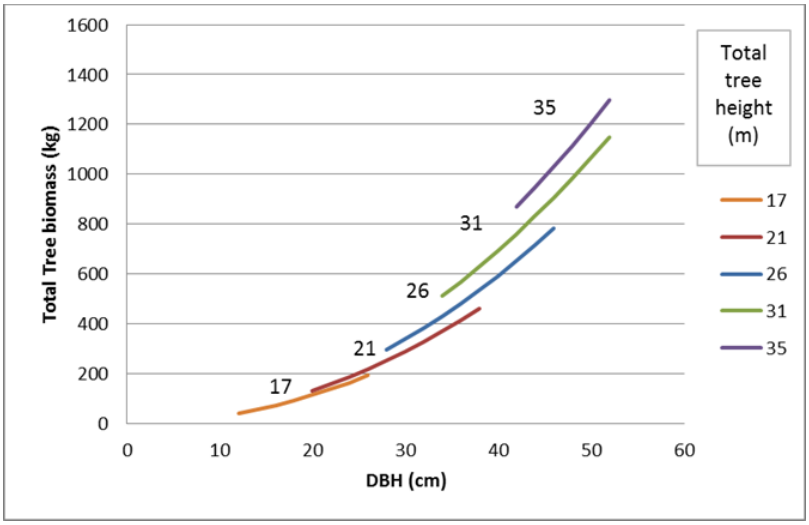


Figure 22. Total aboveground tree biomass predicted from SMC general forced additivity model. Total tree biomass (kg) is extrapolated across the overall range of height and dbh. Crown length for each DBH-HT combination is estimated by the following regression equation: CL=-0.01985 + 0.24436*DBH + 0.22442*HT (MSE=2.075, DF=669).

Table 31. Parameter estimates, standard errors, and p-values from the forced additivity model [15] fitted to data from the PC site only.

Parameter	Estimate	Std. Error	P-value
f10	1.05E-03	2.12E-03	0.622643
f11	2.30E+00	2.69E-01	>0.001
f12	-4.03E-01	8.53E-01	0.63741
f13	9.82E-01	3.14E-01	0.002184
f20	1.11E-04	2.29E-04	0.627636
f21	2.09E+00	2.48E-01	>0.001
f22	-2.18E-01	8.51E-01	0.797753
f23	1.66E+00	3.45E-01	>0.001
f30	1.15E-05	9.47E-06	0.227353
f31	2.17E+00	1.84E-01	>0.001
f32	2.21E+00	3.11E-01	>0.001
lb0	2.38E-03	4.28E-03	0.578359
lb1	2.03E+00	2.35E-01	>0.001
lb2	-4.49E-01	7.64E-01	0.557394
lb3	1.20E+00	2.75E-01	>0.001
bk0	5.03E-02	7.71E-02	0.515622
bk1	1.56E+00	2.15E-01	>0.001
bk2	4.40E-01	6.79E-01	0.51829
bk3	4.77E-02	2.10E-01	0.820449
s0	3.28E-02	2.18E-02	0.135627
s1	1.49E+00	9.71E-02	>0.001
s2	1.15E+00	2.93E-01	>0.001
s3	-8.93E-02	9.27E-02	0.33716
h0	5.79E-04	4.54E-04	0.203776
h1	1.45E+00	1.25E-01	>0.001
h2	2.49E+00	3.19E-01	>0.001
h3	-2.31E-01	1.22E-01	0.061024
MSE = 0.8186		DF = 141	

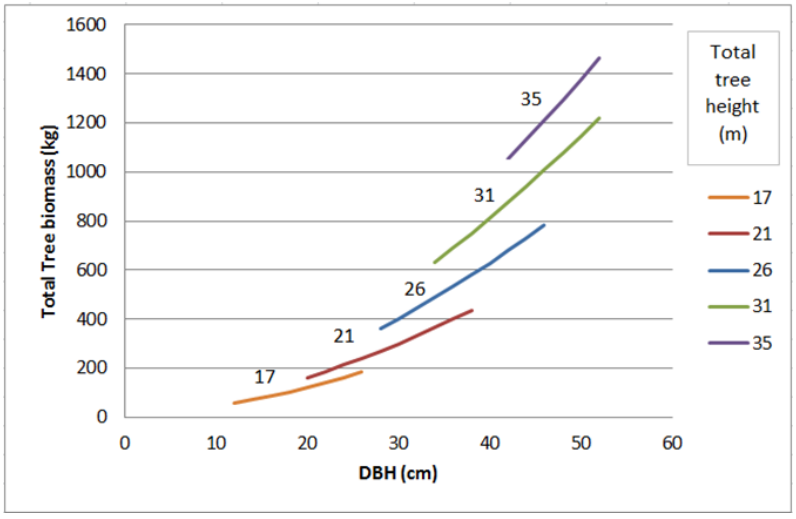


Figure 23. Total aboveground tree biomass predicted from PC-specific forced additivity model. Total tree biomass (kg) is extrapolated across the overall range of height and dbh. Crown length for each DBH-HT combination is estimated by the following regression equation: CL=-1.81282 + 0.06550*DBH + 0.54842*HT (MSE=1.779, DF=165).

Table 32. Parameter estimates, standard errors, and p-values from the forced additivity model [15] fitted to data from the RR site only.

Parameter	Estimate	Std. Error	P-value
f10	3.26E-03	9.47E-03	0.73113
f11	2.27E+00	4.55E-01	>0.001
f12	-5.35E-01	1.07E+00	0.61852
f13	7.33E-01	4.57E-01	0.11073
f20	3.40E-05	7.71E-05	0.66025
f21	1.93E+00	3.62E-01	>0.001
f22	2.67E-01	8.19E-01	0.7447
f23	1.75E+00	3.43E-01	>0.001
f30	1.18E-04	5.94E-05	0.0495
f31	1.47E+00	2.64E-01	>0.001
f32	2.31E+00	2.53E-01	>0.001
lb0	2.45E-04	5.45E-04	0.65419
lb1	1.87E+00	3.55E-01	>0.001
lb2	1.23E-01	8.12E-01	0.87935
lb3	1.59E+00	3.40E-01	>0.001
bk0	4.03E-02	8.17E-02	0.62246
bk1	2.01E+00	3.11E-01	>0.001
bk2	6.87E-02	7.48E-01	0.92688
bk3	3.58E-02	3.10E-01	0.90826
s0	3.37E-02	3.14E-02	0.28472
s1	1.41E+00	1.49E-01	>0.001
s2	1.02E+00	3.50E-01	0.00435
s3	1.59E-01	1.44E-01	0.27227
h0	5.12E-04	4.33E-04	0.23929
h1	1.77E+00	1.52E-01	>0.001
h2	1.91E+00	3.13E-01	>0.001
h3	7.91E-02	1.52E-01	0.60285
MSE=0.7786		DF = 141	

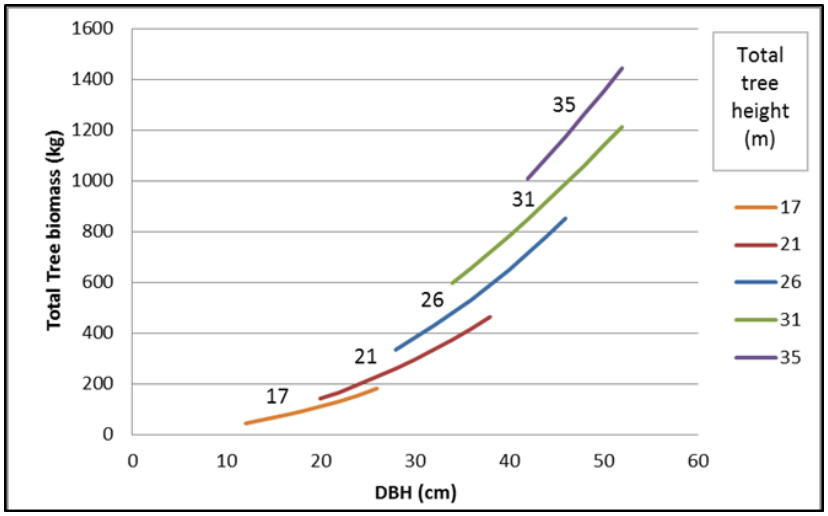


Figure 24. Total aboveground tree biomass predicted from RR-specific forced additivity model. Total tree biomass (kg) is extrapolated across the overall range of height and dbh. Crown length for each DBH-HT combination is estimated by the following regression equation: CL=-3.51475 + 0.33234*DBH + 0.25397*HT (MSE=1.635, DF=165).

Table 33. Parameter estimates, standard errors, and p-values from the forced additivity model [15] fitted to data from the LF site only.

Parameter	Estimate	Std. Error	P-value
f10	6.22E-03	1.47E-02	0.673442
f11	1.75E+00	4.80E-01	>0.001
f12	-7.57E-01	9.42E-01	0.423295
f13	1.43E+00	5.37E-01	0.00886
f20	1.45E-03	2.65E-03	0.585991
f21	1.84E+00	3.97E-01	>0.001
f22	-9.20E-01	7.39E-01	0.215478
f23	1.90E+00	4.21E-01	>0.001
f30	2.12E-04	8.63E-05	0.015098
f31	1.79E+00	2.56E-01	>0.001
f32	1.62E+00	3.11E-01	>0.001
lb0	1.14E-02	1.42E-02	0.422656
lb1	1.95E+00	2.65E-01	>0.001
lb2	-8.58E-01	4.97E-01	0.086348
lb3	1.36E+00	2.90E-01	>0.001
bk0	2.06E-02	2.71E-02	0.448836
bk1	2.13E+00	2.72E-01	>0.001
bk2	5.27E-01	5.23E-01	0.314826
bk3	-4.05E-01	2.97E-01	0.174307
s0	4.13E-02	2.86E-02	0.151645
s1	1.62E+00	1.29E-01	>0.001
s2	8.91E-01	2.75E-01	0.001512
s3	-5.79E-02	1.41E-01	0.681168
h0	5.31E-04	3.80E-04	0.164209
h1	2.08E+00	1.38E-01	>0.001
h2	1.86E+00	2.85E-01	>0.001
h3	-2.88E-01	1.19E-01	0.017032
MSE= 0.8411		DF=141	

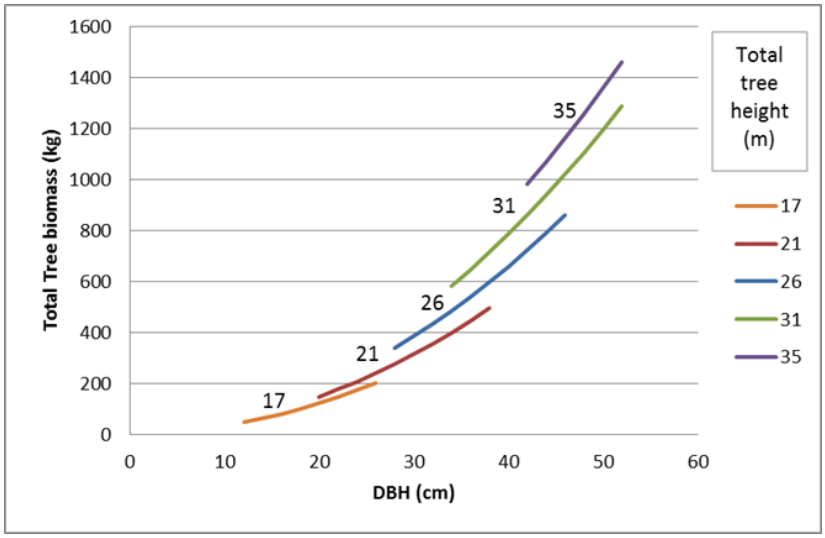


Figure 25. Total aboveground tree biomass predicted from LF-specific forced additivity model. Total tree biomass (kg) is extrapolated across the overall range of height and dbh. Crown length for each DBH-HT combination is estimated by the following regression equation: CL= 4.11023 + 0.36395*DBH – 0.06607*HT.

Table 34. Parameter estimates, standard errors, and p-values from the forced additivity model [15] fitted to data from the ET site only.

Parameter	Estimate	Std. Error	P-value
f10	1.44E-03	6.05E-03	0.812092
f11	2.28E+00	1.03E+00	0.028966
f12	-3.44E-01	2.04E+00	0.866312
f13	5.14E-01	7.01E-01	0.464822
f20	3.44E-04	8.77E-04	0.695238
f21	2.23E+00	6.27E-01	>0.001
f22	-3.34E-02	1.22E+00	0.978183
f23	6.53E-01	4.51E-01	0.149693
f30	3.23E-04	1.25E-04	0.011006
f31	1.77E+00	1.93E-01	>0.001
f32	1.53E+00	2.22E-01	>0.001
lb0	1.19E-03	2.16E-03	0.583439
lb1	1.99E+00	4.47E-01	>0.001
lb2	2.24E-02	8.69E-01	0.979455
lb3	8.89E-01	3.20E-01	0.00626
bk0	1.48E-05	2.25E-05	0.512622
bk1	7.81E-01	4.14E-01	0.061184
bk2	3.73E+00	7.29E-01	>0.001
bk3	7.70E-03	3.01E-01	0.979612
s0	1.87E-01	1.30E-01	0.152519
s1	1.99E+00	1.68E-01	>0.001
s2	2.33E-02	3.40E-01	0.945349
s3	-5.94E-02	1.10E-01	0.589563
h0	1.89E-03	1.29E-03	0.145127
h1	2.30E+00	1.74E-01	>0.001
h2	1.26E+00	3.00E-01	>0.001
h3	-3.17E-01	1.55E-01	0.042645
MSE = 0.8957		DF=141	

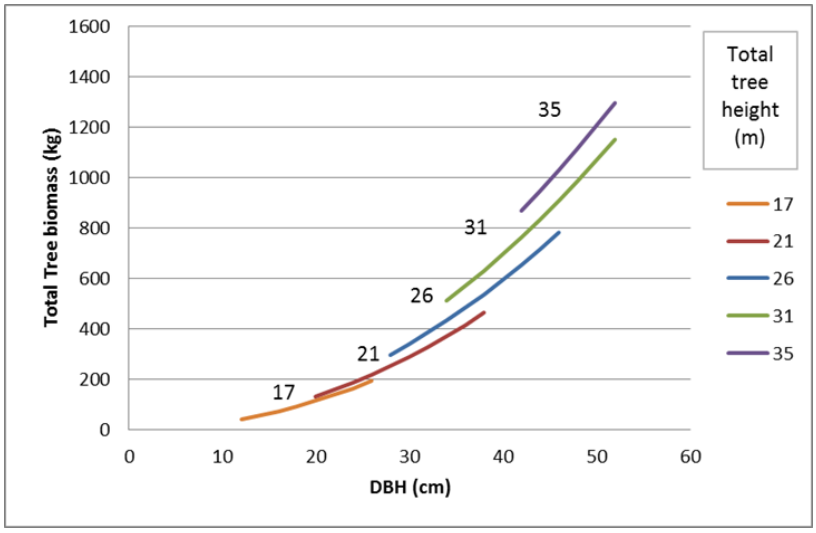


Figure 26. Total aboveground tree biomass predicted from ET-specific forced additivity model. Total tree biomass (kg) is extrapolated across the overall range of height and dbh. Crown length for each DBH-HT combination is estimated by the following regression equation: CL= 3.46784 + 0.31013*DBH + 0.06218*HT (MSE=2.034, DF = 165).

4.1.7 Forced additivity stand-level biomass estimates

The total stand-level aboveground biomass (Mg/ha) estimates from the site-independent model were 38.5 (3.6 se), 44.9 (3.0 se), 28.3 (1.4 se) and 30.2 (2.4 se) for the ET, LF, PC and RR sites, respectively. The site-specific biomass (Mg/ha) estimates for the ET, LF, PC and RR sites were 35.6 (3.3 se), 46.3 (3.0 se), 28.4 (1.8 se) and 29.2 (2.4 se), respectively. Site-specific aboveground biomass estimates were greater for the PC and LF sites and lower for the RR and ET sites relative to the site-independent estimates. Site-specific and site-independent estimates had the largest difference on the ET site (2.8 Mg/ha) and the smallest difference on the PC site (0.07 Mg/ha).

The relative (%) biomass per ha of each component from the site-specific forced additivity model [15] averaged 1.9 (1.0-3.6 range) for 1-yr-old foliage, 1.0 (0.6-1.7 range) for 2-yr-old foliage, 1.4 (0.8-3.0 range) for ≥3-yr-old foliage, 3.0 (2.2-4.5 range) for live branch wood (wood + bark), 13.8 (10.6-16.0 range) for stem bark, 42.9 (36.8-47.3 range) for stem sapwood, and 36.1 (30.2 – 42.2 range) for stem heartwood. The relative (%) biomass per ha of each component from the site-independent forced additivity model [15] averaged 2.0 (1.2-3.4 range) for 1-yr-old foliage, 1.1 (0.7 – 1.7 range) for 2-yr-old foliage, 1.3 (0.8-2.8 range) for ≥3-yr-old foliage, 3.2 (2.3-4.6 range) for live branch wood (wood + bark), 13.5 (12.9-13.8 range) for stem bark, 43.1 (37.4-47.4 range) for stem sapwood, and 35.9 (31.9-42.1 range) for stem heartwood (Fig. 27).

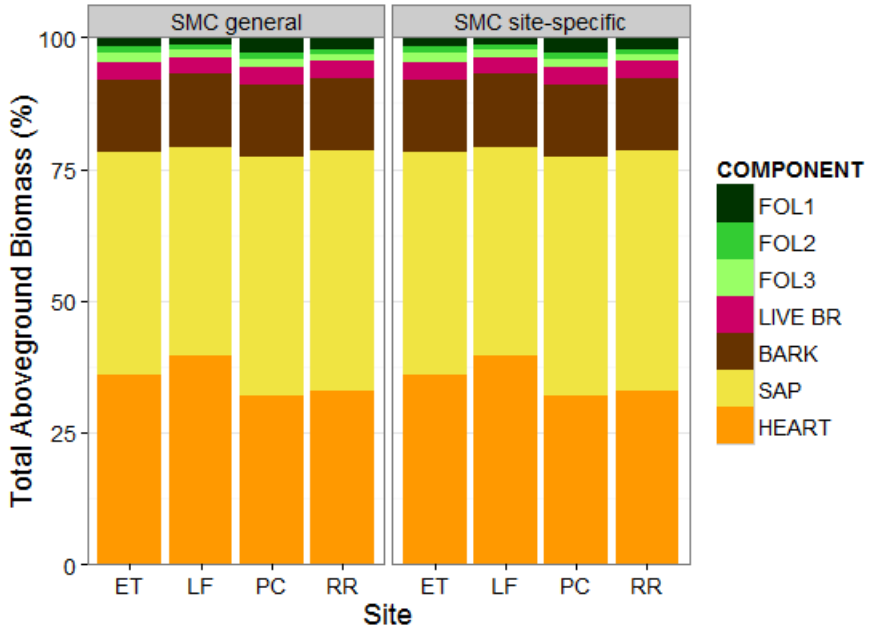


Figure 27. Percent of total aboveground biomass contributed by each biomass component based on both the site-specific and site-independent forced additivity model [15].

4.2 Nutrient Concentration

The mean nutrient concentrations (MNCs) applied to the biomass components from the most recent SMC Type I measurements were determined from 6094 samples collected across sites, treatments (fertilized or unfertilized), and components (Fig. 28 and Fig 29).

Nutrient concentrations varied across sites, component and fertilization treatment with each nutrient. The highest concentrations of macro- and micro-nutrients varied among sites. The concentrations of S, P, N, Mg, K and Ca were higher in the foliage components than stem components on all sites. The highest Ca concentrations on all sites

were in ≥3-year-old foliage. The highest K concentrations were typically in the 1-year-old foliage. The PC site had the lowest concentrations of Ca overall. The highest N concentrations across the LF site were in the 1-year-old foliage (Figs. 28-29, Table 35 and Table A4 in the Appendix).

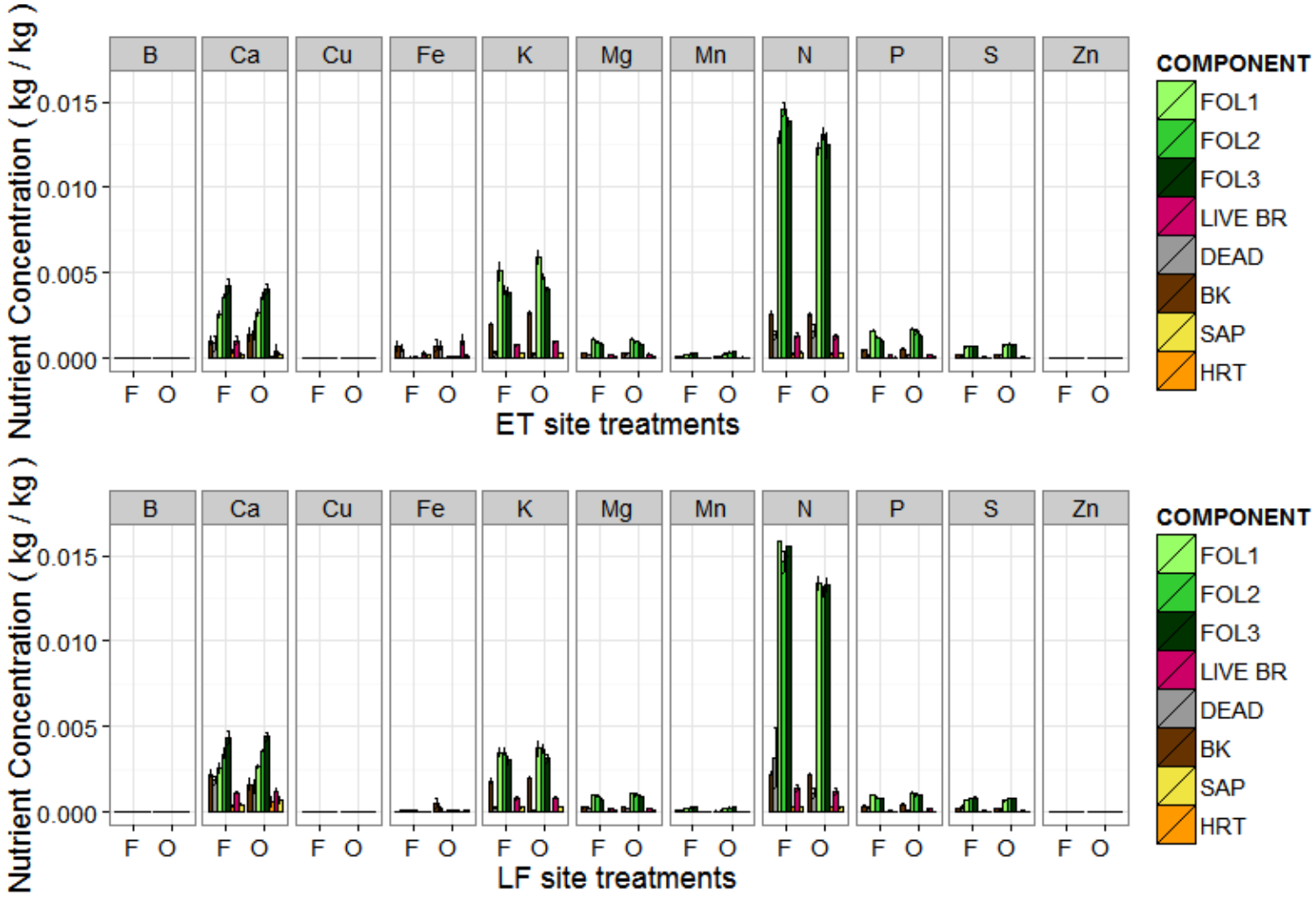


Figure 28. Elemental nutrient concentrations of biomass component for fertilized (F) and unfertilized (O) plots at ET and LF.

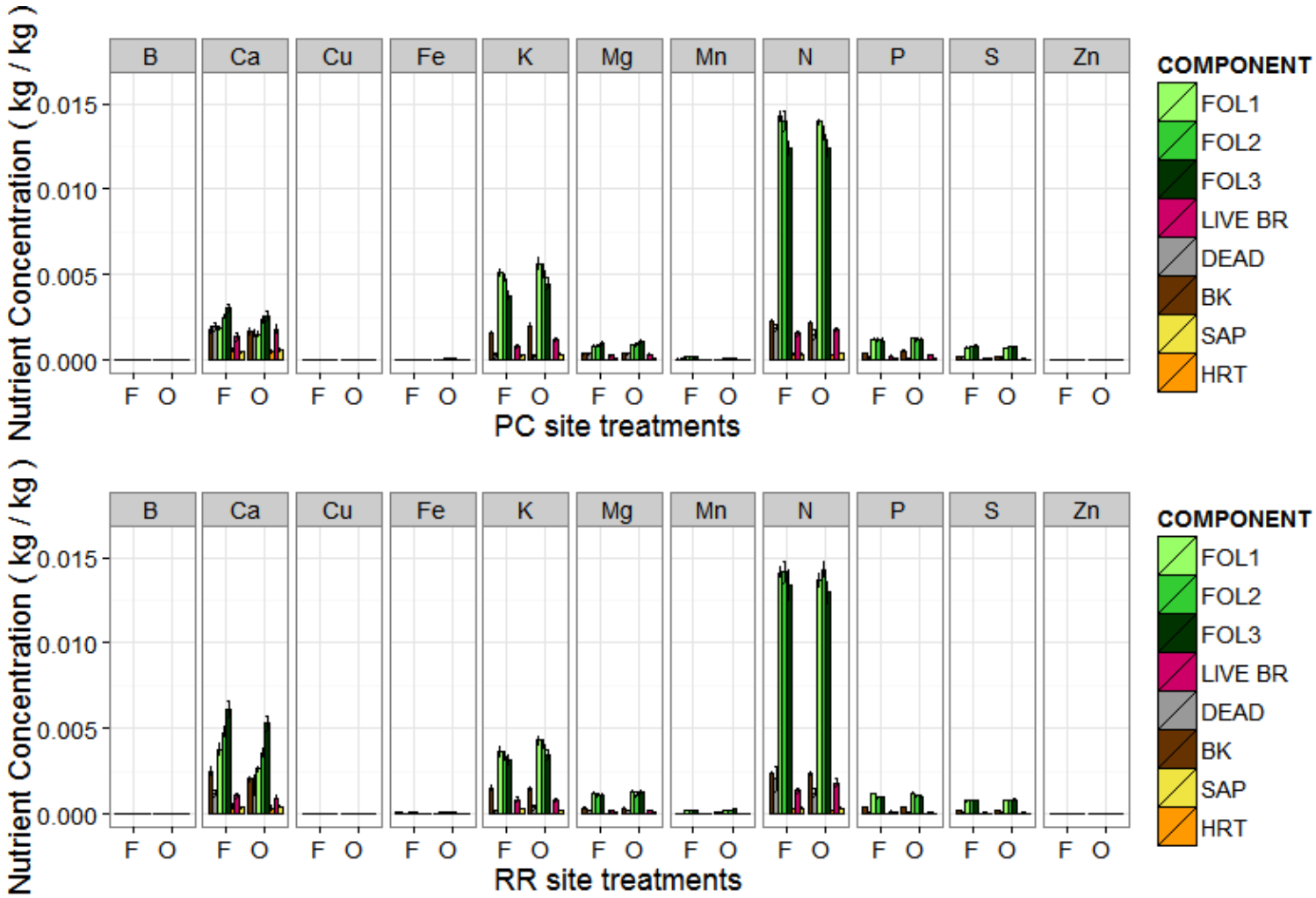


Figure 29. Elemental nutrient concentrations of each biomass component for fertilized and unfertilized plots at PC and RR.

Table 35. Average 1-yr-old foliage nutrient concentrations (%) averaged for all fertilized (*) and unfertilized plots separately on SMC Type I installations.

Site	Nutrient					
	N	**P**	**K**	**Ca**	**Mg**	**S**
ET*	1.29	0.15	0.51	0.26	0.11	0.07
LF*	1.58	0.10	0.35	0.26	0.10	0.07
PC*	1.43	0.12	0.52	0.18	0.08	0.07
RR*	1.41	0.12	0.36	0.38	0.12	0.08
ET	1.23	0.17	0.59	0.26	0.11	0.07
LF	1.34	0.11	0.37	0.27	0.11	0.07
PC	1.39	0.13	0.57	0.15	0.09	0.07
RR	1.37	0.12	0.43	0.27	0.13	0.08

Ballard and Carter (1986) identified three N-deficiency levels in Douglas-fir on the basis of foliar N concentration (%, dry-mass basis): 1) Very severe: <1.05%, 2) Severe: >1.05 to 1.3%, 3) Slight-moderate: >1.3 to 1.45%. According to a study by Carter (1992) a foliar N of 1.35% in Douglas-fir is considered the threshold for N sufficiency. All plots on the ET site and the unfertilized plots on the LF site had severe N deficiencies. The unfertilized plots on the three other sites had no N deficiencies according to Carter (1992) and slight-moderate N deficiencies according to Ballard and Carter (1986). The fertilized plots on the LF, PC and RR sites had no deficiencies according to Carter (1992) and slight N deficiencies according to Ballard and Carter (1986) on the PC and RR sites (Table 35).

4.3 Nutrient Content

4.3.1 Stand level nutrient content by component

The bark contained the largest portion of most nutrients with the exception of Ca and N in some instances. The foliage, live branches and bark displayed similar nutrient distribution patterns; each contained much higher contents of N and Ca than the 9 other nutrients. The bark contained the highest quantities of K, while heartwood contained little to no K. Overall, Ca and N nutrient content was highest for bark. The LF site had the highest with 34.8 kg ha^{-1} N and 28.6 kg ha^{-1} Ca (Fig. 30a, Fig. 30b, Table A5 in the Appendix).

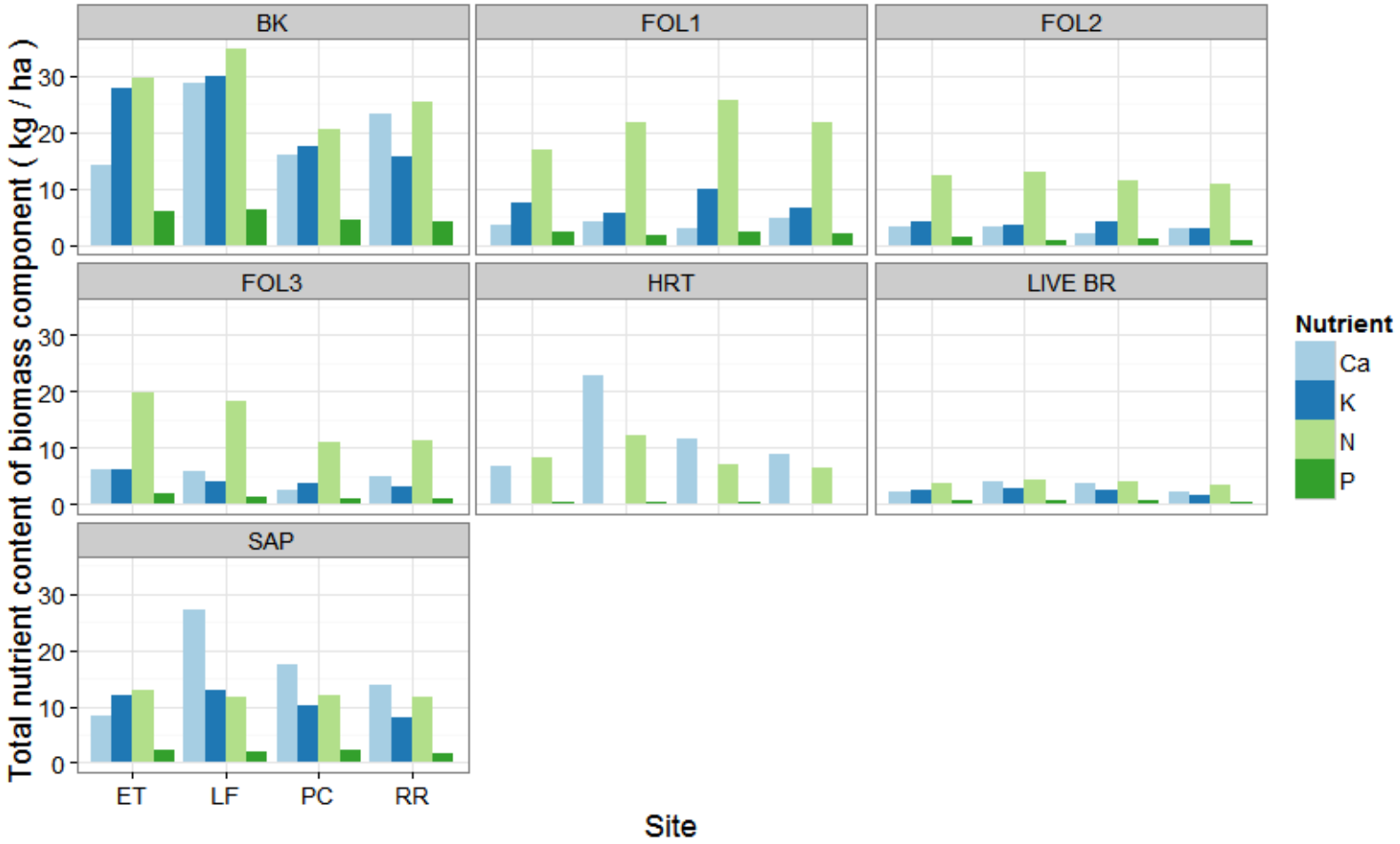


Figure 30a. Mean nutrient content (kg/ha) of Ca, K, N and P in each biomass component across SMC Type I installations in 2011.

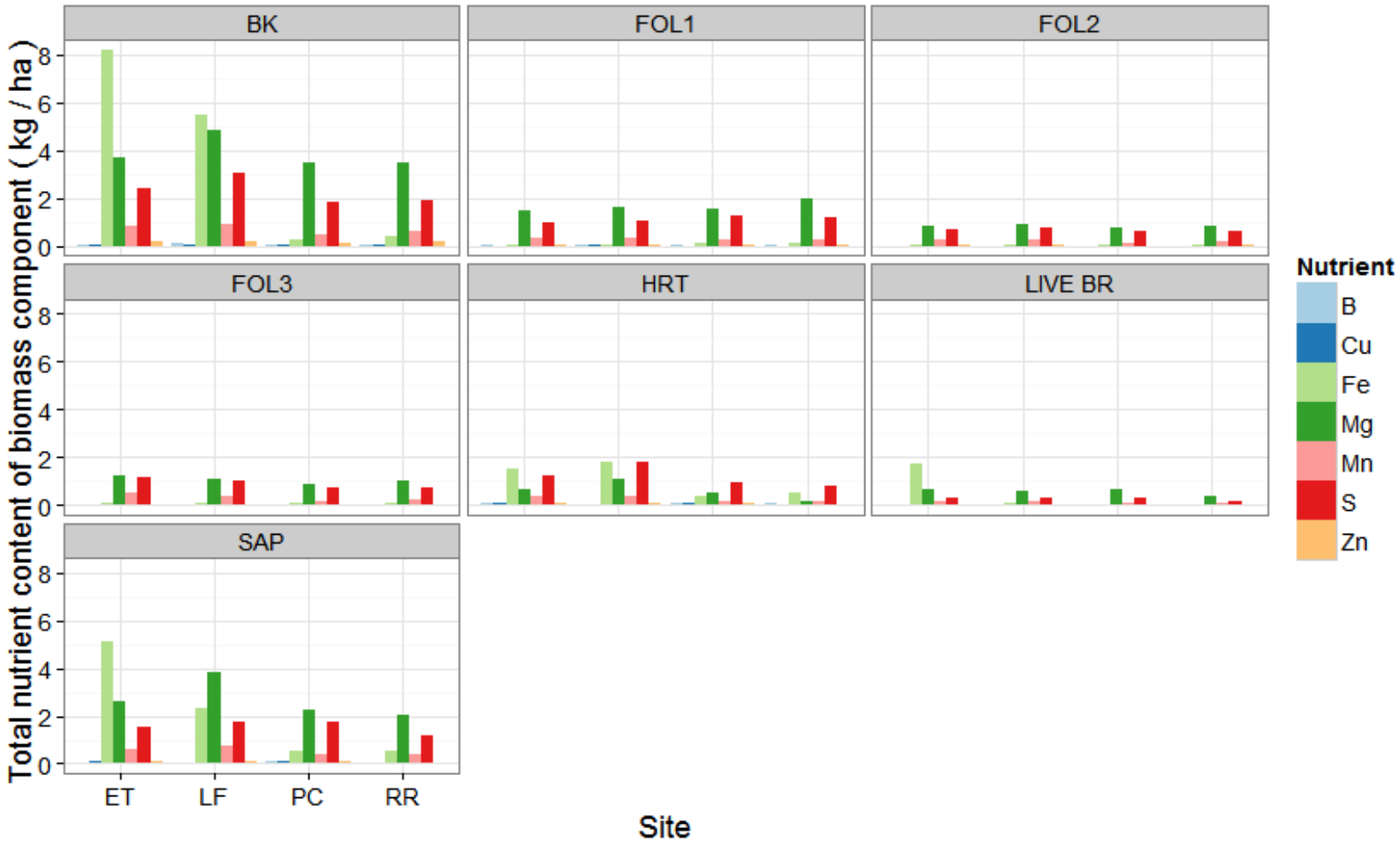


Figure 30b. Mean nutrient content (kg/ha) of B, Cu, Fe, Mg, Mn, S and Zn in each biomass component across the SMC Type I installations in 2011.

4.3.2 Relative overall stand level nutrient content by component.

Nutrient content of harvested or otherwise removed material is a function of both the mass of a given component and the nutrient concentration in that component. The foliage contained 50% of N and over 31% of K, Mg, Mn, P and S on average despite comprising no more than an average of 9% of the total stand level aboveground biomass (Fig. 31). Components with relatively high concentrations of nutrients, such as the foliage, represent a relatively large portion of nutrients despite comprising a minimal amount of the total above ground tree biomass. This translates in to a large amount of nutrients that can be potentially removed under harvesting scenarios that yard trees with branches and foliage attached and remove greater portions of the yarded forest residuals from the site.

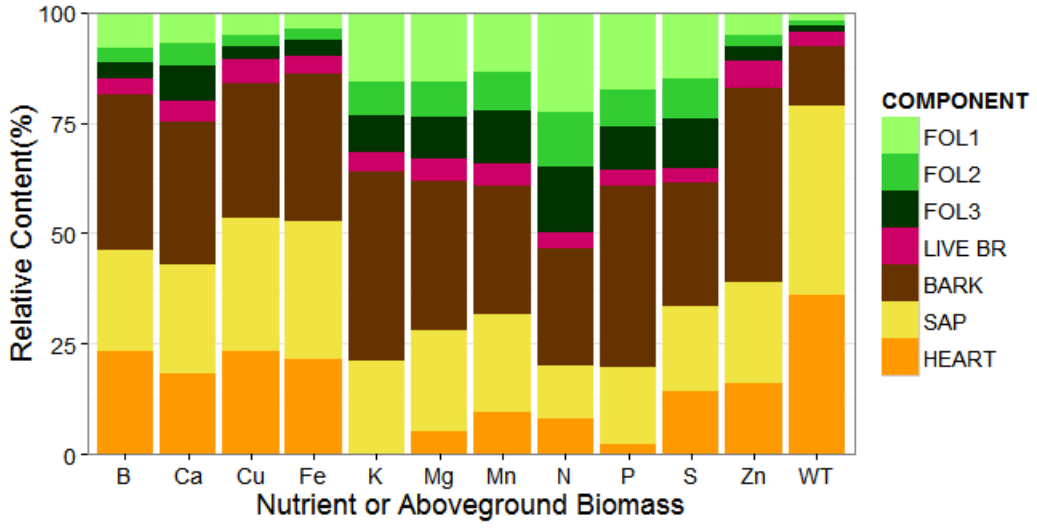


Figure 31. Relative nutrient content (%) for 11 nutrients (B, Ca, Cu, Fe, K, Mg, Mn, N, P, S and Zn) and relative aboveground biomass (WT, %) averaged across installations for each of 7 aboveground components.

4.3.3 Relative stand level nutrient content by component, site and fertilization treatment.

When initially assessing the average variability of relative nutrient content (%) in regards to fertilization (Fig. 32) there appears to be a higher relative content of some nutrients (Ca, Fe, K, Mg, Mn, N, P and S) in the foliage of fertilized plots averaged across installations. However, when further assessing the variability of relative nutrient content (%) ***among installations*** this pattern is less obvious or, in the case of Fe on the PC and RR sites, the opposite trend is apparent (Fig. 33). Each of the SMC sites has differing quantities and distributions of soil nutrients and site conditions that affect the productivity, nutrient allocation and overall nutrient use efficiency. Deficiencies of N are not apparent on fertilized plots as the N fertilization treatments were applied at an intensity and level to eliminate N limitations.

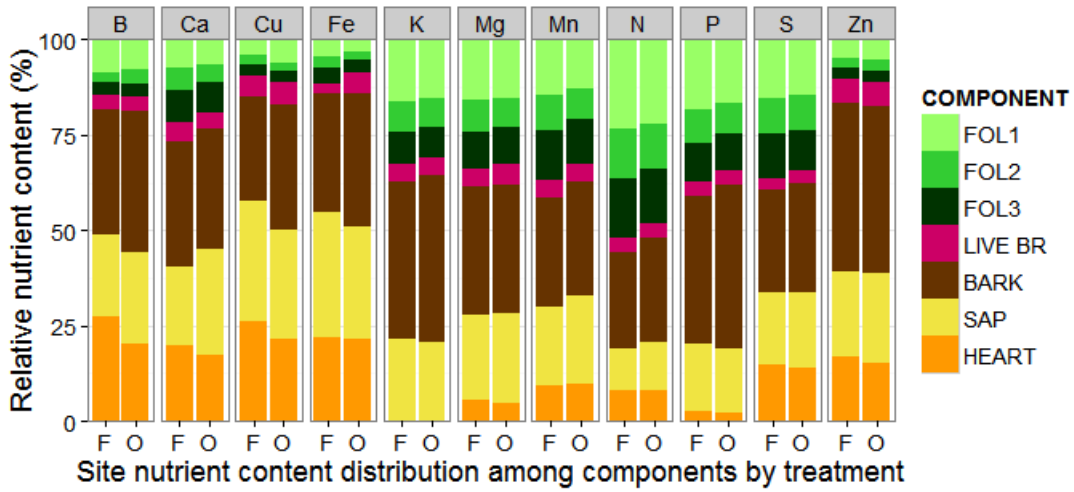


Figure 32. Relative nutrient distribution among biomass components for fertilized (F) and unfertilized (O) plots averaged across all installations.

The relative nutrient distribution among biomass components varied among installation, by fertilized versus unfertilized treatment within each installation, and by nutrient. On average 34% (17-59% range) of the nutrients was contained in the bark. The PC site had the highest relative quantities of N (29%) in year 1 foliage, and the highest relative quantities of N (59%) for total live crown content. The LF site had the lowest average relative quantity of K (27%) in live crown components on unfertilized plots (Fig. 33).

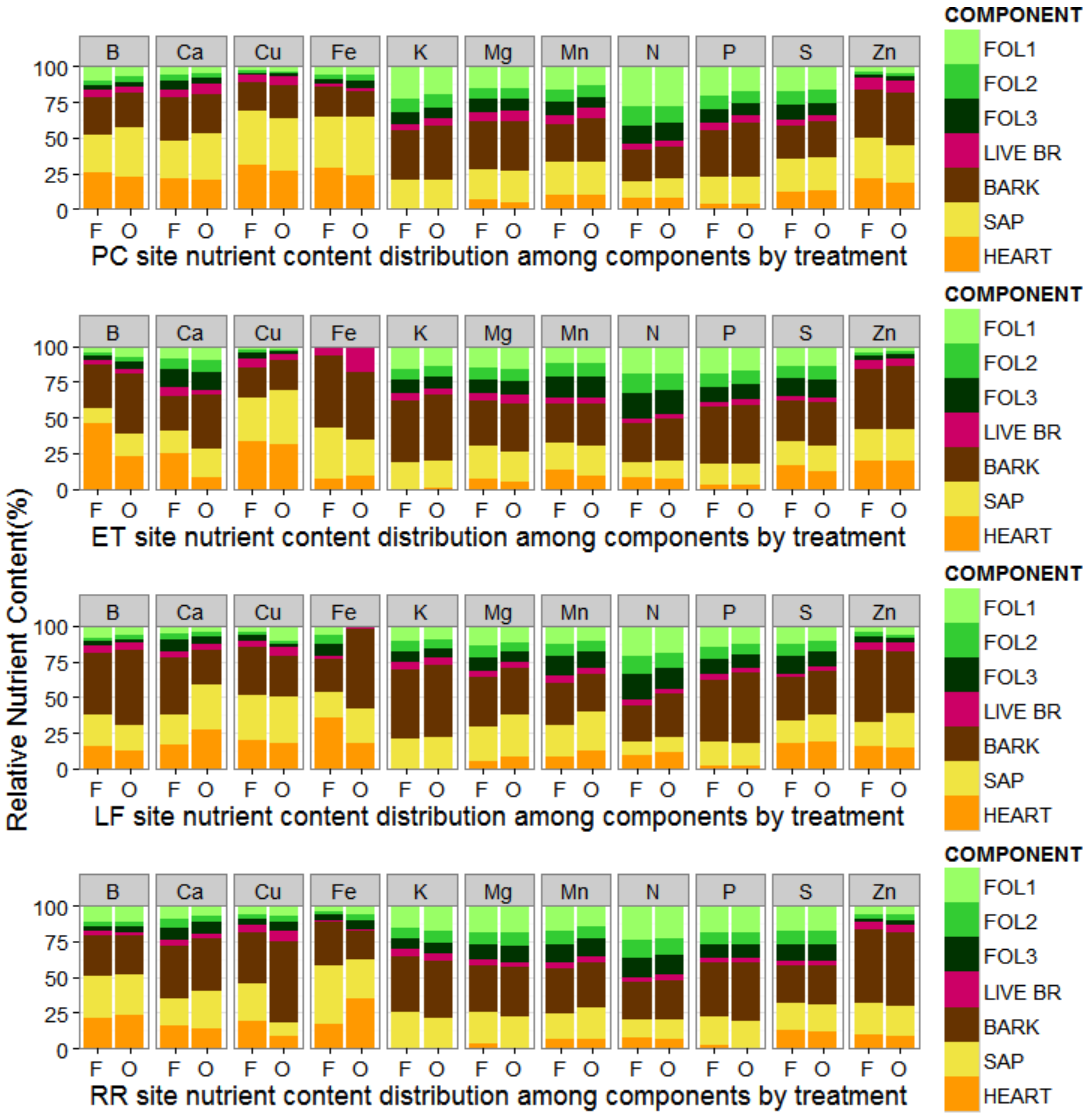


Figure 33. Relative nutrient distribution among biomass components on fertilized (F) and unfertilized (O) plots on each sample SMC installation .

4.3.4 Total aboveground nutrient content by fertilization treatment

Nutrients were calculated with average nutrient concentrations (Fig. 28 and Fig. 29) and the site-specific forced additivity biomass model [15] applied to all of the trees on each of the 7 plots at the four SMC Type I sites. Content of individual nutrients was

averaged over all fertilized and unfertilized plots separately across all four installations (12 fertilized and 16 unfertilized plots) (Fig. 34).

The total aboveground mean nutrient content does appear to differ by treatment for most nutrients. This aboveground nutrient content is closely tied to whether the specific installation was responding to the treatment, in addition to inherent nutrient availability, because any growth increase will change the total amount of nutrient unless perfectly reversed by a decline in concentration. However, this is not consistent among sites for every nutrient. The ET site appeared to have differences in total aboveground nutrient content for B, Ca, Mg and N. The LF site appeared to have differences in total aboveground nutrient content for Ca, Fe, K, Mg, Mn and P. The PC site appeared to have differences in total aboveground nutrient content for Cu. Fe, K, Mn and P. The RR site appeared to have differences in total aboveground nutrient content for B, Cu, and Mn. The mean aboveground N content averaged higher on fertilized plots than on unfertilized plots, with the exception of those on the RR site were the opposite pattern occurred (Fig 34) due to a greater extent to a change in concentration than a change in total biomass for a fixed concentration (Table 36). When comparing the % difference due to biomass amount and the % difference in nutrient content, each of the sites had a variety of nutrients whose content was attributable to the nutrient concentration alone. Differences in total aboveground nutrient pools can result from changes in nutrient concentration only, change in biomass amount or distribution only, or a combination of the two. When comparing differences in biomass and differences in pools of the various nutrients, most differences seem to be coming from a combination of the two (Table 36). On the RR site

the differences in nutrient content were due to an increase in concentration on fertilized plots for the majority of nutrients rather than an increase in total biomass. The opposite pattern occurred with the majority of nutrients on the other three sites. For instance, N content (kg/ha) on the fertilized plots of the LF site averaged 8.8% less biomass and 4.1% more content than unfertilized plots; indicating a greater change in N concentration than in biomass at a fixed concentration.

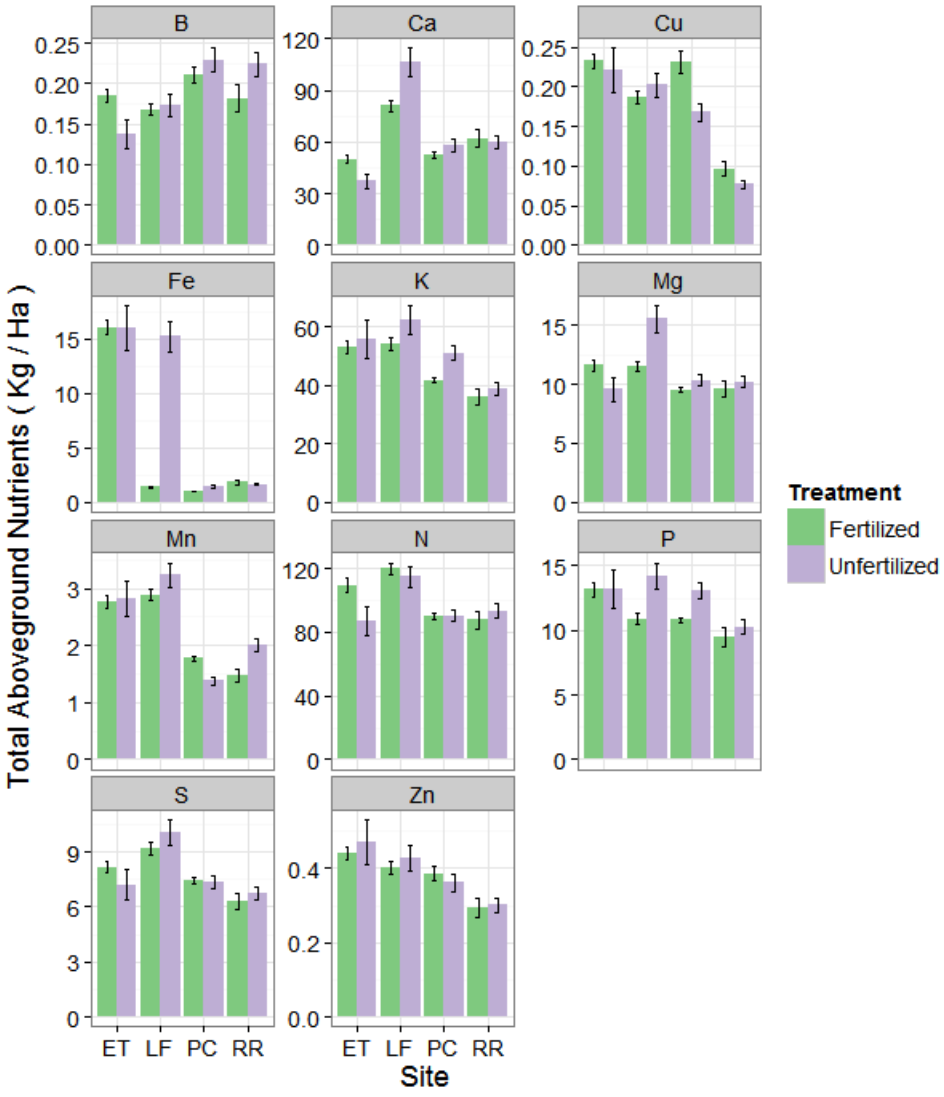


Figure 34. Total above ground nutrient pools (kg/ha) on fertilized and unfertilized plots for each SMC installation. The standard errors are indicated by the black bars.

Table 36. Mean difference in biomass and nutrient content between fertilized and unfertilized plots by site.

Site	Nutrient	Biomass Difference (%)	Nutrient Content Difference (%)
ET	B	16.0	**34.9**
	Ca		**35.0**
	Cu		5.5
	Fe		0.2
	K		-5.2
	Mg		**21.3**
	Mn		-2.4
	N		**26.1**
	P		-0.2
	S		13.3
	Zn		-6.1
LF	B	-8.8	**-3.1**
	Ca		-23.8
	Cu		**-7.5**
	Fe		-90.8
	K		-13.1
	Mg		-25.7
	Mn		-10.7
	N		**4.1**
	P		-23.4
	S		**-8.7**
	Zn		**-6.2**
PC	B	-7.2	-7.7
	Ca		-9.8
	Cu		**37.8**
	Fe		-30.7
	K		-18.5
	Mg		-7.9
	Mn		**28.0**
	N		**-0.1**
	P		-17.4
	S		**1.1**
	Zn		**6.7**
RR	B	-12.7	-18.9
	Ca		**3.3**
	Cu		**25.4**
	Fe		**12.2**
	K		**-6.7**
	Mg		**-6.2**
	Mn		-26.4
	N		**-6.0**
	P		**-7.5**
	S		**-6.3**
	Zn		**-2.6**

4.4 Harvest Removals

4.4.1 Comparative biomass estimates

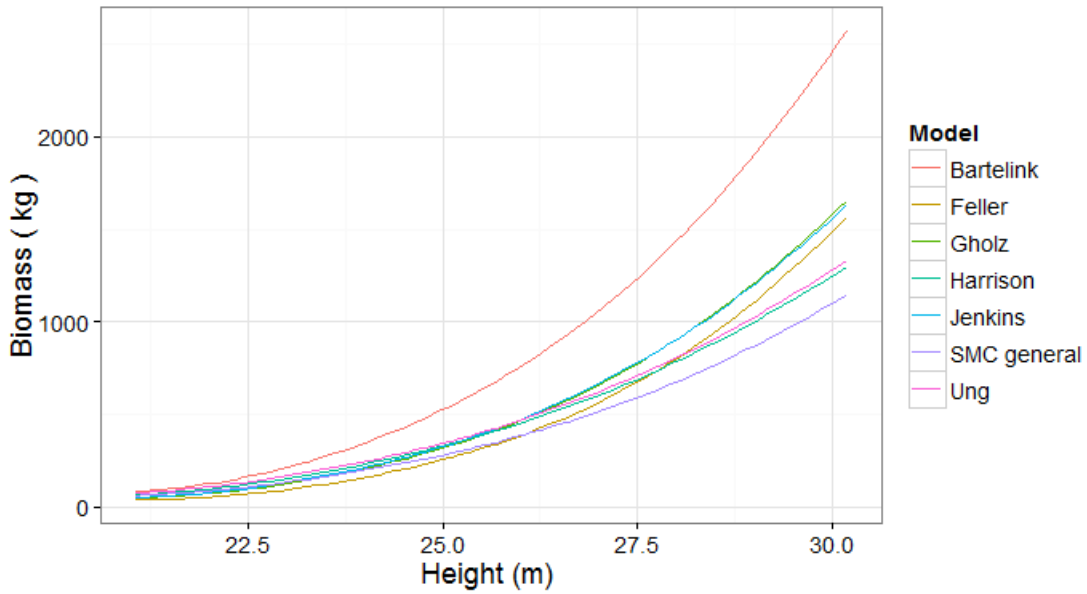


Figure 35. Aboveground tree biomass (kg) with variation in height (m). Diameter (D) and crown length (CL) for each height was calculated based on the sample data by the following regression equations: D= -84.21442 + 4.43444*D (MSE = 0.5074) and CL = -20.8229+ 1.3166 *D (MSE=2.204).

Estimates calculated from published equations applied to the 84-tree dataset, in general, overestimated tree biomass with greater increase in tree size, i.e., diameter, height and crown length. Bartelink, (1996) estimates exceeded estimates from the SMC Type 1 equations by 99% for the tree of median diameter (31.3 cm); all other equations exceeded the SMC equations by approximately 20% (Figures 35 and 36). At the minimum diameter (11.5 cm), minimum crown length (3.94 m), and a height of 21.1 m and estimates based on Harrison et al. (2009) were less than those based on the SMC equation by 3.9%, and estimates based on Feller (1992), Gholz (1979), Jenkins et al.

(2004), were lower by 24% and 27% at the minimum diameter. Estimates based on Bartelink (1996) and Ung et al. (2008) were higher at minimum diameter, by 26% and 21%, respectively. At maximum diameter (51 cm) and height (30.2 m) all models exceeded SMC estimates by at least 13% (Harrison et al., 2009) to 125% (Bartelink, 1996). At maximum crown length (22.22 m), diameter (49.5 cm), and height (29.9 m) all models exceeded SMC estimates by 14% (Harrison et al., 2009) to 124% (Bartelink, 1996) (See Fig. 35 and 36 for an approximation). With the exception of estimates from Feller (1992) at the minimum diameter, all models overestimated total tree biomass in comparison to the SMC equations across the entire range of crown ratios, assuming a height of 26.23 m and diameter of 32.08 cm. Estimates from Feller (1992) were smaller than those from the SMC model estimates up to a diameter of 30.25 (cm). At the smallest crown ratios (0.23) estimates deviated from those based on the SMC models as follows: 1) Bartelink (1996) by 88%, 2) Feller (1992) by 3%, 3) Gholz (1979) by16%, 4) Harrison et al. (2009) by 10.9%, 5) Jenkins et al. (2004) by18% , and 6) Ung et al. (2008) by 14%. At maximum crown ratio (0.80) every model estimated on average 6.3% greater total biomass than the SMC equations.

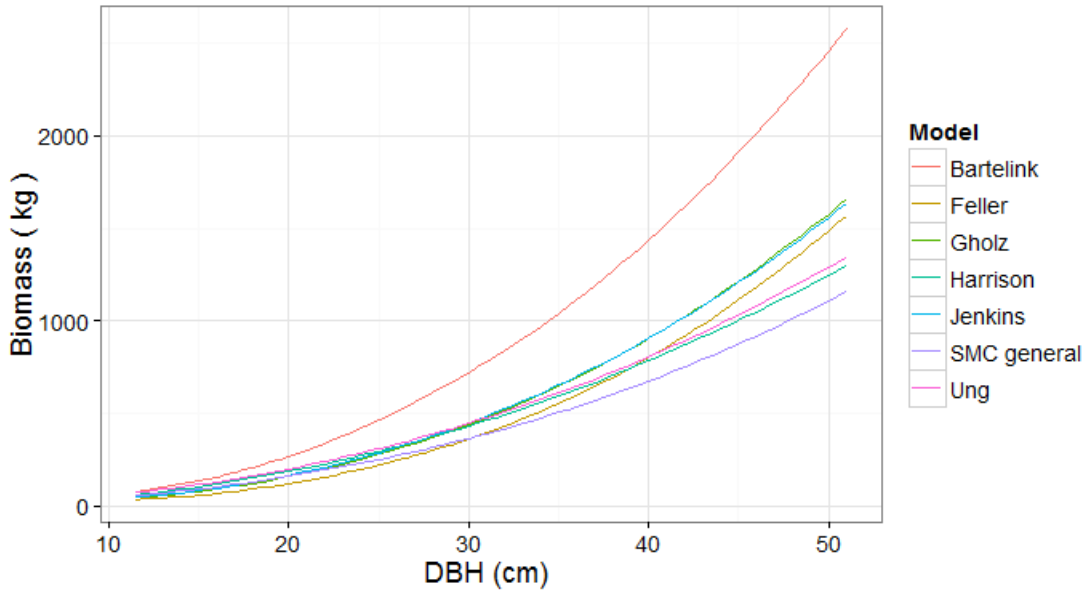


Figure 36. Alternative estimates of total aboveground tree biomass (kg) as a function of dbh (cm). Crown length (CL) and height (HT) for each DBH was calculated based on the sample data by the following regression equations: CL= 4.25224+ 0.29466*D (MSE = 2.222) and HT = 19.015223 + 0.224752*D (MSE= 0.1142).

Eight models were applied to the four SMC Type I sites to estimate total stand level above-ground biomass based on the most recent plot remeasurements (Figure 37 and Table 37). The mean stand level estimates for each of the models are as follows 1) Bartelink, (1996) 177.3 Mg/ha (5.4 se), 2) Feller, (1992) 93.6 (Mg/ha) (2.9 se), 3) Gholz, (1979) 109.8 (Mg/ha) (3.3 se), 4) Harrison et al.,(2009) 103.1 (Mg/ha) (3.5 se), 5) Jenkins et al., (2004) 110.9(Mg/ha) (3.3 se), 6) Ung et al.,(2008) 105.5 (Mg/ha) (4.9 se), 7) SMC site-specific 86.2 (Mg/ha) (4.6 se) and 8) SMC general 87.7 (Mg/ha se) (4.5 se).

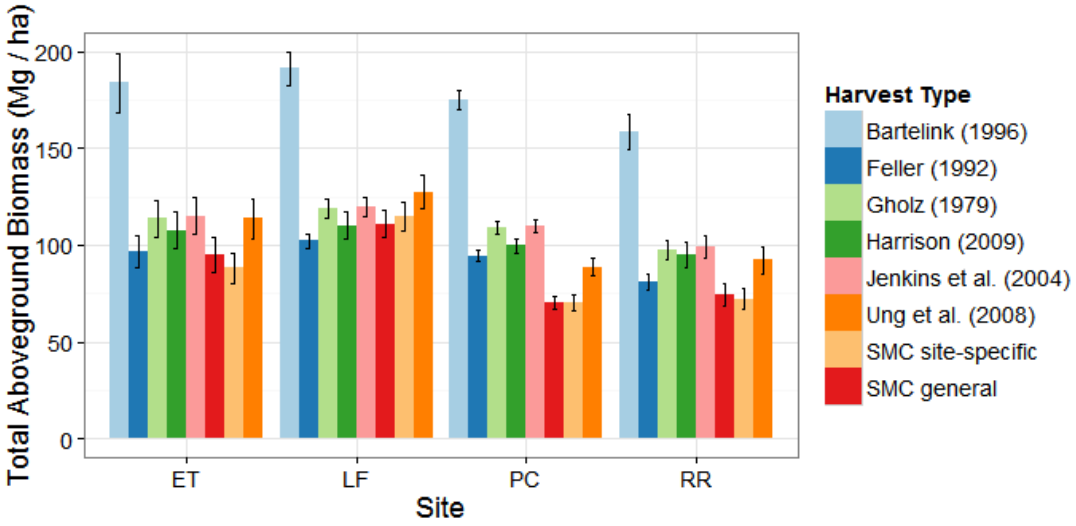


Figure 37. Total aboveground biomass estimates from eight alternative biomass models. The standard errors are indicated by the black bars.

Table 37. Total aboveground biomass estimates from eight alternative biomass models applied to the four SMC Type I installations.

Site	Model	Mean Biomass (Mg/ha)	Standard Error (Mg/ha)
ET	Bartelink	183.86	15.29
	Feller	96.60	8.27
	Gohlz	113.74	9.46
	Harrison	107.52	9.56
	Jenkins	114.99	9.55
	Ung	113.61	10.46
	Site Dependent	95.02	8.76
	Site Independent	88.08	7.99
LF	Bartelink	191.24	8.67
	Feller	102.11	3.76
	Gohlz	118.79	4.99
	Harrison	110.22	7.07
	Jenkins	119.78	5.26
	Ung	127.52	8.84
	Site Dependent	111.05	7.31
	Site Independent	114.48	7.44
PC	Bartelink	175.32	5.03
	Feller	94.41	3.10
	Gohlz	109.17	3.07
	Harrison	99.63	3.99
	Jenkins	109.94	3.11
	Ung	88.77	4.23
	Site Dependent	70.01	3.47
	Site Independent	70.18	4.37
RR	Bartelink	158.64	9.03
	Feller	81.11	3.97
	Gohlz	97.45	5.31
	Harrison	95.10	6.60
	Jenkins	98.96	5.53
	Ung	92.09	7.22
	Site Dependent	74.54	5.97
	Site Independent	72.11	5.54

4.4.2 Estimates of felling and yarding losses of crown biomass

As indicated in the previous section, a large portion of some nutrients is concentrated in the crowns of trees. As a result, the relative proportion of the crown that is yarded to the landing can be surprisingly important for site nutrient retention and sustainability of using residues as biofuel feedstock. Because different portions of the crown will be lost during felling and yarding, a model was needed to allow exploration of different scenarios for branch loss. As described in the Methods section, a number of alternative models were explored for estimating the proportion of branch wood (wood + bark) and foliage that would be left on the forest floor if differing proportions of the live crown length were broken or sheared off.

Table 38. Models for estimating cumulative % of crown wood and foliage biomass as a function of increasing relative depth into crown.

Model ID	Model	Component			
Crown component mass up to 4 inch inside bark top diameter		Foliage (1 yr.)	Foliage (2 yr.)	Foliage (≥ 3 yr.)	Live Branch
Model 1	$B = 1/ (1+ \exp(\beta_0 + \beta_1 * RDINC))$	0.07415	0.08105	0.08451	0.08112
Model 2	$B = 1/ (1+ \exp(\beta_0 + \beta_1 * RDINC + \beta_2 * D + \beta_3 * CL))$	0.07652	0.08200	0.08549	0.08114
Model 3	$B = 1/ (1+ \exp(\beta_0 + \beta_1 * RDINC + \beta_2 * D + \beta_3 * H))$	0.30505	0.30505	0.30505	0.30505
Component mass from 1 foot stump to 4 inch inside bark top diameter		Bark	Sapwood	Heartwood	
Model 1	$B = 1/ (1+ \exp(\beta_0 + \beta_1 * RDINC))$	0.03973	0.02191	0.05161	
Model 2	$B = 1/ (1+ \exp(\beta_0 + \beta_1 * RDINC + \beta_2 * D + \beta_3 * CL))$	0.04359	0.02967	0.05196	
Model 3	$B = 1/ (1+ \exp(\beta_0 + \beta_1 * RDINC + \beta_2 * D + \beta_3 * H))$	0.30505	0.30505	0.30505	
Component mass from 1 foot stump to tree top		Bark	Sapwood	Heartwood	
Model 1	$B = 1/ (1+ \exp(\beta_0 + \beta_1 * RDINC))$	0.05161	0.00823	0.04989	
Model 2	$B = 1/ (1+ \exp(\beta_0 + \beta_1 * RDINC + \beta_2 * D + \beta_3 * CL))$	0.05196	0.00830	0.05026	
Model 3	$B = 1/ (1+ \exp(\beta_0 + \beta_1 * RDINC + \beta_2 * D + \beta_3 * H))$	0.30505	0.30505	0.30505	

The best models for estimating the proportional loss of crown (foliage and branch wood (wood + bark) were a function of relative depth into crown and implied the vertical

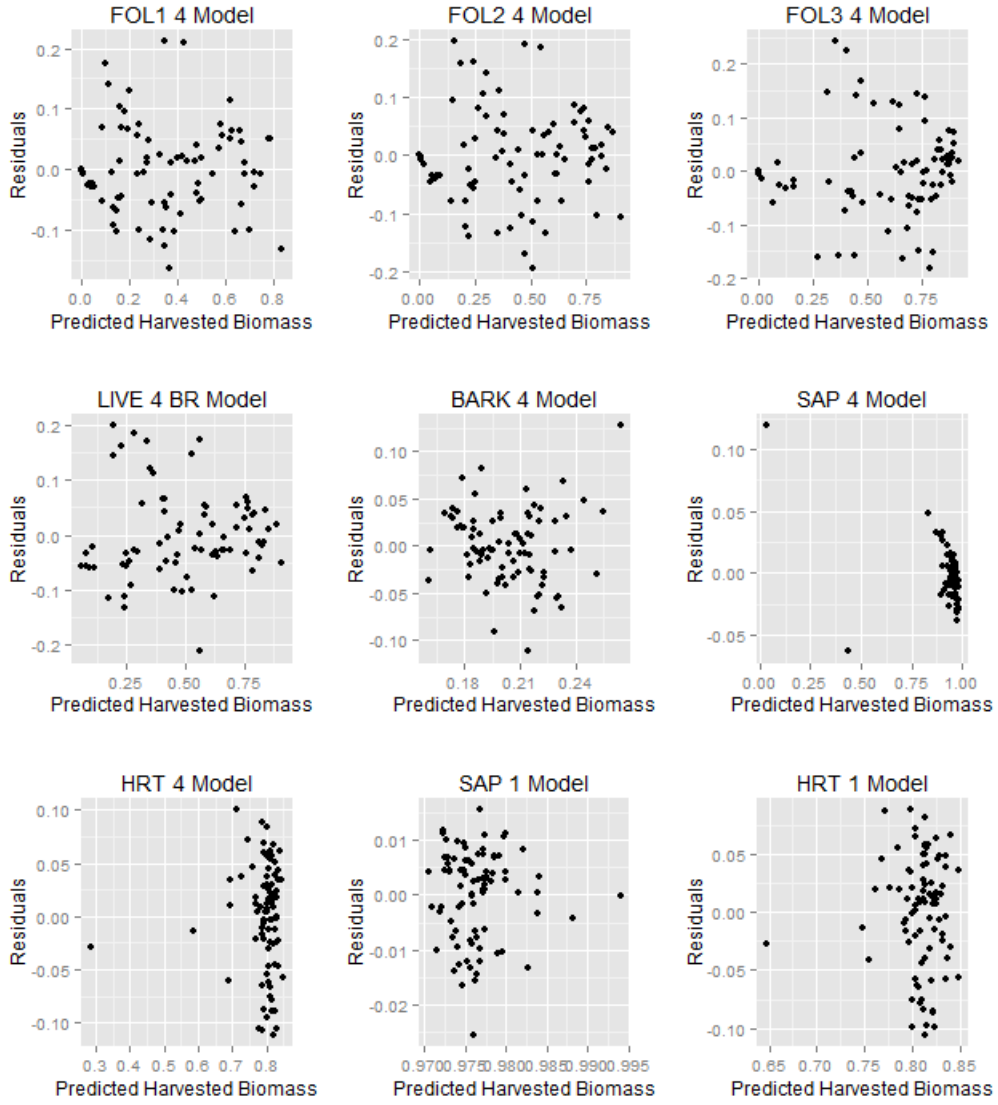
distribution of foliage and branch wood biomass (Table 38). The following model form was selected as best for all components:

[16] $B = 1 / (1+ \exp(\beta_0 + \beta_1 \ RDINC + \beta_2 \ D + \beta_3 \ CL))$

where B represents component biomass (kg), RDINC was relative depth into crown, D was diameter at breast height (cm) and CL was crown length (m) (Table 38).

As described in the Methods section, biomass and nutrient removals were estimated for the four following scenarios: (i) WT: Whole Tree (entire tree from ground level), (ii) BO: Bole Only to 4-inch top (1 foot stump), (iii) BT: Bole and all crown components to 4 inch top (1 foot stump), (iv) WC: Whole tree with vertical half of crown sheared off (1 foot stump). Variance homogeneity was verified with plots of standardized residuals on predicted values (Fig. 38).

Figure 38. Residuals plotted on estimated harvested biomass, , from 1 foot stump to 4 inch inside bark top diameter by component model for the harvesting scenarios. The components include 1-yr-foliage (FOL1 4), 2-yr-foliage(FOL2 4), ≥3-yr-foliage (FOL3 4), live branches (LIVE BR 4), bark (BK 4), sapwood (SAP 4) and heartwood (HRT 4) and 1 ft stump to tree tip for sapwood(SAP 1) and sapwood (HRT 1).).



Total branch wood or foliage mass can be estimated from the biomass equations described above, and then the proportion of the total lost during felling and yarding can be measured or estimated from the equations. The latter equations allowing the total

biomass left in the woods to be predicted as the product of the estimated total component mass and estimated proportion broken or cut from the yarded material (Table 39a and 39b). Corresponding nutrient content can be estimated from the nutrient content of tip of the bole, branch wood, and foliage.

Table 39a. Parameter estimates for models estimating the relative proportion of biomass components contained above a 4 inch top diameter.

Parameter	Estimate	Standard Error	P-value
Foliage yr 1			
β_0	-1.80631	1.78E+00	0.3132
β_1	7.31429	1.69E+00	>0.001
β_2	-0.03423	1.60E-02	0.0354
β_3	-0.00437	3.74E-02	0.9072
Foliage yr 2			
β_0	-1.90604	1.79E+00	0.2902
β_1	6.96577	1.60E+00	>0.001
β_2	-0.03128	1.66E-02	0.0632
β_3	-0.02949	4.05E-02	0.4684
Foliage ≥3 yr			
β_0	-8.83711	1.90064	>0.001
β_1	11.722	1.58969	>0.001
β_2	0.03505	0.01884	0.0664
β_3	0.0665	0.04604	0.1526
Live Branches			
β_0	-2.05818	1.73E+00	2.38E-01
β_1	6.76345	1.51E+00	>0.001
β_2	-0.01862	1.63E-02	2.57E-01
β_3	-0.05314	4.00E-02	1.88E-01
Bark			
β_0	1.524549	2.10E-01	>0.001
β_1	0.029732	9.17E-02	0.74655
β_2	-0.022035	4.98E-03	>0.001
β_3	0.038745	1.31E-02	0.00405
Sapwood			
β_0	-5.02727	3.43E-01	>0.001
β_1	2.07371	1.18E-01	>0.001
β_2	-0.05415	1.11E-02	>0.001
β_3	0.18018	2.11E-02	>0.001
Heartwood			
β_0	-1.5760274	2.57E-01	>0.001
β_1	0.6439443	9.25E-02	>0.001
β_2	0.0001091	6.70E-03	0.987
β_3	-0.01381	1.77E-02	0.437

Table 39b. Parameter estimates for models estimating the relative proportion of bole biomass components contained above a 1-foot stump to tree tip.

Parameter	Estimate	Standard Error	P-value
Sapwood			
β_0	-3.7316594	4.50E-01	>0.0001
β_1	-0.3719122	2.91E-01	0.205
β_2	0.0065791	7.84E-03	0.404
β_3	0.0005286	0.0194404	0.978
Heartwood			
β_0	-1.22939	2.52E-01	>0.0001
β_1	0.179336	8.51E-02	0.0382
β_2	0.001603	6.59E-03	0.8084
β_3	-0.028049	1.77E-02	0.1175

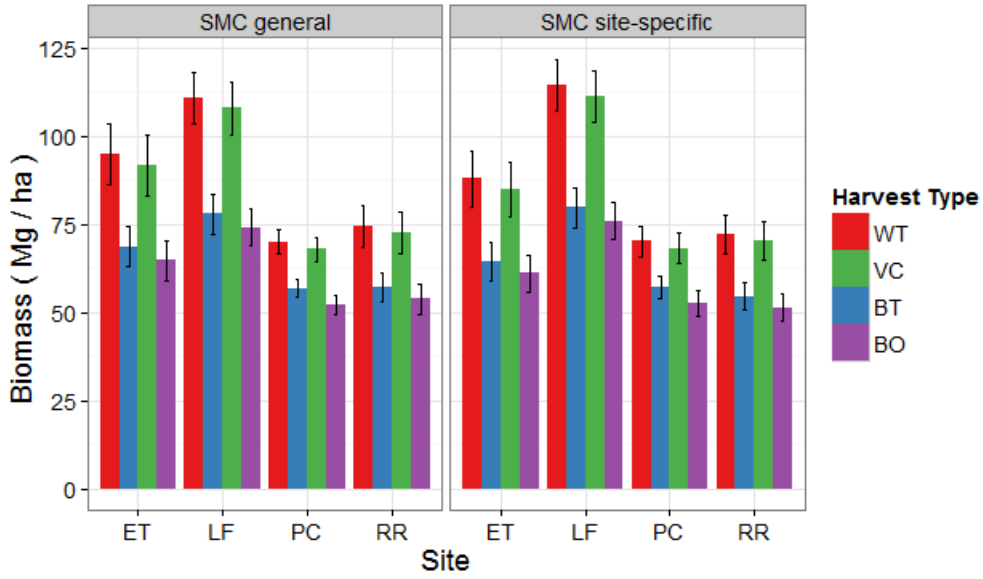


Figure 39. Aboveground biomass removed in each of the four harvesting scenarios by site for the SMC site-specific and SMC general equation. The standard errors are indicated by the black bars.

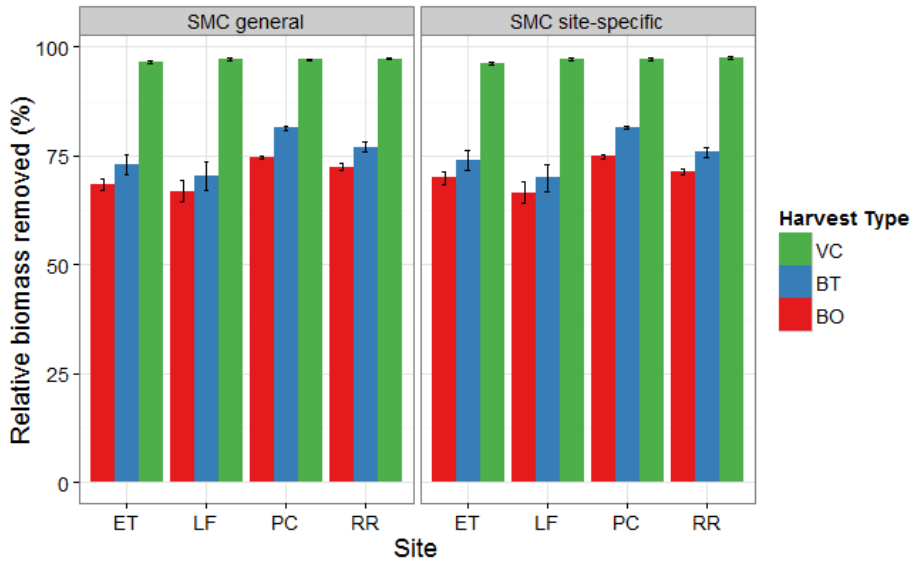


Figure 40. Mean relative biomass removed (% of total aboveground biomass) in each of the three harvesting scenarios by site for the SMC site-specific and SMC general equation. The standard errors are indicated by the black bars.

The difference in relative aboveground biomass (%) removed in the BO and BT scenarios differed by not more than 10.4 % among plots and model type used (Fig. 40, Table A7 in the Appendix). The relative (%) total aboveground biomass removed by each of the scenarios calculated with the site-specific and site-independent models, respectively, and averaged across sites was: 1) 70.7 and 70.6% for the merchantable stem only (BO), 2) 75.3 and 75.4% for loss of the top above the four inch stem diameter (BT), and 3) 97.0 and 97.0% if a vertical half of the crown is sheared off. The LF site had the highest biomass removals (Fig. 39 and Table A7 in the Appendix) The LF site had the widest range in removals, i.e., 60.9 -154.2 (Mg/ha) and 59.7-150.1 (Mg/ha) by site-specific and site-dependent model estimates, respectively. The LF site also had the highest removals of 99.1 (Mg/ha) and 95.9 (Mg/ha) site-specific and site-dependent

model estimates, respectively. The RR site had the lowest biomass removals of 33.7 and 34.0 (Mg/ha) by site-specific and site-dependent model estimates, respectively. The PC site had the narrowest range in removals 40.9-92.2 (Mg/ha) and 43.5-87.9 (Mg/ha) as predicted by site-specific and site-dependent models.

4.4.3 Aboveground nutrients removed in yarded and harvested biomass

WT nutrient removals were approximately 55% to 77% greater than removals under the BO scenarios, with the exception of Cu (44%) and Fe (52%). The removals with WT were similar to VC, while BT was similar to BO. This pattern was less apparent with the removal of nutrients other than Ca, K or N. The four scenarios differed most in regard to the quantity of N removed (Fig 41 and Table 40 below). The harvest scenarios consistently removed increasing nutrient content in the following order BO < BT < VC < WT. On average the WT harvesting scenario removed 50.8 and 51.9% more B than the BO scenario from fertilized and unfertilized plots, respectively, 58.9 and 51.3% more Ca, 42.7 and 45.1% more Cu, 48.8 and 55.1% more Fe, 70.6 and 70.4% more K, 67.1 and 65.8% Mg, 66.8 and 63.7% more Mn, 77.3 and 75.2 % more N, and 72.3 and 72.5% more P, 64.5 and 63.6% more S and 58.8 and 56.0 % more Zn. When comparing the VC and WT scenarios the WT removed ≤21% more of all nutrients on average by nutrient (Fig. 42). Relative aboveground nutrient removal (%) did not differ more than 3% between fertilized and unfertilized plots with the exception of Ca under the BO scenario (7% less) and BT scenario (6% less), and Fe under the BO (6% less) and BT (5% less) scenarios.

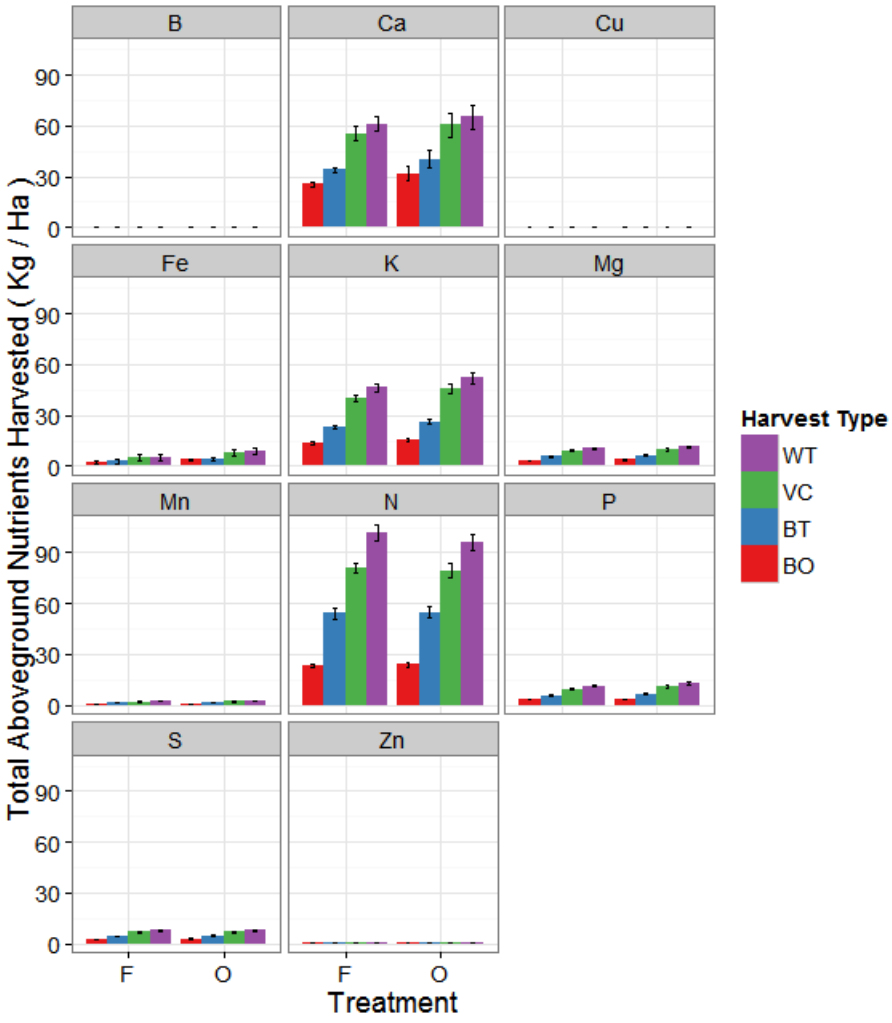


Figure 41. Nutrients removed under each harvest scenario on both fertilized (F) and unfertilized (O) plots: whole tree (WT), broken top at 4 inch inside diameter (BT), vertical half of crown (VC) and merchantable bole (BO). The mean +/- the standard error is indicated in black bars.

Table 40. Estimated nutrient removals from fertilized (F) and unfertilized (O) plots under the four harvest scenarios.

Harvest Type	Treatment	Nutrient	Mean Nutrient Content (kg)	Range	
				Min (kg)	Max (kg)
BO	F	B	0.092	0.058	0.126
BT			0.111	0.066	0.160
VC			0.173	0.125	0.214
WT			0.186	0.138	0.230
BO	O		0.092	0.035	0.173
BT			0.113	0.051	0.199
VC			0.178	0.070	0.275
WT			0.190	0.081	0.284
BO	F	Ca	25.402	16.838	33.708
BT			34.217	26.137	44.081
VC			55.496	36.578	82.409
WT			61.342	44.780	88.894
BO	O		31.817	7.331	70.387
BT			40.474	16.171	79.293
VC			60.516	17.393	129.215
WT			65.359	23.950	135.773
BO	F	Cu	0.107	0.032	0.176
BT			0.121	0.044	0.195
VC			0.176	0.068	0.247
WT			0.187	0.073	0.255
BO	O		0.091	0.017	0.197
BT			0.107	0.030	0.210
VC			0.156	0.056	0.296
WT			0.167	0.062	0.308
BO	F	Fe	2.595	0.540	8.234
BT			2.813	0.660	8.754
VC			4.889	0.829	16.966
WT			5.067	0.879	17.488
BO	O		3.846	0.727	9.255
BT			4.349	0.973	10.987
VC			8.186	1.205	20.719
WT			8.572	1.261	22.383
BO	F	K	13.596	8.371	16.956
BT			23.094	16.392	29.014
VC			40.013	25.284	53.376
WT			46.345	28.910	59.253
BO	O		15.419	8.137	24.794
BT			26.301	18.035	34.567
VC			45.891	26.244	73.981
WT			52.136	31.982	80.094
BO	F	Mg	3.474	2.040	4.199
BT			5.699	4.293	7.143
VC			9.093	6.654	10.932
WT			10.550	7.761	12.435
BO	O		3.900	1.812	7.750
BT			6.446	4.219	10.116
VC			9.976	4.457	17.952
WT			11.401	6.213	19.613

Table 40. continued.....

Harvest Type	Treatment	Nutrient	Mean Nutrient Content	Range	
				Min (kg)	Max (kg)
BO	F	Mn	0.737	0.305	0.992
BT			1.232	0.728	1.787
VC			1.869	1.036	2.662
WT			2.219	1.205	3.078
BO	O		0.857	0.453	1.613
BT			1.390	0.826	2.257
VC			2.032	1.121	3.632
WT			2.357	1.254	4.016
BO	F	N	23.064	14.761	26.866
BT			54.325	39.554	70.547
VC			80.887	60.587	100.001
WT			101.688	73.160	125.536
BO	O		23.858	12.736	36.177
BT			54.805	34.897	74.411
VC			79.288	38.314	118.269
WT			96.290	60.337	138.044
BO	F	P	3.048	1.945	3.597
BT			5.590	3.538	7.539
VC			9.414	6.591	11.315
WT			11.090	7.642	14.259
BO	O		3.487	1.932	5.214
BT			6.398	3.984	8.399
VC			10.990	6.031	16.224
WT			12.689	8.450	18.004
BO	F	S	2.763	1.491	3.313
BT			4.467	3.196	5.593
VC			6.719	4.426	8.689
WT			7.787	5.119	9.847
BO	O		2.859	1.490	4.745
BT			4.656	3.348	6.601
VC			6.883	3.391	11.432
WT			7.853	4.771	12.522
BO	F	Zn	0.168	0.082	0.232
BT			0.202	0.112	0.281
VC			0.356	0.209	0.446
WT			0.381	0.224	0.481
BO	O		0.172	0.086	0.302
BT			0.211	0.130	0.342
VC			0.365	0.219	0.621
WT			0.390	0.237	0.659

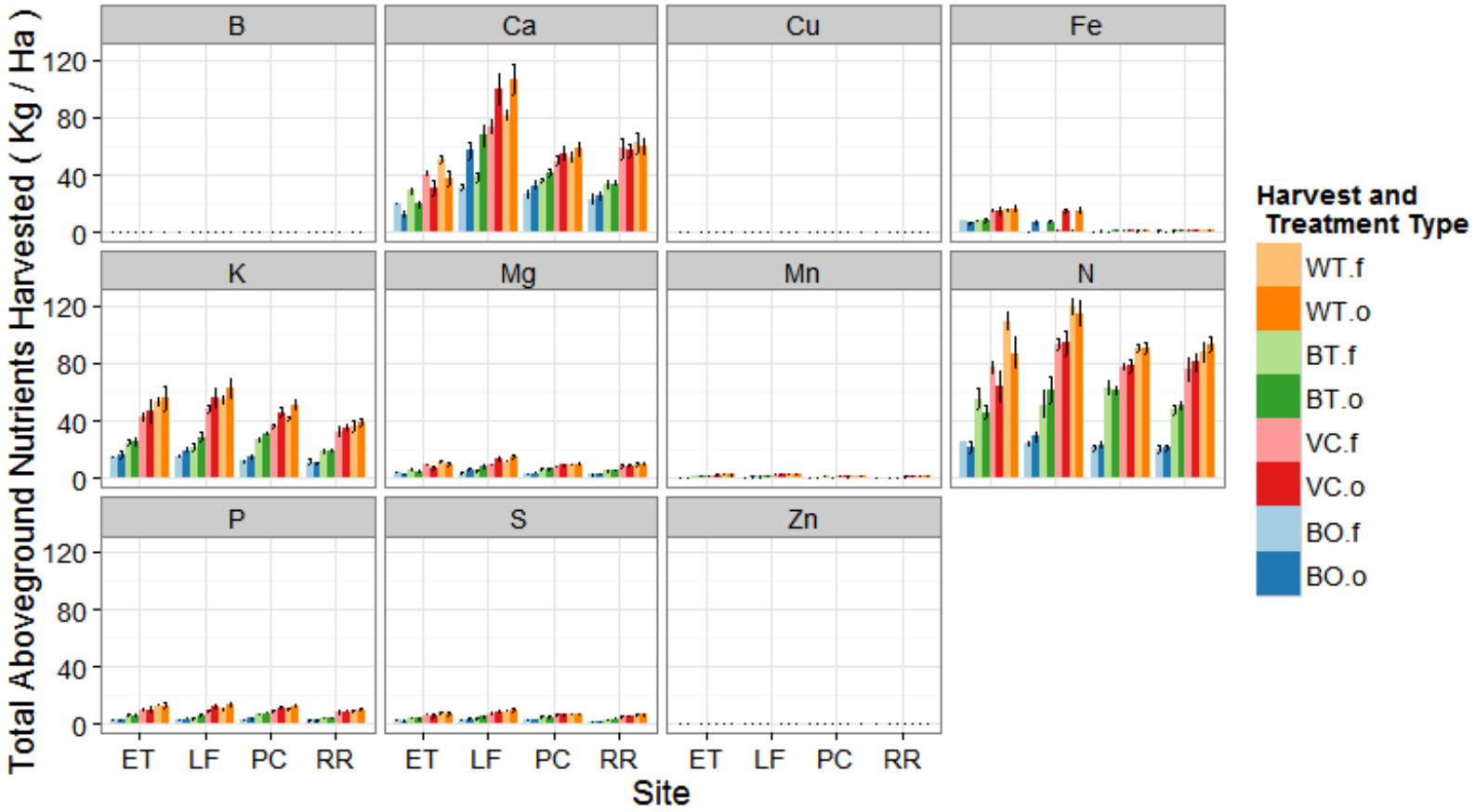


Figure 42. Nutrients removed from fertilized (.f) and unfertilized (.o) plots in each installation and under each harvest scenario: whole tree (WT), broken top at 4 inch inside diameter (BT), vertical half of crown (VC) and merchantable bole (BO). The mean +/- standard errors are indicated in the black bars.

In summary, total nutrient removals varied among the four yarding/harvesting scenarios, but also among the different installations and between fertilized and unfertilized plots. The patterns were driven by the biomass components removed under each scenario, increasing in the following order BO<BT<VC<WT (Fig. 41 -43), but also by the large differences in nutrient concentrations among biomass components.

The relative quantity of nutrients harvested under each scenario also varied by site and treatment. Total and relative (%) N was removed on fertilized plots was not consistently higher than unfertilized plots under the four scenarios (Fig. 41 - 43). More Cu was removed under all scenarios on fertilized plots. The LF site had the widest range in relative nutrients (%) removed for B and FE, and the highest relative nutrient (%) removals of K. The ET site had the widest range in relative nutrients (%) removal for Ca, K and P. The PC site had the narrowest range in relative nutrient (%) removals for all nutrients, except N. The RR site had the widest range in relative nutrient removal for Cu, Mg, Mn, N, S and Zn. Th RR site had the highest relative nutrient (%) removals of Ca, Fe, K, Mg, N, P and S (Fig. 43).

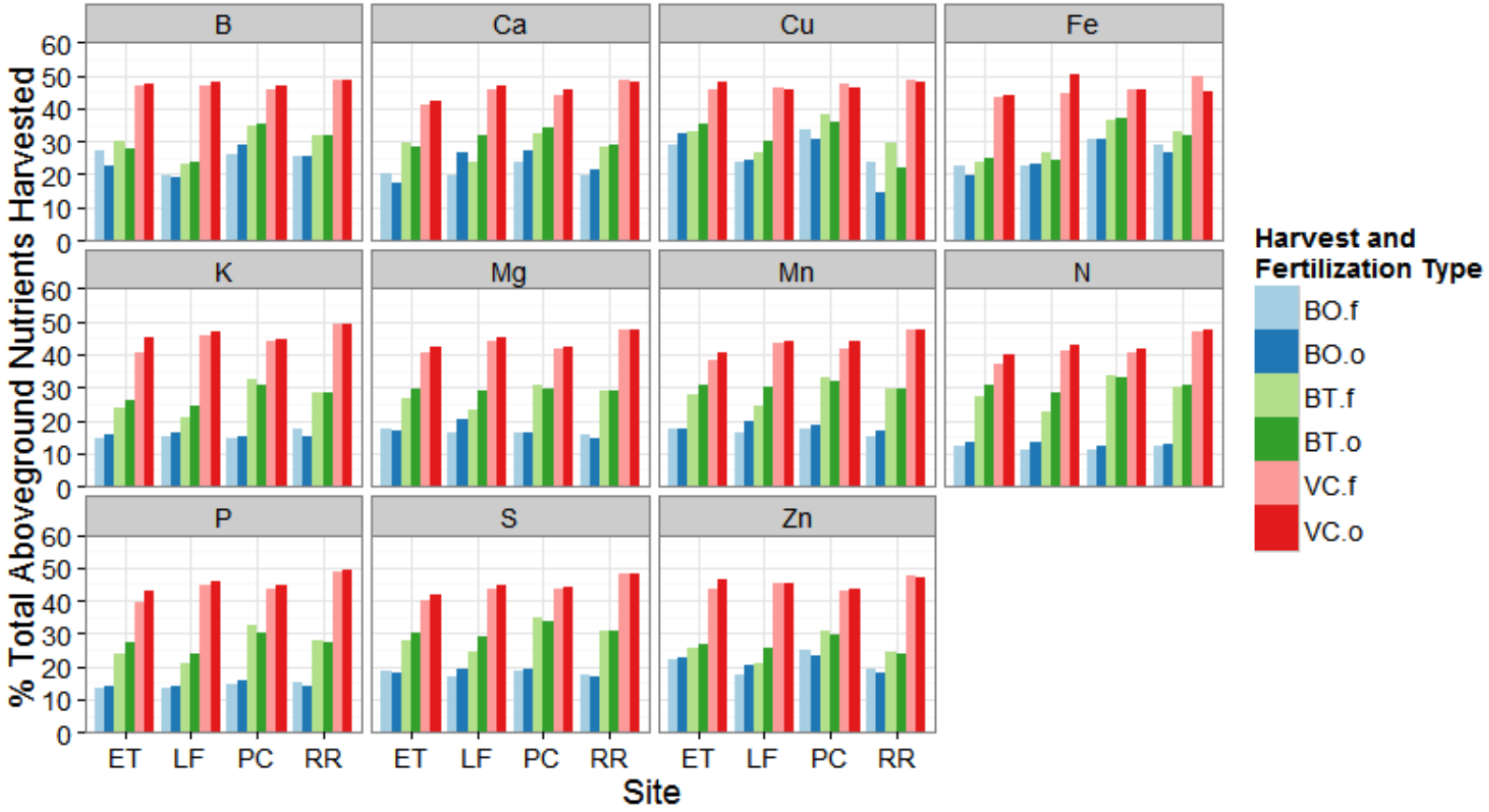


Figure 43. Percentages of total above-ground nutrients removed from fertilized (.f) and unfertilized (.o) plots under the different harvesting scenarios: whole tree (WT), bole and all crown components to 4 inch top (BT), vertical crown and bole (VC) and merchantable bole (BO).

4.5 Soil nutrient pool

4.5.1 Total soil nutrients to one meter

Total soil nutrient content to a 1 meter depth on the control plots of each site are orders of magnitude greater than the highest nutrient content in aboveground biomass (Fig. 44, Fig. 45 and Table 41). For instance, the highest stand level estimate of N in aboveground biomass was 227.7 (kg/ha) on a fertilized plot at the LF site and the lowest N content in the top 1m of soil in the control plots was 9959 (kg/ha). The total aboveground nutrient pool contained no more than 6% (average of 0.7%) of the total nutrient content of the soil N, P, Ca, Mg and S. The total aboveground pool contained not more than 34% (average of 5%) of total K content in the soil. On only the LF site was the total aboveground pool more than 6% of the total K content in the soil. In a dynamic sense, however, soil nutrient content does not differentiate between plant available and unavailable nutrients, so the implications for removals in harvested aboveground biomass are difficult to assess without some understanding of mineralization, weathering, leaching and deposition rates and their variation both within and among stands.

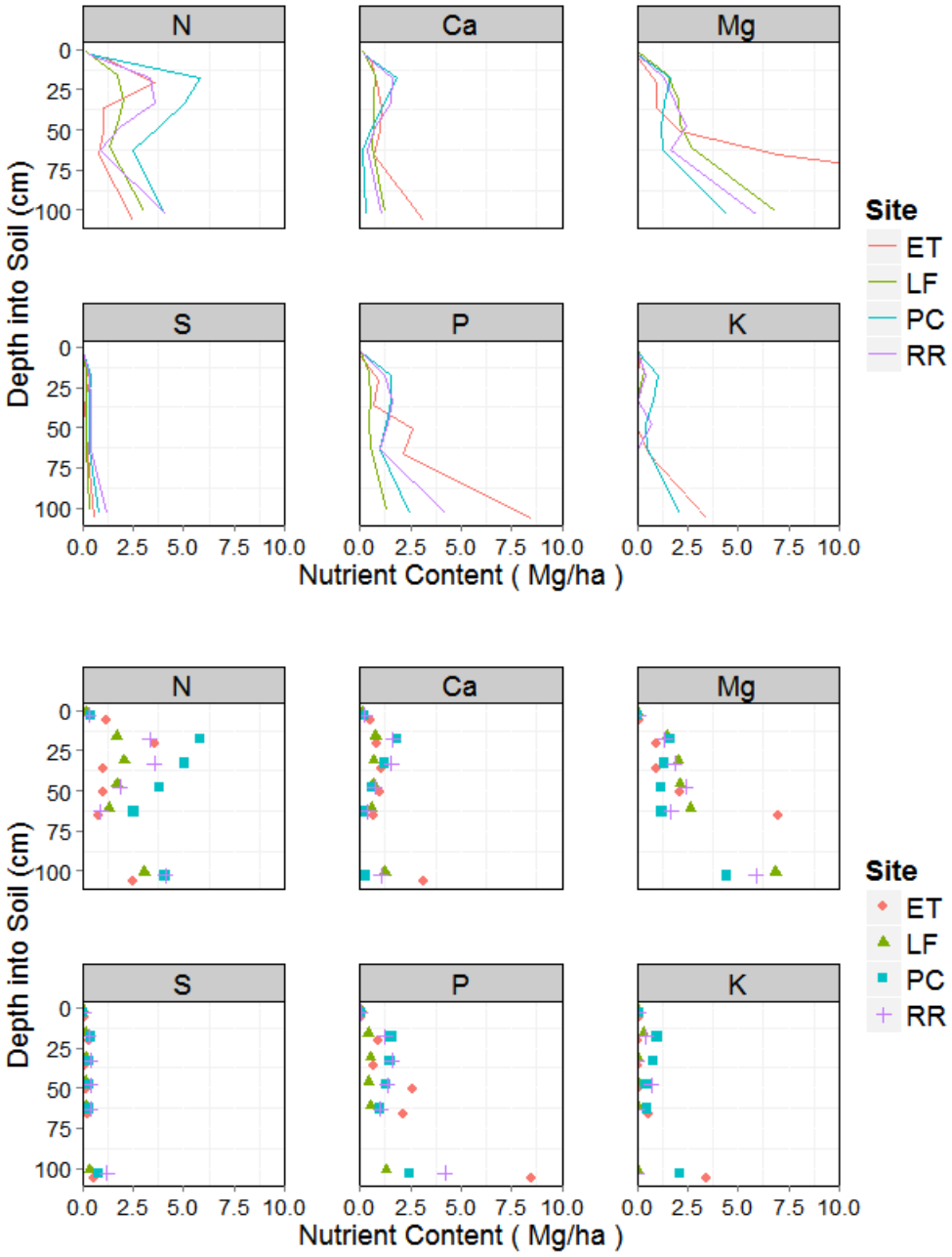


Figure 44. Content of six key plant nutrients by 15-cm soil layer for the four SMC Type I installations (data from Paul Footen, Erika Knight, and Rob Harrison at University of Washington).

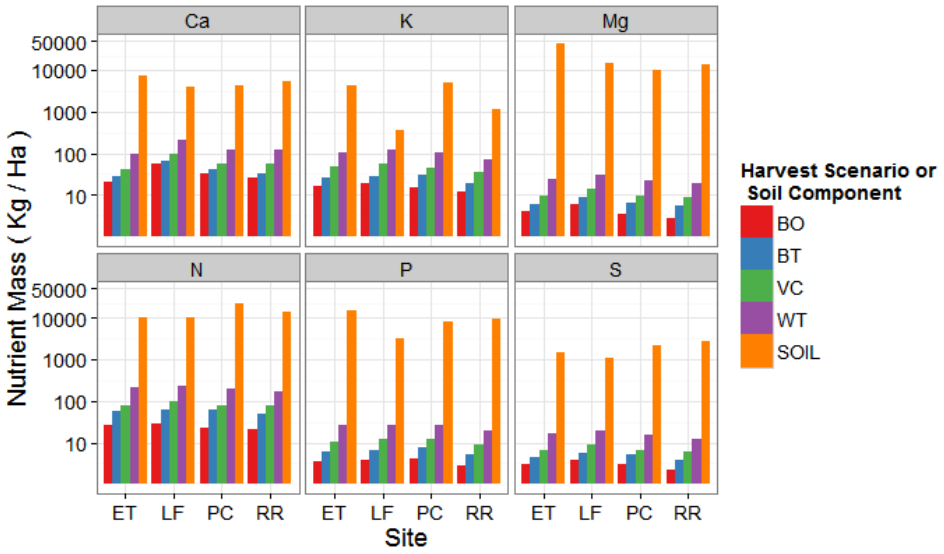


Figure 45. Estimated nutrient content of soil to one-meter depth and total aboveground biomass at each SMC Type I installation (soils data from Paul Footen, Erika Knight, and Rob Harrison at University of Washington).

Table 41. Estimated nutrient content of soil to one-meter depth and total aboveground biomass on fertilized and unfertilized plots at each SMC Type I installation (soils data from Paul Footen, Erika Knight, and Rob Harrison at University of Washington).

Nutrient	Site	Soil Nutrient Contents (kg/ha)	Fertilized Aboveground Mean Content (kg/ha)	Fertilized aboveground nutrient content/total soil pool nutrient content (%)	Min. (kg/ ha)	Max. (kg/ ha)	Unfertilized Aboveground Mean Content (kg/ha)	Unfertilized aboveground nutrient content/total soil pool nutrient content (%)	Min. (kg/ ha)	Max. (kg/ ha)
Ca	ET	7209	99.30	1.38	89.42	106.36	71.16	0.99	43.98	98.44
Ca	LF	4090	160.56	3.93	147.03	178.03	213.00	5.21	178.99	274.10
Ca	PC	4299	112.42	2.62	96.94	123.14	120.91	2.81	101.96	151.98
Ca	RR	5582	119.79	2.15	90.46	137.21	118.58	2.12	91.78	140.44
K	ET	4163	105.69	2.54	95.22	113.79	102.69	2.47	62.23	142.75
K	LF	347	104.07	29.98	95.12	114.94	119.51	34.43	100.18	153.92
K	PC	4960	83.17	1.68	75.30	89.81	102.05	2.06	89.46	124.67
K	RR	1191	67.04	5.63	51.15	76.55	70.31	5.91	55.61	82.27
Mg	ET	42772	23.23	0.05	20.95	24.91	18.02	0.04	11.20	24.89
Mg	LF	15222	22.33	0.15	20.44	24.53	30.44	0.20	25.71	38.96
Mg	PC	9931	20.62	0.21	18.34	22.37	22.37	0.23	19.44	27.51
Mg	RR	13246	17.98	0.14	13.84	20.42	19.07	0.14	15.16	22.26
N	ET	10154	207.70	2.05	186.39	222.05	157.42	1.55	101.89	215.07
N	LF	9959	227.65	2.29	208.67	244.86	220.70	2.22	192.54	275.15
N	PC	21632	189.06	0.87	174.22	202.96	187.88	0.87	168.37	225.49
N	RR	14022	162.73	1.16	127.60	182.71	169.19	1.21	136.82	195.41
P	ET	14880	26.15	0.18	23.54	28.13	24.16	0.16	15.03	33.35
P	LF	3247	20.88	0.64	19.10	22.91	27.27	0.84	23.10	34.84
P	PC	7858	21.84	0.28	19.73	23.60	26.46	0.34	23.09	32.43
P	RR	9455	17.51	0.19	13.45	19.90	18.63	0.20	14.75	21.78
S	ET	1485	16.23	1.09	14.61	17.39	13.67	0.92	8.56	18.83
S	LF	1042	18.05	1.73	16.55	19.76	19.87	1.91	16.98	25.21
S	PC	2202	15.59	0.71	13.94	16.89	15.37	0.70	13.39	18.86
S	RR	2644	11.89	0.45	9.15	13.48	12.61	0.48	10.03	14.70

4.5.2 Relative soil nutrient distribution

The vertical distribution of nutrients throughout the soil varies by nutrient and site. The majority of the nutrients that enter the soil pool through atmospheric deposition and litterfall (N and Ca) were concentrated in the upper half of the 100 cm sampled profile. The majority of all other nutrients, with the exception of K, were distributed more evenly through the soil profile, with some slight increase below 50 cm (Figs. 46 and 47).

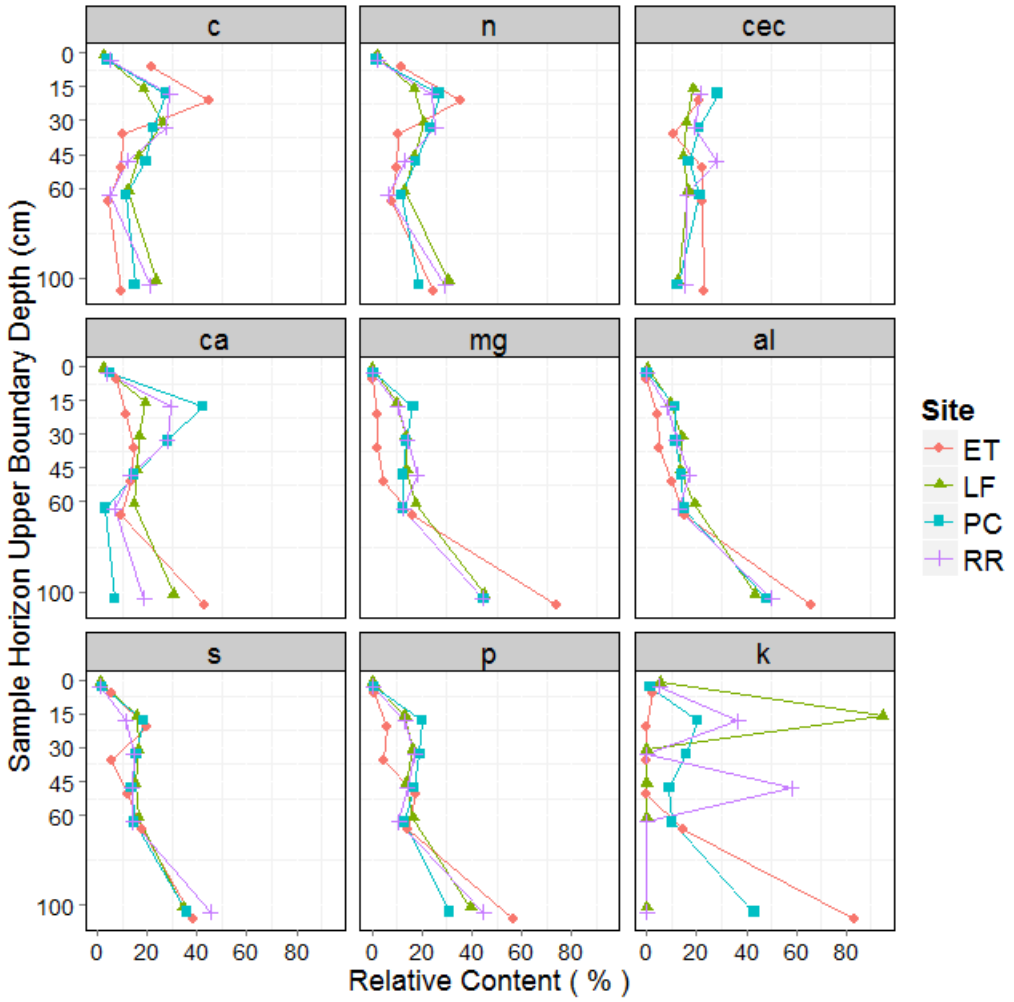


Figure 46. Relative content (%) of seven key plant nutrients, carbon and CEC in each 15-cm layer of mineral soil and in the forest floor for the four SMC Type I installation (data from Paul Footen, Erika Knight, and Rob Harrison at University of Washington).

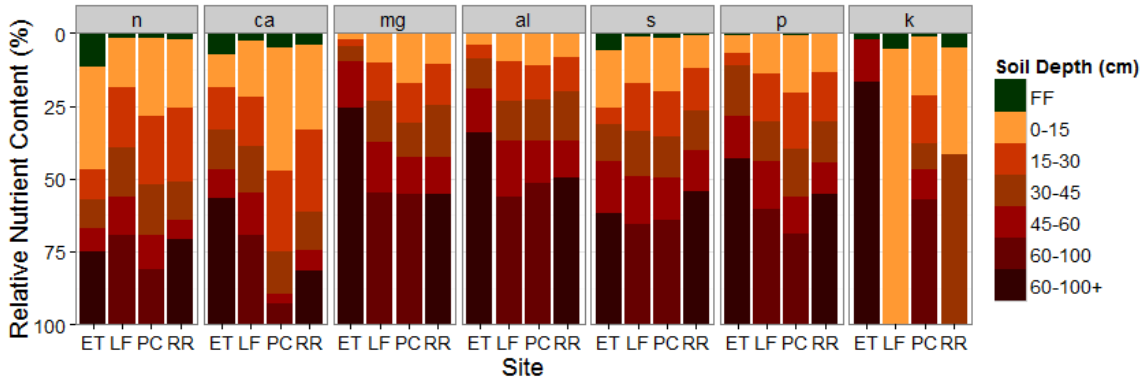


Figure 47. Relative content (%) of seven key plant nutrients in each 15-cm layer of mineral soil and in the forest floor at the four SMC Type I installations (data from Paul Footen, Erika Knight, and Rob Harrison at University of Washington).

4.5.3 Stability Ratio

Evans, (2009, 1999) proposed the "stability ratio" as a simple risk assessment tool by which many regional sites (Himes et al., 2014a) can be compared to identify those most susceptible to nutrient depletion. The stability ratio is defined as the proportion of a given nutrient removed in a single forest harvest, relative to the corresponding total site nutrient capital. Site nutrient capital may be calculated in various ways, such as total soil nutrient content or soil plus aboveground nutrient content. Evans (2009, 1999) used a stability ratio of 0.1 (i.e., 10% of the site total) as an example of a harvest removal level below which there is little or no risk to long-term productivity. A stability ratio (SR) of 0.3 potentially represents a significant risk to productivity, and a stability ratio of 0.5 will probably result in a significant and immediate site productivity decline. The maximum ratio among all nutrients, except K, (Figure 48 and Table A8 in the Appendix) in this study was 0.050 and at a full rotation of 50 years would be not higher than 0.065. Currently the risk thresholds would be exceeded on only the LF site in regards to K

removals under the VC (0.12 and 0.14 SR) and WT (0.23 and 0.26 SR) scenarios on fertilized and unfertilized plots, respectively. At a full rotation of 50 years the risk thresholds would be exceeded on only the LF site in regards to K removals under the BT on unfertilized plots (0.1), VC (0.16 and 0.18 SR) and WT (0.23 and 0.26 SR) scenarios on fertilized and unfertilized plots respectively. Based on the stability ratios of N, P, S, Ca, Mg, and the majority of K there is low risk of nutrient depletion and associated productivity loss under all harvest scenarios on similar Douglas-fir sites in western Oregon and Washington.

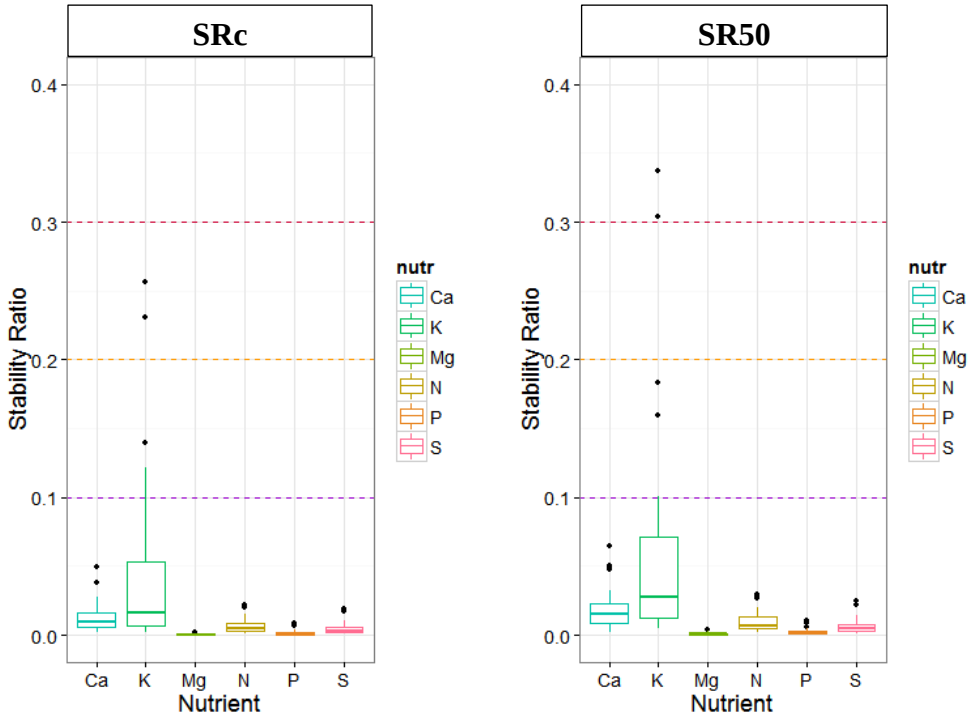


Figure 48. Stability Ratio (SRc) and 50 year Stability Ratio (SR50) by site nutrient for whole tree harvesting for all nutrients. Slight (0.1), moderate (0.2) and significant (0.3) risk thresholds are represented in purple, orange and red lines, respectively.

5 Discussion

5.1 Biomass Estimation

5.1.1 Branch component mass estimates

Over all sites, 1-yr-old, 2-yr-old, and ≥3-yr-old foliage comprised 23% (12-34% range), 14% (10-16% range), and 21% (6-35% range) of total crown mass. Live branches (wood + bark) comprised 41% of the live crown biomass (35-49% range). The estimates of relative foliage mass of crown mass from this study are 18% higher on average than those from a 30 year old western Washington plantation described by Long and Turner (1975) and similar to estimates made by Ranger et al. (1995). The relative distribution of crown biomass components differed among sites (Fig. 14). The PC site had the highest relative proportion of 1-yr-old foliage and the lowest proportion of all other age classes perhaps due in part to SNC, but also to the higher site quality (e.g., Schoettle, 1990). On the PC site the 68% higher live crown biomass due to mainly to this installation having the lowest tree density (362 tpa), reduced height with a lower density and higher site productivity than the other SMC sites of this study. The ET installation had the highest average proportion of ≥3-yr old foliage, but trees on this installation and on the LF installation retained the oldest foliage (up to 10 years in contrast to 7 and 8 years at the other sites; (Table A1 in the Appendix), probably due to the slightly lower site quality at these sites.

The patterns and variability in branch biomass across the covariates DINC and RHACB can be attributed to regional conditions and local conditions which each

influence differing portions of the crown. Branch size, and therefore individual branch mass, in the upper crown is influenced more by regional conditions, in contrast to the lower portion of the crown which responds more strongly to local stand density and other aspects of stand structure created by silvicultural treatments (Makinen, 1996). Douglas-fir needle production has been shown to increase 23 % four years after fertilization on unthinned plots and 7 years after fertilization on thinned (Brix, 1981). Although not explicitly stated as an objective of this analysis, the sampling design for the SMC Type I branches captured the effects of silvicultural treatments (thinning and fertilization) on the vertical distribution of foliage within the crown. Fertilization has the strongest effect on the top half of the crown and thinning on the bottom half (Brix, 1981). Brix (1983) noted that thinning improves light conditions primarily in the lower crown and that fertilization increases foliage mass and diminishes light intensity in the lower crown. However, after fertilization trees benefit from increased N concentrations in the short term and increased total canopy N in the long term (Brix ,1983). Both thinning and fertilization have been shown to increase the number of branches of differing order on a tree (Brix, 1981; Mäkinen et al., 2001). Fertilization has also been shown to increase (Brix, 1971, 1981) or reduce average needle weight and content of N, Ca and P (Velazquez-Martinez et al., 1992), depending largely on time since fertilization. Weiskittel et al., (2007) found diameter growth of relatively young branches in the upper crown of coastal Douglas-fir accelerated in response to fertilization, whereas diameter growth of older branches in the lower crown decelerated slightly.

5.1.2 Whole tree component mass estimates

The relative distribution of biomass components in the sampled Douglas-fir trees was more similar than might be expected across a wider range of sites differing more in stand age and tree size (Fig. 15). Trees on different sites have been found to share the same pattern of development of the relative shares of biomass components, although growth rates have been found to be faster on more fertile sites (Vanninen et al., 1996). On average, sapwood mass comprised 44% (24-59% range) of total stem mass, heartwood comprised 35% (24-44% range) and bark 13% (8-31% range). These 29 to 35–year-old Douglas-fir trees had at least 20% more stem mass than 20-year-old planted stands in France (Ranger et al., 1995) and at least >5% more than the 30-49-year-old planted stand described by Turner and Long (1975). However, the stem biomass was only 5 % greater than the 40-year-old planted stand described by Ranger et al., (1995). The proportion of bark mass (13%) was relatively invariant among sites, similar to previous observations on bark volume (18%) in Douglas-fir (Maguire and Hann, 1990). The LF site had the greatest proportion of heartwood (38%) and the lowest proportion of sapwood (41%), as would be expected given the greater height of that stand and the relatively small differences in crown length between LF and the other installations. The PC site had the lowest proportion of heartwood (31%) and the highest proportion of sapwood (46%), again consistent with the relatively short heights and crown ratios that differed little from other installations. On the PC site the slightly higher sapwood proportion is likely due mainly to this installation having the lowest tree density (362 tpa), reduced height and increased diameter growth with a lower density and higher site productivity than the other SMC sites of this study. The presence of Swiss needle cast

may also contribute to the slightly higher relative proportion of sapwood and lower relative heartwood on the PC site. The ET and RR proportions were more similar to those of the LF site than the PC site. Each of the study sites had plots with a range of relative densities, leading to the expectation of substantial differences in sapwood:heartwood proportions even within an installation; ET, LF, PC and RR ranged from 0.15-1.52, 0.17-1.42, 0.13-0.67 and 0.16-0.98, respectively (Curtis, 1982).

Sapwood-heartwood proportions result from a balance between two critical functions of tree boles, providing mechanical support for the upper stem and crown and delivering a water supply to the foliage (Long et al., 1981). As a tree grows, the number of branches, foliage mass and area increase. At the same time sapwood enlarges exponentially with foliage mass, accompanied by a proportionate increase in maintenance respiration. The cost of maintenance respiration to support the living parenchyma cells in sapwood balances the benefits of water conduction, sapwood storage and mechanical support (Ryan, 1989). As a tree increases in size, the growing respiration costs contribute to a deceleration in tree growth, along with hydraulic limitations and other probably more minor mechanisms (Bond et al., 2007). Sapwood enlargement ceases substantially earlier in suppressed trees because carbohydrate reserves are always lower in trees growing under stress (Waring, 1987). Additionally, Saffell (2014) suggested that under disease-induced reductions in carbon supply, Douglas-fir trees retain non-structural carbohydrates (NSCs) (either actively or due to sequestration) at the expense of trunk radial growth.

5.1.3 Site differences in branch-level biomass equations

Across all sites the branch-level ≥3-yr foliage biomass increased as DINC increased up to a depth of approximately 18 m (Fig. 18). The PC site showed the greatest difference among all sites between DINC of maximum ≥3-yr-old foliage and DINC of maximum 1-yr-old foliage at the branch level (654 g), with over 4 times difference between maximum foliage estimates (Fig. 18). Maximum branch diameter of ET, LF, PC and RR occurred at 46, 11, 9 and 48% of DINC, respectively, which occurred much lower in the crown (79%) than those in Maguire et al., (1999). In general, the maximum foliage biomass across each of the age classes concurred with results from Maguire and Bennett, (1991) in that the maximum foliage biomass per branch peaked at mid crown.

The pattern in predicted biomass of dead branches (wood + bark) is strongly influenced by early brush competition, early stand density, early stand density control, and the pattern of mortality from ground line up, particularly in regard to mortality of interwhorl versus whorl branches. The ET and RR sites, as well as the LF site to a large degree, followed a pattern with height on tree that would be most typical of trees that withstood early competition from brush or other trees (hardwood and conifer), but then had more space to grow and develop larger branches going up the stem (Fig. 19). This increase, however, is a balance between size attained by the branch before it died and how much it has deteriorated and lost biomass since mortality. The progression of interwhorl branch mortality is much more rapid than whorl mortality, so the highest dead branches will always be relatively small interwhorl branches. The pattern of decreasing

dead branch biomass with height at PC probably reflects a smaller branch size associated with mortality of many interwhorl branches further up the stem, a behavior that would be consistent with the substantially higher relative (%) foliage biomass at this site due to the lowest ISPA, subsequent height and diameter growth responses and potentially effects of lowered productivity from SNC.

The PC site had a relatively steep positive increase in branch biomass with DINC and RHCB in comparison to the other three SMC Type I sites. This behavior of branch-level biomass may be influenced by the presence of SNC on the youngest and highest site index site. Weiskittel et al. (2007) suggested foliage loss in the top portion of the crown may reduce self-shading and increase branch radial growth in the lower portion, which would partially explain a peak in maximum branch diameter lower in the crown for the PC site despite a high site index.

5.1.4 Bole component volume estimates

Total stem volume estimates for this study included the entire stem from ground line to tree tip, as the starting point for estimating stem biomass and nutrient content. Conventional tree volume equations (e.g., Hann et al., 1985) could not be applied because the volumes of four separate stem sections were needed to match to the sample stem disks from which bark, sapwood, and heartwood densities were determined. Biomass of each section was the sum of products of volume and density of these three stem components. Maguire et al. (manuscript in preparation) developed a heartwood taper

system that can estimate height of the heartwood core and the width of the heartwood as a percentage of the measured or predicted diameter inside bark.

5.1.5 Developing tree-level biomass equations

In general, crown structural attributes were readily predicted from DBH, HT, and HCB, because specific combinations of these variables reflect the silvicultural regime under which the tree was grown, so the response of crown structural attributes to silvicultural regimes are well represented by the net effect on DBH-HT-CL combination. The adequacy of DBH, HT, and CL was consistent with results from many other studies of branch size and distribution in coniferous species (Mäkinen and Colin, 1998; Weiskittel et al., 2007b).

5.1.6 Forced additivity tree-level biomass equations

The relative (%) biomass per ha of each component from the forced additivity models [15] were very similar, averaging 2% for 1-yr-old foliage, 1% for 2-yr-old foliage, 1% for ≥3-yr-old foliage, 3% for live branch wood (wood + bark), 14% for stem bark, 43% for stem sapwood, and 36% for stem heartwood (Fig 27). Relative (%) foliage estimates are similar to those reported by Long and Turner (1975) and Ranger et al. (1995). Relative (%) stem mass estimates are likewise similar to those reported by Long and Turner (1975) and higher than Ranger et al., (1995). Relative (%) branch mass was approximately one half to one third of results reported by Ranger et al. (1995) and Long and Turner (1975).

The forced additivity (Cunia and Briggs, 1984) of the nonlinear component level biomass equations do have a disadvantage over other approaches. The advantage of this approach is that optimal estimates of total biomass are considered because the sum of squared errors around total biomass are considered. Conversely, correlations among the residuals of biomass components are not considered unless a systems-of-equations approach like seemingly unrelated regression (SUR) is applied (Parresol, 2001). Residuals among the biomass components equations are correlated with SUR because over-estimates in one component often are associated with under- or over-estimates in other components within a given tree (Carvalho and Parresol, 2003).

5.2 Nutrient Concentration

The distribution of nutrients observed in the Douglas-fir SMC Type I stands are similar to previous studies; the smaller biomass components such as foliage are typically the most concentrated in nutrients, even though the components of the live crown form 7.3% of average stand biomass. The definition of adequate nutrients have been approximated for a variety of nutrients for Douglas-fir in multiple studies (Radwan and Brix, 1986). The presented definitions are general guidelines to be utilized in conjunction with other site and physiological attributes. The definitions of adequate S, for example, indicate these sites are deficient in S on all four sites, however prior published studies on the SMC sites (e.g. Sucre et al., 2008) have demonstrated productive growth rates. According to standards from Ballard and Carter, (1986),Van den Driessche, (1979) and Burg, (1985) there were also varying levels of deficiencies of N, K, Ca , Mg and S on various fertilized and unfertilized plots across all sites. Ballard and

Carter (1986) identified three N-deficiency levels in Douglas-fir on the basis of foliar N concentration (%, dry-mass basis): 1) Very severe: <1.05%, 2) Severe: >1.05 to 1.3%, 3) Slight-moderate: >1.3 to 1.45%. Foliar N in 1-yr foliage at 3 of the 4 sites on fertilized plots and 2 out of 3 on unfertilized plots exceeded 1.35% N (Table. 42), which is considered above the threshold of N-limitation in coastal Oregon Douglas-fir by Carter (1992). The other two were 0.12% or less below the Carter (1992) threshold.

Table 42. Concentrations of macronutrients in current-year foliage considered minimal requirements for growth in Douglas-fir, along with average nutrient concentrations (%) on fertilized (*) and unfertilized plots at the SMC Type 1 installations.

Author	**Nutrient**					
	N	**P**	**K**	**Ca**	**Mg**	**S**
Van den Dressche (1979)	1.8	0.22		0.2	0.12	0.18
Ballard and Carter (1986)	1.45	0.1	0.75	0.2	0.08	
van den Burg (1985)	0.9-2.4	0.1-0.31	0.4-1.55	0.2-0.57	0.04-0.22	0.10-0.27
Site						
ET*	**1.29**	0.15	0.51	0.26	0.11	**0.07**
LF*	1.58	0.10	**0.35**	0.26	0.10	**0.07**
PC*	1.43	0.12	0.52	**0.18**	0.08	**0.07**
RR*	1.41	0.12	**0.36**	0.38	0.12	**0.08**
ET	**1.23**	0.17	0.59	0.26	0.11	**0.07**
LF	**1.34**	0.11	**0.37**	0.27	0.11	**0.07**
PC	1.39	0.13	0.57	**0.15**	0.09	**0.07**
RR	**1.37**	0.12	0.43	0.27	0.13	**0.08**

Douglas-fir foliar N levels, which range from 0.85% to 1.74%, are positively correlated with soil N levels and negatively correlated with foliage retention. It has been suggested that nitrate-leaching of Ca on N-rich sites, combined with low rates of atmospheric Ca deposition relative to tree demands, contribute to Ca depletion and N oversaturation on coastal sites, possibly contributing to low needle retention. It is

difficult to interpret the relationship between foliar and soil Ca and N levels and SNC severity in observational studies, as these factors covary with distance-from coast along with many climatic variables that are known to strongly influence abundance of the causal fungus (Manter et al., 2005; Stone et al., 2008). N fertilization (as urea) has been a common management practice for increasing tree growth and yield in the Douglas-fir region of the Pacific Northwest (Bengtson, 1979), but some foresters in coastal Oregon and Washington are concerned that, in areas of moderate to severe SNC, N fertilization may worsen disease severity (Filip et al., 2000). Plantations are traditionally fertilized with urea at the time of pre-commercial thinning (8- to 15-years-old) or commercial thinning (20- to 25-years-old), and may be fertilized at regular intervals (e.g., every 5 years) until harvest (Mulvey et al., 2013). As such, the level of fertilization may have exacerbated the negative impacts of SNC on the PC site in the fertilized plots. Each of the SMC Type I fertilized plots were fertilized with 220 kg/ha of nitrogen as urea at every 4-year remeasurement, up to a maximum of five applications for a total of 1100 kg N/ha in order to eliminate N as a limiting factor to growth. This intensity of fertilizer application is in excess of what would be operationally applied.

The implications of foliar nutrient concentrations of this study to long term productivity are limited, meaning the concentrations are strictly relevant to the adequacy of the current year nutrient supply. As nutrient concentrations are influenced by other fluctuating environmental factors and tree physiological conditions the nutrient status of the stands for 2011 cannot be used as a sole inference for long term nutrient status. Foliar concentrations of nutrients change with stand age and growth rate, and cultural practices

(e.g., fertilization) have been shown to both increase (Brix, 1981) and reduce average needle weight and content of N, Ca and P (Velazquez-Martinez et al., 1992). In addition, most plants have the ability to down-regulate uptake of most non-limiting nutrients so that proper foliar balance is maintained even when growth is limited by N supply (Knecht and Göransson, 2004). Therefore, low foliar levels of macronutrients (Ca, K and S) in a N-deficient stand should not necessarily be interpreted as deficiencies. The nutrient concentrations from this study are from a single instance of measurement and should only be used as an indicator of current nutrient status of the aboveground biomass, not as an independent indicator of trend in long-term site productivity.

5.3 Nutrient Content

5.3.1 Stand level nutrient content by component

On some SMC sites and for many components the stand level nutrient content was lower in general when compared to the study sites of Ranger et al.,(1995) in France (Fig 49 and 50). The stem wood and bark of a single tree of the SMC sites contained lower levels of Mg (27 g/tree), P (20 g/tree) and higher levels of S (23 g/tree). Stand level estimates of 20 and 40 year-old Douglas-fir (Ranger et al., 1995) compensated for density indicate variation in total nutrient content with site, nutrient and component. The average tree of this study (293.4 kg) was intermediate in dry biomass between the 20 (100.5 kg) and 40 (534.9 kg) year-old stands in Ranger et al., (1995). The distribution of the nutrient contents among components is likely due to the higher productivity of the French stands in comparison to the SMC stands due mainly to the timing of maximum

precipitation. Precipitation in France peaks in the summer months, unlike the PNW forests which experience drought in the summer months. The average French stands is more productive than 3 out of the 4 SMC sites, and Bouchon, (1982) evaluated a mean annual increment of 17 m^3 h^{-1} yr^{-1} (243 ft^3 ac^{-1} yr^{-1}) overall Douglas-fir stands in France.

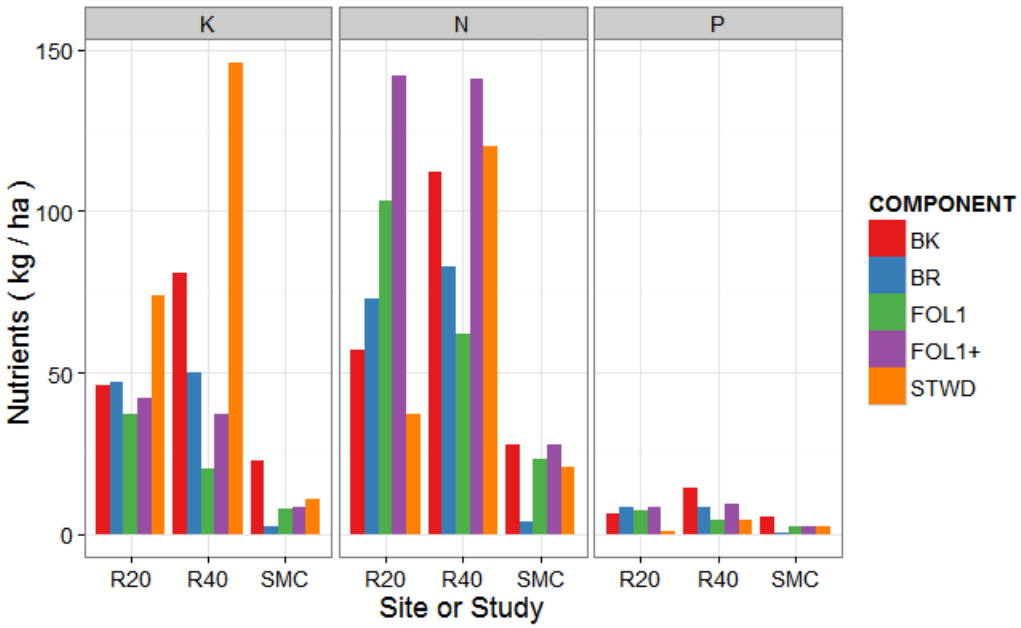


Figure 49. Total stand level nutrient content in components of the SMC stands and of a 20 year-old (R20) and 40 year-old stand (R40) of Douglas-fir in France (Ranger et al., 1995) STWD = stemwood = sapwood+ heartwood).

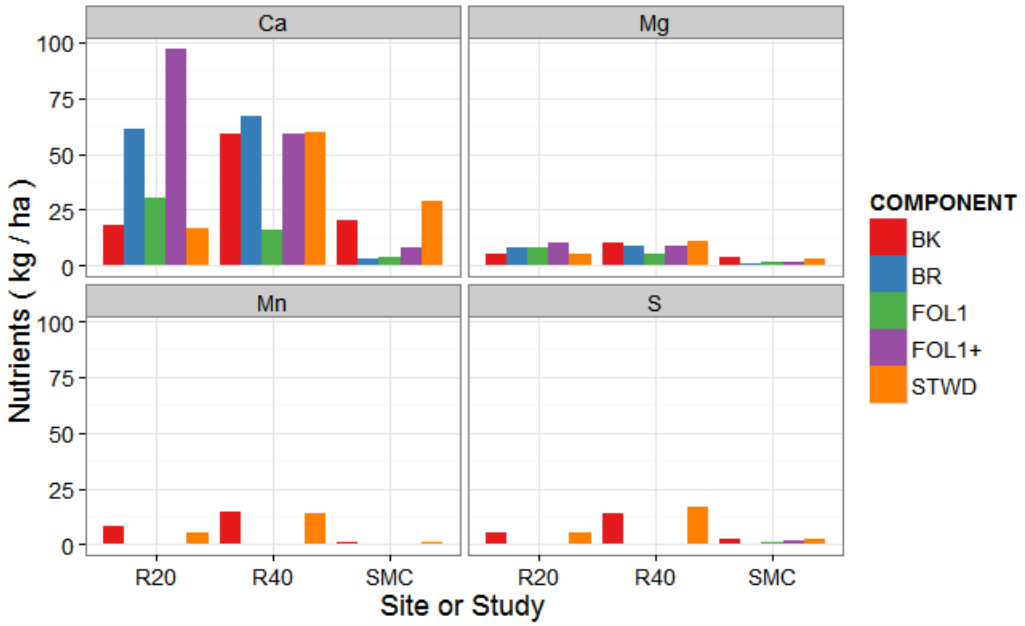


Figure 50. Total stand level nutrient content in components of the SMC stands and of a 20 year-old (R20) and 40 year-old stand (R40) of Douglas-fir in France (Ranger et al., 1995) (STWD = stemwood = sapwood+ heartwood).

This study and many others calculate nutrient contents removed based on pre-harvest stand nutrient contents and predicted biomass removals for harvesting scenarios. The differences between full-tree and tree-length nutrient removals in (Hazlett et al., 2014) were substantially less than calculated in previous nutrient budget studies of boreal stands (Foster and Morrison, 1989; Morrison et al., 1993; Paré et al., 2002). For nutrients with a greater relative proportion of aboveground storage in branches and foliage such as N, P, and K, Foster and Morrison (1989) reported theoretical removals for stands that were 2.5 times greater for full-tree than tree-length harvesting, and Hazlett et al. (2014) found a theoretical difference (tree length bole) of 1.2 times greater. In contrast, the theoretical difference for the SMC sites was 1.3-1.8 times (merchantable bole) more. The theoretical N removal of whole tree harvesting were greater than tree

length (bole only) harvesting by 1.4-2.0 times, 1.1-1.3 times and 1.7-1.8 times, for studies by Powers et al. (2005), Hazlett et al. (2014), and in the SMC installations, respectively. The studies cited above calculated removals based on preharvest stand nutrient contents and predicted biomass removals for the harvesting methods. The results from Hazlett et al. (2014), demonstrated that theoretical removals can underestimate actual tree-length removals (for C, N, P, K, Mg, not Ca) and slightly overestimate actual whole tree removals for some elements (e.g., N and P) . For this reason, estimates of slash remaining on site should be incorporated whenever possible when evaluating possible levels of residue available for bioenergy production and estimating site nutrient capital remaining after harvest.

5.3.2 Relative overall stand level nutrient content by component

The relative distribution of biomass and nutrients in the various stand components clearly illustrates that tree crown, which represents a limited part of total biomass (7.3% mean), retains the large quantities of all N (53%) and a large portion of K (36%), Mg (38%), Mn (39%), P (40%)and S(39%) on average (Fig.31). Ranger et al. (1995) found the largest quantities of N, P, K, Ca, and Mg in the live crown compoents in their young (20 year-old) Douglas-fir stand. The values are more equally distributed between crown and stem in the 40 year-old and 60 year-old stands. Multiple studies have found that younger stands possess the highest concentrations of nutrients (Das and Ramakrishnan, 1987a; Ranger et al., 1995). The comparison between the 40- and 60-year-old stands showed that for P, Ca and Mg, no change occurred in their relative

distribution; for N a slight but significant increase in relative distribution, and for K a relatively large decrease were observed. This is likely due to the slow weathering rates (in comparison to increased removals) or potentially a higher ratio of sapwood:heartwood in the 40-year-old verses the 60-year-old stand. The dynamics of the nutrient budgets of these stands showed nutrient losses occurred mainly before 40 years of age (Ranger et al., 2002). The SMC stands in this study have a smaller range in relative foliage nutrient content (10-36%) than the 20 to 53% measured by Ponette et al. (2001). The resulst of this study and Ranger et al. (1995) found that in the crown, needles contained the greater quantity of certain elements (N, P and Ca). In the stem, bark contained almost the same or often larger quantities of nutrients (e.g. N, P, K, Mg, Ca) than wood, but bark biomass represented only 8-11% of total biomass in Ranger et al. (1995) and 13-14% in this study.

In the sampled SMC Type I stands, stem wood accounted for approximately 93% of the aboveground biomass of Douglas-fir, but total stem contribution of the stemwood (heartwood, sapwood and bark) to relative aboveground nutrient content exceeded 60% of each sampled nutrient with the exception of N (46%). With the exception of N the relative nutrient values were double or triple those described by Ponette et al. (2001) for trees of similar size, but 61 years in age . The stem components of the SMC plot contain 13-62% more relative nutrients (Ca, K, Mg, P and N) in the stem components than the 20- and 40-year-old stands measured by Ranger et al. (1995). This is likely due to differences in nutrient availability and stand density. The densities were 922, 490 and 312 trees ha^{-1} for 20-, 40 and 60-year-old Douglas-fir stands and the SMC plots averaged 597 trees ha^{-1} (237-1616 trees ha^{-1}).

The whole tree nutrient content at the stand level was consistently the highest for the oldest site (LF) with a higher site index (37). The nutrient content for the PC site, the youngest by eight years, was typically lower than all other sites. This can be partially attributed to the accumulation of less total biomass due to the effects of lowered productivity from SNC on the site stand and minimally to a slightly younger stand age (by 4 years) than all other sites. SNC is a foliage disease that is specific to Douglas-fir and is caused by the fungal pathogen *Phaeocryptopus gaeumannii*. Overall, Weiskittel et al. (2006), found that severe SNC resulted in a 27% reduction in total foliage mass on an average-sized tree (D=33.2 cm, H=26.2 m and crown ratio = 0.61) relative to total foliage mass on a tree with low SNC. Corresponding reductions in each foliage age class were 6%, 10%, 33%, 56%, and 91% for the 1-, 2-, 3-, 4-, and ≥5-year-old foliage age-classes, respectively. Some have speculated that high levels of N relative to other macro- and micro-nutrients may increase nutrient availability in the apoplast where it can be accessed by *P. gaeumannii* (El-Hajj et al., 2004; Perakis et al., 2006). Any increase in N nutrient content due to SNC are likely to be small, or nonexistent, as on average the PC site had a 7.2% increase in biomass on fertilized (to the point of eliminating N deficiency) plots with a mean increase of foliage N concentration of 0.04% (Table 36.)

In the region of the SNC epidemic in the Pacific Northwest (USA), foliar N levels often exceed the established 1.4% threshold for N-deficiency in coastal Oregon Douglas-fir, as all SMC sites do with the exception of the ET site (Weetman et al., 1992). Douglas-fir foliar N levels, ranging from 0.85% to 1.74%, have been found to be positively correlated with soil N levels and negatively correlated with foliage retention.

As mentioned above, foliage retention has long been recognized as negatively correlated with site fertility and fertilization. In areas of north coastal Oregon where Swiss needle cast has become a problem, it has been suggested that nitrate-leaching of Ca on N-rich sites, combined with low rates of atmospheric Ca deposition relative to tree demands, contributed to Ca depletion and N oversaturation on coastal sites, possibly contributing to stimulation of the fungus causing Swiss needle cast. It is difficult to interpret the relationship between foliar and soil Ca and N levels and SNC severity in observational studies, as these factors co-vary with distance-from coast along with many climatic variables that are known to strongly influence abundance of the causal fungus (Manter et al., 2005; Stone et al., 2008). In addition, N levels can be high due to this natural N surplus and the common practice of N fertilization for increasing yield throughout the region (Bengtson, 1979). This particularly concerning on the SMC sites because some of the plots were fertilized with N at the rate of 224 kg ha^{-1} every four years for up to five times. Although never demonstrated experimentally, suspicion remains that nitrogen fertilization in areas of moderate to severe SNC may worsen disease severity (Filip et al., 2000).

The proportion of nutrients contained in above ground tree components varies with age, and hence rotation length, which may be altered to meet biofuel production goals. For example, the proportional nutrient content in foliage tends to become less with an increase in age while the proportional nutrient content in the bole and bark becomes greater as the stem accumulates biomass over time (Bowen and Nambiar, 1984). In a study of Douglas-fir biomass and nutrient content across chronosequence of stand ages

(20, 40 and 60 years), Ranger et al. (1995) found the maximum accumulation for Ca and K tends to be earlier than biomass accumulation, the reverse to be true for Mg and P, and that N accumulation was proportional to biomass during stand development in the aboveground biomass. When considering only the stem, accumulation of N, K and to a lesser extent Mg and P tended to be earlier than biomass accumulation, with the reverse tendency for Ca (Ranger et al. 1995).

Nutrient uptake and immobilization are the primary processes affecting nutrient allocation with age. Nutrient uptake tends to decrease with stand age, while the reverse occurs with the quantity of immobilization. The rate of nutrient uptake over age is controlled by three main characters: (i) the stabilization or decrease of foliar biomass and associated litterfall with age; (ii) the pattern in declining current annual stand increment; (iii) the decrease of nutrient immobilization rate (definitive nutrient storage, not able to change within a given year) with stand age according to the 'dilution effect' linked to cumulative growth. In relation to biogeochemical cycling immobilization is defined as the conversion of inorganic compounds to organic compounds by microorganisms so that the nutrient(s) become(s) inaccessible to plants. The immobilization rate is defined as the quantity of nutrients sequestered in the quantified portion of the tree each year in the research by Ranger et al., (1995). There was a strong decrease in nutrient concentrations with age in stem wood, with the decrease in relative proportion of sapwood to heartwood. Young stands have been found to immobilize almost the same quantity of nutrients as the older ones which produce twice the biomass. The quantity of immobilization is smallest for the young stand and highest at the maximum mean and current annual increment. In

Douglas-fir immobilization represents no more than 40% of total nutrient uptake (Ranger et al., 1995).

5.3.3 Relative overall stand level nutrient content by component, site and fertilization treatment

Initial assessments appeared to indicate a higher relative content of some nutrients (Ca, Fe, K, Mg, Mn, N, P and S) in the foliage of fertilized plots averaged across installations. However, when further assessing the variability of relative nutrient content (%) ***among installations*** this pattern is less obvious or, in the case of Fe on the PC and RR sites, the opposite trend is apparent (Fig. 33). The variability in the relative distribution of nutrients can be attributed to differing quantities and distributions of soil nutrients and site conditions that affect the productivity, nutrient allocation and overall nutrient use efficiency. Consistent effects on nutrient concentration of different elements (N, P K, Ca Mg and P) from fertilization and thinning treatments have not been documented in this study or others. However, fertilization has been shown to increase the uptake of all elements except P. It has been documented that C allocation to needles and branches increases with fertilization (Albaugh et al., 2006; West, 1998) and decreases to the roots following fertilization (Friedman-Thomas, 1986; Keyes and Grier, 1981; Vogt et al., 1983). Additionally trees may also produce stem wood with decreased density after fertilization (Erickson and Harrison, 1974). In a review, Cahill and Briggs (1992) found several studies that report a decrease in density after N fertilization, leading to an overestimation of C sequestration when using tree diameter as the sole predictor (Shryock et al., 2014).

5.3.4 Total aboveground nutrient content by fertilization treatment

Each of the SMC sites appeared to have differences in total nutrient content under the N fertilization regime; B, Ca, K, N and S at ET; Ca, Cu, K, Mg, and S at LF; Cu, K and Mn at PC, and Cu, Mg, Mn and S at RR. The mean aboveground nitrogen content was greater on fertilized plots than on unfertilized plots at all installations except RR (Fig 34). Some of the variation in response depends on initial N status, fertilization treatment, moisture availability, foliar nutrient balance, and soil parent material. A total of 1220 kg N/ha as urea was applied on the fertilized plots. This relatively high dosage over a 16-year period could induce other nutrient deficiencies as the system becomes saturated with N. In particular, these high N additions over a relatively short periods could cause increased nitrification and leaching (Aber et al., 1998) resulting in the loss of base cations such as Ca and Mg (Johnson and Cole, 1980). Nutrient deficiencies or imbalances due to N fertilization are quite possible. In fact, the inconsistency of nutrient content among sites and N fertilization treatments indicates that N is not solely limiting growth, so that availability of other nutrients may play a role at some of the sites. Since neither pretreatment or treatment plot samples were taken, it is difficult to ascertain the effect that N fertilization had on soil chemical properties (Sucre et al., 2008).

5.4 Harvest Removals

5.4.1 Comparative biomass estimates

Many previously existing equations from the literature, with the exception of Ung et al., (2008), presume a constant height-diameter-crown length and taper relationship for Douglas-fir, i.e., that trees of a given diameter have similar height, crown size, and form. In contrast, the equations developed here for trees sampled from the SMC Type I plots include both diameter and height or diameter and crown length as explicit predictor variables. Differences in published biomass estimates are attributable to changes in allometrics in response to a number of factors that pertain to the populations sampled, including geographic location, stand ages, soils, and climate, but seldom apparently to differences in silvicultural regime.

Bartelink (1996) sampled stands that were grown on acid brown podsolic soils which in combination with the acid rain in the Netherlands leads to a low nutrient status, low level of available moisture and low soil-pH. Both organic and inorganic amendment use is prevalent in the Netherlands in order to mitigate aluminum toxicity and phosphorus deficiency. The trees sampled by Feller (1992) were from a high quality study site with high mineral soil N content at elevations similar to the SMC Type I sites in central Vancouver Island, BC. The Canadian national biomass equations in Ung et al. (2008) cover a similar range in allometrics to the SMC Type I equations, however sample size was small (14 trees) and was probably influenced by the specific stand densities and morphological effects of colder climates. The diameter-only equations developed by Harrison et al.,(2009) were derived from the data from a productive 47-year-old coastal mixed coniferous forest plantation in Washington. The site is among the most highly productive site classes of the coastal Douglas-fir region, with an estimated site index of

41–43 m. Site index is a measure of a forest's productivity defined as the height of the dominant or codominant trees at a breast-height (1.37 meters) age of 50 years (King, 1966). Site index equations differ by tree species and region. This higher site productivity and other stand characteristics, relative to the SMC Type I site indexes ranging from 27-41, is likely the reason for the overestimation of the Harrison et al. (2009) equations. The average dbh of the latter equations was 35.6 cm (39.1 cm for Douglas-fir and 33.3 cm for western hemlock) with a minimum of 4.4 cm and a maximum of 98.6 cm. The study was located quite close to the study sites of this project in comparison to the other published equations. Harrison et al. (2009) found a similar average difference from Gholz, (1979), i.e., 21%, as was found in this study of SMC sample trees (16-24%).

The trees sampled by Gholz et al. (1979) covered a wide breadth of unmanaged stands across western Oregon and Washington. The trees sampled by Jenkins et al., (2003) likewise covered a wide geographic distribution of unmanaged stands across the western North America. In contrast, the data from the SMC Type I sites were from intensively managed stands, a narrower range in tree size, but a wider multivariate range in dbh, height, and crown length relative to unmanaged stands. The data used to produce both the Gholz, (1979) and Jenkins et al., (2003) equations are a compilation of data from five and eleven separate studies, respectively, that include unmanaged stands of different ages, stand density and other conditions. All of the small diameter (1.8-19.0 cm) Douglas-fir trees included by Gholz, (1979) were from four sites in western Washington, where it is reasonable to assume the growth was more constrained due to

high densities and subsequent diameter growth reductions with the progression through stem exclusion which, explains the underestimation at lower diameters. The SMC study sites were managed to explore intensive density control and elimination of N limitations to maximize growth in both height and diameter. Their relative density was maintained at a level well below the point of self-thinning in most of the density regimes, and as a result their diameter growth was less constrained by stand density than unmanaged trees sampled by Gholz (1979). The largest trees (78-162 cm) were from Blue River, Oregon, and these trees of much larger diameter can reasonably be assumed to have had a higher height - diameter ratio than of the SMC trees. This was due to a higher density and reduced diameter growth, with relatively little effect on height growth. In short, the pooling of these data from unmanaged stand into equations based on diameter alone imply a consistent relationship between height and diameter that was probably reasonable for application to unmanaged stands but not representative of intensively managed Douglas-fir trees on the SMC Type I plots.

When diameter can be supplemented with height as a predictor of aboveground biomass, the results are typically more favorable because a constant height-diameter relationship is not assumed and because a given dbh-height combination implies live crown size; hence, the variability in tree dimensions and the implications for biomass content are more accurately accounted for (Vallet et al., 2006). Although of less dramatic effect, correlated differences in tree stem taper can be also be accounted for (Case and Hall, 2008). Increasing density can reduce dominant diameter growth, with relatively little effect on height growth except at extreme stand densities (Cremer et al., 1982;

Knowe, 1994, 1991; Omule et al., 1987; Wagner and Radosevich, 1991). Exceptions have been documented; for example, height growth was substantially reduced at high stand densities in the Wind River spacing trials (Reukema, 1979, 1970).

5.4.2 Estimates of felling and yarding losses of crown biomass

Each of the above ground biomass components varied between sites. For instance, mean removed whole tree biomass (Mg/ha) and coefficients of variation (%CV) were 31.9-45.1 (18.5-24.9% CV), 22.7-45.9 (13.7-24.9%CV), and 0.9-1.6 (9.7-18.9% CV) for sapwood, heartwood and ≥3-year-old foliage, respectively among sites. This variation in component mass leads to considerable variation in removed biomass even in the theoretical sense demonstrated in this study. The WT scenario will remove 24.9 (36.3% CV), 33.9 (32.6 %CV), 13.1 (18.8 %CV) and 17.5 (27.7%CV) more biomass (Mg/ha) than the BT scenario for the ET, FL and PC and RR sites, respectively. The WT scenario will remove 28.6 (30.0 %CV), 37.6 (25.1 %CV), 17.6 (11.3 %CV) and 20.6 (21.9 %CV) more biomass (Mg/ha) than the BO scenario for the ET, LF and PC and RR sites, respectively. The harvest scenarios have a wide range in total removed biomass; 33.7-100.4 (Mg/ha) (60.4 Mg/ha mean, 25.2 %CV), 36.0-103.9 (Mg/ha) (64.0 Mg/ha mean, 24.0 %CV), 45.8-151.12(Mg/ha) (83.7 Mg/ha mean, 28.4%CV) and 48.2-154.2(Mg/ha) (86.2 Mg/ha mean, 28.2%CV) under the BO, BT, VC and WT scenarios respectively. This estimated range in removed biomass indicates wide variation in logging residues, even across these idealized removal scenarios for a relatively narrow

range in stand types and ages (although probably wider range in silvicultural regimes that implemented operationally at present).

In addition to variation among sites, the relative quantity of the aboveground biomass forest residuals harvested varies with management objectives, logistical, operational and economic constraints. The type of harvesting system will dictate the slash pile distribution, size and probable composition. The contrasts in forest residue distribution between cable logging and ground based forest harvesting operations are very relevant to the quantity harvested and even the economic and logistical potential of harvest. In a cable logging operation slash piles will be substantially larger and consolidated at landings. Slash piles constructed during ground logging operations will be smaller, far more variable in size and in distribution throughout a unit, if they are present at all. Slash piles are generally absent in cut-to-length operation as slash is distributed within the unit. The large piles at the cable system landings would typically be far more accessible due to pile consolidation and road access than many of those scattered throughout a ground logged unit. The low recovery of residues (in some cases below 10% of available residues) suggested that conventional volume estimations may overestimate availability of forest-based residues for bioenergy production (Ralevic et al., 2010). This variability in supply is a function of both technical and economic harvest limitations and feedstock quality. Harvest limitations include technical and economic constraints such as terrain, equipment capabilities, harvest costs and market prices. Feedstock quality is determined by species mix, residue age, moisture content, harvest

method, as well as the amount of contaminants (dirt, rocks and trash) mixed with the wood.

The average percent of total aboveground biomass removed by each of the scenarios ranged from approximately 86% for merchantable stem harvesting to 92% for both partial crown harvesting scenarios. This estimate is best regarded as maximum potential removal because operational and logistical constraints inevitably lead to lower removals. Hazlett et al. (2014) found that tree length harvesting (merchantable bole) retained 72% of the harvested residue biomass on a site in comparison to the whole tree harvesting which removed 65% of the potentially available biomass calculated using preharvest stand data and theoretical harvest removals on 14 undisturbed sites.

Perhaps surprisingly, the operational biomass harvesting undertaken by Ralevic et al. (2010) removed a lower amount of potentially available biomass for the two mixed-wood stands (spruce–birch 44%, spruce–poplar 31%) than the operational full-tree harvesting in their study due to variation in location, condition and location of roads, harvest system type, supply chain adopted, residue contamination and moisture content. They also found after harvesting limitations and planned retentions (such as wildlife trees) were taken into consideration, 41% (41.2 ovendry Mg/ha) and 59% (99.1 Mg/ha) of total above-ground biomass were estimated to remain on site in two mixedwood blocks, and 25% (25.3 Mg/ha) in a black spruce block. Energy-wood harvests in a variety of forest types (softwood, mixed wood, hardwood) in Maine removed on average 55% of the potentially available residues (Briedis et al., 2011a). Together, these results, along with the wide range of removals of potentially available biomass from the Hazlett et al.'s

(2014) 14 sites (merchantable bole harvesting 0–70%, whole tree harvesting 10–90%) reinforce the fact that many factors can influence biomass recoverability (Dymond et al., 2010; Nurmi, 2007; Ralevic et al., 2010). As not all of the aboveground biomass is recoverable due to operational constraints and contamination, it represents a significant potential feedstock that is not left on forest cutovers to address soil nutrient, biodiversity and other ecosystem functions, but is instead piled at landings and roadsides. This is contrary to popular perceptions and beliefs that increasing bioenergy mandates and demand for forest residues will result in a "clearing" or "vacuuming" of all biomass from the forest floor. The operational limitations in collecting small, low-quality and dispersed fiber impose technical restrictions on the amount of fiber that can actually be removed. The remaining fiber contributes to ecosystem functions. Stand characteristics and conditions including species composition, age distribution, and biomass quality interact with technical factors such as equipment type, harvesting methods, and economic considerations to determine removals at any specific site. Forest management policies and guidelines for a variety of values also play a role in deciding what proportion of harvested residue biomass will be removed from any specific site (Hazlett et al., 2014).

In Finland, it is recommended that 30% of the logging residue nutrient content be left on site (Soimakallio et al., 2009). This is a conservative estimate based on logging residues on nutrient rich Norway spruce (*Picea abies*) stands consisting of primarily foliage and branches after harvest and needle drop. In jack pine forests in boreal forest one-third of the forest residuals would represent an average of 13 oven dry Mg ha^{-1} to be left on cutovers after harvest, slightly less than the 15 Mg ha^{-1} average that resulted from

operational full-tree harvesting. Briedis et al., (2011a) reported slightly lower debris retention of 30.3 m^3 ha^{-1} (estimated 11 Mg ha^{-1}) for four full-tree energy-wood harvested softwood stands in Maine. Under the assumptions of our study and taking into account the 25% biomass left behind in full tree harvesting of spruce in Relavic (2010), this relative amount was exceeded on all plots on the PC and RR sites under all scenarios, all plots harvested under the VC scenario on all sites and the majority of BT and BO scenarios on the ET and LF sites. On the ET site 57% (BT scenario) and 28% (BO scenario) and the LF site 43% (BT scenario) and 14% (BO scenario) of the plots were above this relative threshold of removed aboveground biomass. Over all SMC sites the maximum relative nutrient content removal estimated was 38% (35% mean), 36% (30% mean) and 98% (97% mean) for the BT, BO and VC, respectively.

5.4.3 Aboveground nutrients harvested

Total nutrients harvested varied by treatment and site for each scenario. Biomass and nutrients removed under each scenario increased in the following order BO<BT<VC<WT (Fig. 41, Table. 40). More biomass was not consistently harvested from fertilized plots than unfertilized plots. The percentage of nutrients harvested under each scenario varied by site and treatment due to site specific differences in available nutrients and a variety of stand characteristics. Each site has varying levels of total and available nutrients. Additionally, fertilization of N can lead to a change in nutrient concentrations in Douglas-fir. In general, sites with higher nutrient availability/productivity such as the LF site will grow faster and accumulate biomass

more quickly, unless additional stresses are inhibiting growth. This more rapid growth can cause a stand to reach the point of stem exclusion and site carrying capacity more quickly. The PC site actually has a higher site index than LF but is infected with SNC which lowers stand productivity (Perakis et al., 2006).

In addition to variations between sites, the total nutrient content in a stand varies with age, and therefore rotation lengths between harvests. Studies (Ponette et al., 2001; Ranger et al., 1995) of nutrient accumulation, allocation, and cycling across a chronosequence of stand development have shown 1) nutrient accumulation does not synchronized with biomass accumulation, with the accumulation rate of biomass being 3.3, 5.4, 3.3, 3.7, and 9. 8 times of that of N, P, K, Ca, and Mg from age 17 to 51 , respectively, 2) nutrient allocation to a specific component is related to the growth rate of the nutrient pool in the component, so that the nutrient allocation to stem as well as the ratio of nutrient allocation to root/shoot increased with plantation age, and 3) the biomass production per unit nutrient, i.e. , nutrient use efficiency, and the nutrient cycling coefficient also increases with age (Das and Ramakrishnan, 1987b) . For instance, in France decreases in rotation length of Douglas-fir from 60 to 40 years resulted in a slight decrease in the collected biomass (-0.8%) with no dramatic consequences on nutrient removal except for K; i.e., Na and P remained stable, Ca decreased (-17%), and increased for Mg (+15%) and K (+96%). The decrease in rotation length in the same study from 60 to 20 years produced more important effects. The biomass decreased by 51% without a proportional decrease for the majority of nutrients (except for Ca) and a severe increase for K (+82%). Decreasing the rotation length from 40 to 20 years produced

approximately the same effect as before except for K. Thinnings represented 14% of the biomass and between 15 and 20% of the nutrients according to elements in the standing crop for the 60-year old stand and 19% of the biomass and between 15 and 30% of the nutrients in the 40 year old stand (Ranger et al., 1995). The coastal PNW has rotations ranging from 38-50+ years (Adams et al., 2002) and the shorter rotations have the potential to remove proportionally higher quantities of K and potentially Mg. The increase in K removal is likely due to increased proportion of sapwood to heartwood with the decrease in rotation length and slow K weathering rates relative to uptake rates.

5.5 Soil nutrient pool

5.5.1 Total soil nutrients to one meter

Plants acquire nutrients from organic and mineral sources in plant available forms located predominately in the upper horizons (the organic (O) and surface mineral soil horizon (A)). Many nutrients are made available to plants as organic matter decomposes. The soil nutrient pool at each of the SMC installations comprised at least 99.0% of the total nutrient capital (sum of soil down to one meter and all aboveground tree biomass). The increased intensity of biomass removal can affect the quantity and composition of the surface organic layers by impacting the quantity and quality of forest residuals incorporated into soil organic matter with decomposition.

Soil organic matter improves soil structure, increases the cation exchange capacity, and improves soil moisture retention. In addition, decomposing organic matter is an important source of nutrients. In this study full-tree harvesting removed an average of 97 % of the potentially available aboveground biomass, which was 28% more than the

merchantable stem only harvests on the SMC plots. The results from this study are comparable to the those found by Hazlett et al., (2014) over 14 boreal forest sites in northern Ontario in which 95 and 65% of the aboveground biomass was removed for whole tree and merchantable harvest scenarios, respectively. The tree-length and whole tree biomass and nutrient removals were more similar than estimated in previous studies.

It is commonly thought that forest management practices that reduce site organic matter and nutrient pools will decrease forest productivity. Sustainable biomass removal and site nutrient retention depend on initial site quality, intensity of removal, rate of nutrient replenishment, and the balance of nutrient demand and supply during stand development (Burger, 2002; Foster, 1996). Variable responses to thick organic horizons were noted by Hazlett et al. (2014) because sandy sites with thin forest floor horizons (10-15 cm) responded positively to increased post-harvest soil C reserves, but organic matter accumulation became a detriment to increased growth for sites with thick forest floors. Many of the 45 North American Long-Term Soil Productivity (LTSP) installations investigated by Ponder et al (2012) for harvest related organic matter removal and soil compaction have not resulted in large losses in stand biomass productivity 10 years after harvest. However, considerable potential for declines still exists in the Ponder et al (2012) sites as most installations have not reached full canopy closure, maximum leaf area, and peak soil nutrient demand. When canopy closure is reached, a stabilization of the proportion of fine root biomass eventually occurs (Vogt et al., 1983). As a stand matures, the mineral soil is gradually depleted of nutrients, and a shift in intensive fine rooting is thought to occur, with fine roots becoming more

concentrated in the organic/upper mineral soil layers, and the type of fine root changing as well (Lalumière and Trofymow, 2011; Santantonio, et al., 1977).

Fine roots are very important to current soil functioning, but are often unaccounted for in input-output budgets as they are never removed. Fine roots are responsible for the bulk of nutrient and water acquisition. Fine roots are typically colonized by mycorrhizae which allows for more efficient soil exploration and acquisition of nutrients and water (Zangaro et al., 2008). According to Lalumière and Trofymow, (2011b) fine root system biomass can represent about 20% of the total stand biomass in Douglas-fir stands. Harvesting kills the root system of cut trees, so increases organic matter input to the soils, including both fine and coarse roots. However, fine roots on live trees also turnover and their input of organic matter into the soil can be substantial. Estimates of fine root and mycorrhizal turnover are as much as three times higher than that of foliage, branches, and boles combined (Fogel and Hunt, 1979). Gaudinski et al. (2010) estimate ~20% of fine root biomass has turnover times of about a year, and ~80% has decadal turnover times. In general, density and biomass of fine roots and mycorrhiza decrease with increasing soil depth (Curt et al., 2001; Grier et al., 1981; Harley, 1959; Kurz and Kimmins, 1987; Olsthoorn and Tiktak, 1991; Persson, 1980; Sainju and Good, 1993; Santantonio and Hermann, 1985; Sylvia and Jarstfer, 1997; Vogt et al., 1981) and most mycorrhizal roots occur in the organic litter layer or just below it (Jonsson et al., 2000; McMinn, 1963; Persson, 1980; Vanninen and Mäkelä, 1999). Fine root density and biomass decrease with decreasing soil nutrient concentrations (Curt et al., 2001; Sainju and Good, 1993), and trees on poor sites

generally allocate more of their biomass to fine roots and mycorrhizae than trees on richer sites (Haynes and Gower, 1995; Keyes and Grier, 1981; Klopatek, 2002; Kurz and Kimmins, 1987; Vanninen and Mäkelä, 1999; Vogt et al., 1983; Vogt et al., 1987). Root biomass or nutrient content was not addressed in the analysis of this study and will need to be further analyzed to assess the extent to which this source of organic matter and nutrients serve as a buffer to maintain site productivity under varying intensities of aboveground biomass removal. However, Ranger and Gelhaye (2001) found at a stand level the belowground compartment for Douglas-for stands in France had a nutrient content that amounted to 14.9, 11.8, 9.5, 14.1 and 11.8% of the N, P, K, Ca and Mg, respectively. Based on comparisons with other aspects of their study, the SMC stands likely have similar relative distributions of nutrients in their roots

5.5.2 Relative soil nutrient distribution

The suite of mechanisms that shape the vertical distribution of soil nutrients can be grouped in at least four major processes which will alter nutrient distribution with time: weathering, atmospheric deposition, leaching, and biological cycling (Trudgill, 1988). Anthropogenic processes affecting nutrients, such as increased removals with biomass harvesting, include compaction and physical redistribution. Weathering dissolution and atmospheric deposition affect the depth at which nutrient inputs occur (Kirby, 1985). Leaching and biological cycling influence the vertical transport of nutrients in opposite ways. Acting in isolation, leaching moves nutrients downward and may increase nutrient concentrations with depth. In contrast, biological cycling generally moves nutrients upwards because some proportion of the nutrients absorbed by plants are

transported aboveground and then recycled to the soil surface by litterfall and throughfall (Stark, 1994; Trudgill, 1988). Plant characteristics like tissue stoichiometry, biomass cycling rates, above- and belowground allocation, root distributions, and maximum rooting depth may all play an important role in shaping nutrient profiles (Jobbágy and Jackson, 2001).

Two opposing strategies help plants obtain scarce nutrients (Jobbágy and Jackson, 2001). The first is to develop a dense root system in the topsoil, exploring the zone of maximum accumulation and intercepting nutrients as they move downward by after mineralization from organic matter and leaching through the soil profile. Alternatively, plants that are able to grow roots below the zone of high depletion may obtain a source of nutrients with relatively little competition Numerous studies have shown that most roots are found in the upper 50 cm of soil, and most root activity and mycorrhizae in the top 20 cm depending on soil aeration, fertility, and organic matter distribution (Fogel, 1983, 1980). Mycorrhizae have a symbiotic relationship with root systems, especially fine roots, which nearly double the area accessible for nutrients of a given tree. Plant cycling exerts a dominant control on the vertical distribution of the most limiting elements for plants (Jobbágy and Jackson, 2001). As such plant cycling should produce nutrient distributions that are shallower or decrease with depth with time and increased soil development and weathering.

Jobbágy and Jackson (2001) explored extractable and exchangeable nutrient distributions in the top one meter of soil for more than 10,000 profiles (90% of which were from the U.S., the rest were from around the globe) and found the ranking of the

vertical distributions from shallowest to deepest in the following order: P > K > Ca > Mg > Na = Cl = SO_4. The vertical ranking of total nutrients of the SMC sites was slightly different: Ca>P>Mg. The vertical distribution of K was variable among plots. The SMC Type I sites had a contrasting pattern to that described by Jobbágy and Jackson (2001); the nutrients strongly cycled by plants, such as P and K, were not consistently more concentrated higher in the topsoil (upper 20 cm) than nutrients usually less limiting for plants. This contradiction could be explained by the intensive fertilization and the high nutrient content of other nutrients at the four SMC sites. The exceptions to this would be the vertical distribution of K on the LF site, Ca on the PC and RR sites and potentially N on the ET. Jobbágy and Jackson (2001) noted along a gradient of weathering-leaching intensity (Aridisols to Mollisols to Ultisols), that total base saturation decreased but the relative contribution of exchangeable K^+ to base saturation increased. The majority of the vertical nutrient distributions on the SMC installations are intermediate and will likely develop a higher relative nutrient content distribution in shallower depths as these highly productive sites become more nutrient limited and nutrients becomes more tightly cycled in the uppermost soil horizons.

In addition to plant cycling timber harvesting redistributes forest residuals in slash piles that act as ‘hot spots’ with fluxes of nutrients that vary with depth, timing, nutrient content and flow paths. Nutrients such as Ca and Mg differentiate in nutrient flux timing, depth, and content with N, P and Na. Johnson et al. (2014) found fluxes of Ca^{2+} and Mg^{2+} in the mineral soil after snowmelt in the spring to be much greater than during autumn precipitation. Removal of forest residuals will reduce the size or eliminate some

of these slash piles, or hotspots. Cable logging already arranges, or concentrates the forest residuals, into one large hotspot (slash pile) at a landing. Biomass harvesting is likely to remove this material from the landing once a satisfactorily low moisture content is reached (Johnson et al., 2014).

5.5.3 Stability ratio

Many long term productivity studies are situated on mesic sites, on recently glaciated soils with relatively high nutrient contents and/or replaced natural forests with substantial nutrient legacies on the forest floor (Ponder et al., 2012). The SMC sites are located in glacial outwash (ET site only) or on non-glaciated soils with a more developed soil profile than sites occurring on glacial outwash with a range of nutrient content and site productivity (Sucre et al., 2008). On older, less fertile and more nutrient depleted soils, and those with fewer nutrient reserves in the forest floor, organic matter removal may have a substantially greater impact on stand productivity, particularly over multiple rotations with fast-growing species (Bowen and Nambiar, 1984; Ponder et al., 2012). The typical rotation length for producing timber from coastal Douglas-fir forests ranges between 30-50 years, far longer than most woody species that are currently being harvested primarily for biomass and biofuel production. In all likelihood the increased intensity of harvesting of forest residuals will occur simultaneously or shortly after merchantable timber harvest on the typical rotation length. If the demand for biofuel feedstock increases the amount of logging slash that is brought out of the harvested

stands, particularly if it consists of more live crown components, a distinct possibility arises of decreasing long term site productivity on nutrient limited sites.

Evans (2009, 1999) proposed the "stability ratio" as a simple risk assessment tool by which many regional sites (Himes et al., 2014a) can be compared to identify those most susceptible to nutrient depletion. Site nutrient capital may be calculated in various ways, such as total soil nutrient content or soil plus aboveground nutrient content. Evans (2009, 1999) used a stability ratio of 0.1 (i.e., 10% of the site total) as an example of a harvest removal level below which he hypothesizes little or no risk to long-term productivity. A stability ratio of 0.3 potentially represents a significant risk to productivity, and a stability ratio of 0.5 potentially could result in a significant and immediate site productivity decline. At a full rotation of 50 years multiple risk thresholds would be exceeded on only the LF site in regards to K removals under the BT scenario on unfertilized plots (0.1), VC (0.16 and 0.18 SR) and WT (0.23 and 0.26 SR) scenarios on fertilized and unfertilized plots respectively (Table A8 in the Appendix). Based on the stability ratios of N, P, S, Ca, Mg, and the majority of K there is low risk of nutrient depletion and associated productivity loss under all harvest scenarios on similar Douglas-fir sites in western Oregon and Washington. On certain sites with high stability ratios, such as those for K on the LF site under the BT, VC and WT harvesting scenarios, additional nutrient conservation measures may be needed.

Biomass removal rate should be kept in balance with the ability of the site to replace adequate nutrients and organic matter for critical processes (i.e., nutrient cycling and maintenance of soil organic matter levels), as determined by natural and

supplemental nutrient input rates. Hazellett et al. (2014) found that metrics derived from nutrient budgets and the level of post-harvest soil C and nutrient reserves could be suitable indicators to assess site sensitivity to biomass removals; however, base cation stability ratios and nutrient replacement times gave differing interpretations as to which sites were most sensitive. It is important to note the soil nutrients collected in the Hazellett et al. (2014) study included only the top 20 cm of the soil profile, representing varying amounts of the total pools of different nutrients, as inferred from the variation in their vertical distribution in the soil profile as described above. The sustainability ratios for the SMC plots were calculated on the basis of soil depths of 1 meter, consistent with the methodology applied by (Himes et al., 2014).

These sustainability ratios are static and do not attempt to account for temporal variability in plant-available or total store of any given nutrient on the site. Inputs from atmospheric deposition, leaching off aboveground vegetation, leaching out of the soil profile, weathering of soil parent material, upward movement commensurate with hydraulic lifting, response mineralization rates to climatic fluctuations, and other processes influencing nutrient flux are not taken into account, primarily because of the complexity and spatial variability in many of these processes. Hazlett et al. (2014) has suggested that stability ratios are not a useful predictor of tree growth until a specific biomass removal threshold is reached. In their study on jack pine sites in Ontario, Canada, the threshold for excessive removal would require a removal of forest residuals greater that whole tree harvesting in addition to forest floor removal. Stability ratio and nutrient replacement time approaches present alternative paradigms for assessing site

sensitivity, but reliably estimating the latter is a huge scientific undertaking even at a single site. Regardless, stability ratios suggest that sites with a low nutrient pool, and significant amounts of that nutrient pool in aboveground biomass, are potentially more sensitive to harvest removal levels. If replacement times are more rapid than would be suggested by the current pools, then sites that otherwise have a high stability ratio may be less sensitive to harvest removal levels because nutrients removed from the site can be replenished at rate adequate for maintaining productivity. The best relationships identified by Hazlett et al. (2014) were for C and N, and C may be the most useful indicator because of its strong linkage to the overall pool of soil nutrients bound in organic matter (Bauhus et al., 2002; Seely et al., 2010), and likewise to organic matter removals under a given harvesting intensity. With considerations for soil texture, C distribution through the soil profile, and forest floor depth, post-harvest soil C reserves seem to have the greatest potential as soil-based indicators of potential impacts to long term site productivity.

The potential impact of whole-tree harvesting and forest harvest residue removal on soil productivity has been studied extensively (see reviews by Morris and Miller (1994), Burger (2002), overview by Lattimore et al. (2009) and meta-analyses and syntheses by Fleming et al. (2006), Page-Dumroese et al. (2000, 2006), and Powers et al. (2005). Forest harvesting machinery and biomass operations have the potential to influence soil physical structure through compaction and thus affect soil porosity, bulk density, and structure (Mann and Tolbert, 2000), all of which influence water holding capacity. In addition, the removal of organic matter in the form of harvest residues affects

the nutrient inputs to the soil, in turn influencing long term nutrient content, mineral soil carbon content, cation exchange capacity, and pH (Mann and Tolbert, 2000). Impacts to these two factors, soil porosity and soil organic matter, have been identified as the most likely mechanisms influencing long-term soil productivity (Mariani et al., 2006). Sites vary in their resilience to disturbance, depending not only on inherent site factors, including climate and soil properties (i.e., site quality), but also on the intensity of the forestry operation and site conditions at the time of harvesting disturbance.

5.6 Logistics and dispersion of forest residuals with different harvest techniques

Forest harvesting removes nutrients in biomass and, along with site preparation operations, removes or displaces nutrients contained in logging slash and the forest floor. The pattern and intensity of the nutrient and organic matter (forest residual) displacement and removal depends on the profitability of the operation, season of harvest, and site conditions, especially moisture content (%). Merchantability standards, harvest cost, and market prices usually determine the proportion of biomass that can be removed from forest stands economically.

The general trend to accomplish profitable biomass harvesting has been for an increasing proportion of stand biomass to be removed from the site during harvesting. This can cause increased soil disturbances such as compaction and additional nutrient loss in the removed biomass. The handling capability of harvesting machinery, along with the quality of logging residues and its value, will determine the removable quantity

of forest residuals based upon logistical and economic constraints. Furthermore, site conditions, accessibility, season and ground characteristics also influence the recovery methods that are adopted (Cormier and Ryans, 2006).

Factors that influence the quality of this potential feedstock are the species mix, residue age, moisture content, harvest method, as well as the amount of dirt, rocks and other contaminants of poor feedstock quality mixed with the wood. These strongly influence the particle size distribution, bulk and energy density, and noncombustible ash content of forest residuals. Woody biomass moisture content after felling is dependent on post-harvest handling, storage conditions, material size, pile structure, baseline moisture content, and seasonal climatic patterns (Kim and Murphy, 2013). In the Pacific Northwest, the forest harvesting operations from which forest residues are utilized are typically fully mechanized. Processing of whole trees into logs also occurs at roadside. In some operations small end-dumping off-highway trucks are used to transport unprocessed residues from difficult access locations to a centralized landing (Zamora Cristales, 2013). Cable logging operations collect forest residues in a few large piles exclusively at landings, effectively removing large quantities of organic matter from the majority of the site. In these systems, the roadside residues are chipped or hogged with a chipper or horizontal grinder and discharged into a van. In cut-to-length (CTL) systems, the trees are delimbed and bucked at the stump, leaving the harvest residues throughout the stand. Recovering forest residues in is expensive, time consuming and inefficient. The residues must then be forwarded to roadside before being comminuted (Ralevic et al., 2008; Stokes, 1992).

5.7 Study Limitations

There are several limitations to the results of this study, including the multiple variance components that result from hierarchical sampling of biomass components and their nutrient concentrations. Likewise, assessing the sustainability of feedstock production and more comprehensively the net primary production of a forest stand requires detailed knowledge about the soil and climatic dynamics, and the ecophysiological processes that integrate soil and climatic factors to result in the production of the organic matter that we refer to as biomass.

With regard to statistical and estimation issues, the forced additivity approach used in this study (Cunia and Briggs, 1984) optimizes the system of equations for estimating total biomass and its components. However, correlations among the residuals of biomass components were not considered. Because errors in estimating biomass components are correlated, i.e., over-estimates in one component often are associated with under- or over-estimates in other components, the system can give biased and inconsistent predictions (Carvalho and Parresol, 2003). Utilizing the non-linear seemingly unrelated regression (NSUR) as described by Parresol (2001) would address this statistical issue and should yield narrower prediction and confidence intervals. However, the model would need to be a simplified version of the one [15] in this study for current statistical program algorithms to converge on parameter estimates.

The estimates of biomass removal from this study are theoretical and likely overestimated under the whole-tree (WT) and partial crown loss (VC) scenarios relative

to the amounts actually removed for biofuel production. However the scenarios assessed clearly represent the two extremes in regard to minimal and maximal amounts of biomass removal from the SMC plots analyzed. Also, the four SMC installations sampled represent relatively high productivity sites in for Douglas-fir in the PNW. However, these types of sites are those from which biofuel feedstock is most likely to be collected due first to the amount of logging residues that should be available relative to less productive sites, and due second to the fact that these sites are least likely to be adversely impacted by the additional nutrient removal. Time of harvest, stand age and soil mineralogy have been found to influence stability ratios and nutrient replacement times across site gradients. In addition, increased intensity of removal of forest residuals has variable effects on stand growth. On sites with limited P, for example, long term productivity may be diminished.

The "stability ratio" derived in this study is a static ratio and gives and approximation of sustainability. Evans (1999) readily admits that the guidelines provided are most effectively calibrated when the threshold of overharvesting has been crossed on a similar site. The ratio does not address nutrient availability, which, depending on the nutrient, can only be estimated by prior or acquired measurements of mineralization rates from organic matter, parent material weathering rates and/or atmospheric input rates. The measure of total soil nutrients documented in this study can be used as a basis for inferences on long term nutrient status, however the flux of plant available nutrients will need quantification in the future to determine sustainability with any level of reliability. Hazlett et al. (2014) demonstrated that metrics derived from nutrient budgets and levels

of post-harvest soil C and nutrient reserves could be suitable indicators to assess site sensitivity to biomass removals, although base cation stability ratios and nutrient replacement times gave differing interpretations as to which sites were most sensitive. With considerations for soil texture and forest floor depth, soil-based indicators such as post-harvest soil C reserves seem to have the greatest potential as indicators of impacts on sustainability of biomass removals and long-term site productivity. Improved estimates of actual forest residuals are necessary to calibrate the results of this study for application to forest inventories and to assist foresters with calculating forest residual potentially available for utilization. With these estimates more accurate assessments of impacts on inputs to site organic matter and soil C, and corresponding impacts on site nutrient reserves will be possible.

6 Conclusion

The live crown biomass of coastal Douglas-fir contains a disproportionately large amount of some nutrients (Ca, Mn, N), as has been documented in this and many other species. This concentration of nutrients in the portion of the tree that is typically left unharvested on the site has no doubt contributed to the impressive continued productivity of second- and third-generation Douglas-fir forests. Conversely, removal of this material for biofuel feedstock production raises concerns about long term site productivity and the sustainability of the practice of substituting fossil fuels with renewable biofuels produced from logging residues. Of particular concern is any increase in removal of crown biomass that might be evoked by increasing demand for biofuel feedstock. The

equations developed in this study for intensively managed Douglas-fir stands should provide significantly more accurate estimates of nutrient removals under varying levels of biomass removal. Based on a review of the literature, use of previous equations likely overestimate actual whole tree harvest removals by 25-30%.

The relative distribution of biomass and nutrient content was relatively consistent among sites. However, total amounts of biomass and total nutrient content varied by site due to differences in age, site quality, and resulting size of the trees. The patterns in biomass and nutrient content found on the SMC plots were similar to other results in the literature, and differences could be explained by variation in stand dynamics, site conditions and management. Unsurprisingly, there were greater differences with estimates from unmanaged stands due to variations in the combinations of height, diameter, and crown length.

Based on the stability ratios and nutrient ratios from this study, negative impacts to long term site productivity from higher intensity of logging residue removals of forest residuals should be minimal on a typical (30-50 year) rotation in coastal Douglas-fir. However, the ratio is a static indicator and the soils data do not take into account availability of nutrients or the inputs and outputs to that pool. A more accurate picture of the impacts to long term site productivity will require a deeper understanding of the variability in the rates of atmospheric deposition, leaching, parent material weathering, organic matter mineralization and changes in organic matter deposition resulting from shifts in harvesting operations.

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8 Appendix

8.1 Sampled Tree Mass

Table A1. Count of branches with foliage of a given age by site.

Site	Foliage Age									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
ET	159	168	164	158	148	117	96	68	36	11
LF	168	166	154	137	105	90	30	14	8	5
PC	175	176	165	135	97	75	15	2		
RR	168	167	165	143	117	85	33			

Table A2. Relative amount (%) of aboveground biomass contributed by each component for each of four SMC Type I installations.

Component	Site	Biomass (%)			
		Mean	Min	Max	Stdv.
SAP	ET	43.6	23.5	58.8	7.3
SAP	LF	41.1	34.9	54.2	5.6
SAP	PC	45.8	38.4	53.0	3.3
SAP	RR	43.5	36.1	52.1	4.2
HEART	ET	35.9	24.0	42.2	4.9
HEART	LF	37.8	26.6	44.2	4.8
HEART	PC	31.2	27.1	37.0	2.3
HEART	RR	34.5	29.8	39.3	2.7
BARK	ET	12.6	8.8	30.8	4.5
BARK	LF	13.7	9.5	19.0	2.4
BARK	PC	13.7	7.5	18.2	2.7
BARK	RR	13.5	9.8	16.1	1.8
FOL	ET	4.8	1.5	7.4	1.3
FOL	LF	4.2	1.9	7.9	1.5
FOL	PC	11.7	1.6	76.5	18.5
FOL	RR	5.5	3.2	10.3	2.0
LIVE BR	ET	3.5	1.3	5.2	0.9
LIVE BR	LF	3.7	1.8	6.7	1.2
LIVE BR	PC	7.1	1.6	41.8	10.4
LIVE BR	RR	3.5	2.0	6.4	1.3

Table A3. Relative amount (%) of live crown biomass contributed by each component for each of four SMC Type I installations.

Component	Site	Biomass (%)			
		Mean	Min.	Max.	Stdv.
FOL1	ET	15.4	12.0	24.9	3.0
FOL1	LF	21.2	17.7	25.6	2.2
FOL1	PC	28.9	21.7	34.7	3.3
FOL1	RR	25.9	19.7	35.0	3.7
FOL2	ET	12.4	10.7	15.0	1.2
FOL2	LF	13.5	11.4	16.0	1.3
FOL2	PC	14.6	11.1	16.1	1.0
FOL2	RR	15.5	13.4	16.6	1.0
FOL3	ET	29.6	14.0	35.2	4.8
FOL3	LF	18.1	14.5	22.1	2.1
FOL3	PC	17.1	6.5	26.3	4.2
FOL3	RR	19.9	14.1	25.4	2.6
LIVE BR	ET	42.7	40.4	46.1	1.3
LIVE BR	LF	47.2	44.2	49.5	1.4
LIVE BR	PC	39.3	35.0	48.7	2.9
LIVE BR	RR	38.7	35.7	39.7	0.9

8.3 Nutrient concentration and content

Table A4. Weighted mean nutrient concentrations from 2011 applied to 2011 SMC tree lists. 1-year-old foliage (FOL1), 2-year-old foliage (FOL2), ≥3-year-old foliage (FOL1), live branches (LIVE), bark (BARK), sapwood (SAP) and heartwood (HEART), are presented for each of the four sites.

Nutrient	Site	Component	Mean	Min	Max	SE	Mean	Min	Max	SE
			Fertilized				*Unfertilized*			
B	ET	BK	4.6E-06	4.6E-06	4.6E-06	4.5E-07	5.5E-06	5.5E-06	5.5E-06	2.3E-07
B	ET	DEAD	1.4E-06	1.4E-06	1.4E-06	4.7E-07	2.1E-06	2.1E-06	2.1E-06	4E-07
B	ET	FOL1	4.4E-06	4.4E-06	4.4E-06	1.2E-06	7.2E-06	7.2E-06	7.2E-06	1.2E-06
B	ET	FOL2	3.6E-06	3.6E-06	3.6E-06	7.4E-07	6.1E-06	6.1E-06	6.1E-06	1.2E-06
B	ET	FOL3	3.7E-06	3.7E-06	3.7E-06	7.7E-07	5E-06	5E-06	5E-06	8.8E-07
B	ET	HRT	2.4E-06	2.4E-06	2.4E-06	1.3E-06	1.2E-06	1.2E-06	1.2E-06	1.3E-07
B	ET	LIVE BR	1.9E-06	1.9E-06	1.9E-06	2.2E-07	2E-06	2E-06	2E-06	2.9E-07
B	ET	SAP	5.2E-07	5.2E-07	5.2E-07	7E-08	6.1E-07	6.1E-07	6.1E-07	1.8E-07
B	LF	BK	5E-06	5E-06	5E-06	3.8E-07	5.6E-06	5.6E-06	5.6E-06	6E-07
B	LF	DEAD	2.1E-06	2.1E-06	2.1E-06	4.6E-07	9.7E-07	9.7E-07	9.7E-07	2E-07
B	LF	FOL1	8.1E-06	8.1E-06	8.1E-06	8.6E-07	6.5E-06	6.5E-06	6.5E-06	2.5E-07
B	LF	FOL2	4.1E-06	4.1E-06	4.1E-06	2.1E-07	4.7E-06	4.7E-06	4.7E-06	4.3E-07
B	LF	FOL3	3.5E-06	3.5E-06	3.5E-06	3.7E-07	3.7E-06	3.7E-06	3.7E-06	3.3E-07
B	LF	HRT	6E-07	6E-07	6E-07	5.4E-07	4.3E-07	4.3E-07	4.3E-07	3.8E-07
B	LF	LIVE BR	2.4E-06	2.4E-06	2.4E-06	2.9E-07	2.3E-06	2.3E-06	2.3E-06	4.7E-07
B	LF	SAP	8.4E-07	8.4E-07	8.4E-07	9.5E-07	6.4E-07	6.4E-07	6.4E-07	3.6E-07
B	PC	BK	6.3E-06	6.3E-06	6.3E-06	4.8E-07	5.9E-06	5.9E-06	5.9E-06	4.5E-07
B	PC	DEAD	3.6E-06	3.6E-06	3.6E-06	6.4E-07	3.9E-06	3.9E-06	3.9E-06	6.8E-07
B	PC	FOL1	1.2E-05	1.2E-05	1.2E-05	1.3E-06	8.6E-06	8.6E-06	8.6E-06	6.3E-07
B	PC	FOL2	7.8E-06	7.8E-06	7.8E-06	1.1E-06	9.9E-06	9.9E-06	9.9E-06	1.5E-06
B	PC	FOL3	5.8E-06	5.8E-06	5.8E-06	8.6E-07	8.6E-06	8.6E-06	8.6E-06	1.3E-06
B	PC	HRT	2.4E-06	2.4E-06	2.4E-06	5E-07	2.2E-06	2.2E-06	2.2E-06	4.5E-07
B	PC	LIVE BR	4.8E-06	4.8E-06	4.8E-06	5.7E-07	4E-06	4E-06	4E-06	4.8E-07
B	PC	SAP	1.9E-06	1.9E-06	1.9E-06	4.2E-07	2.4E-06	2.4E-06	2.4E-06	3.1E-07
B	RR	BK	5.6E-06	5.6E-06	5.6E-06	2.8E-07	5.8E-06	5.8E-06	5.8E-06	2.3E-07
B	RR	DEAD	2.1E-06	2.1E-06	2.1E-06	2.1E-07	3.2E-06	3.2E-06	3.2E-06	1.1E-06
B	RR	FOL1	1.4E-05	1.4E-05	1.4E-05	1.3E-06	1.6E-05	1.6E-05	1.6E-05	1.7E-06
B	RR	FOL2	7.7E-06	7.7E-06	7.7E-06	6.4E-07	1.1E-05	1.1E-05	1.1E-05	1.6E-06
B	RR	FOL3	6.9E-06	6.9E-06	6.9E-06	5.5E-07	8.4E-06	8.4E-06	8.4E-06	7.3E-07
B	RR	HRT	1.7E-06	1.7E-06	1.7E-06	3.2E-07	2E-06	2E-06	2E-06	2.4E-07
B	RR	LIVE BR	2.3E-06	2.3E-06	2.3E-06	3.7E-07	2.2E-06	2.2E-06	2.2E-06	3.4E-07
B	RR	SAP	1.7E-06	1.7E-06	1.7E-06	3.7E-07	1.7E-06	1.7E-06	1.7E-06	2.1E-07
Ca	ET	BK	1.00E-03	1.00E-03	1.00E-03	3.00E-04	1.36E-03	1.36E-03	1.36E-03	4.03E-04
Ca	ET	DEAD	8.55E-04	8.55E-04	8.55E-04	4.67E-04	1.58E-03	1.58E-03	1.58E-03	5.48E-04
Ca	ET	FOL1	2.56E-03	2.56E-03	2.56E-03	2.12E-04	2.63E-03	2.63E-03	2.63E-03	1.91E-04
Ca	ET	FOL2	3.56E-03	3.56E-03	3.56E-03	1.48E-04	3.57E-03	3.57E-03	3.57E-03	2.30E-04
Ca	ET	FOL3	4.19E-03	4.19E-03	4.19E-03	3.97E-04	4.03E-03	4.03E-03	4.03E-03	2.67E-04
Ca	ET	HRT	3.50E-04	3.50E-04	3.50E-04	1.24E-04	1.06E-04	1.06E-04	1.06E-04	2.32E-05
Ca	ET	LIVE BR	1.04E-03	1.04E-03	1.04E-03	2.52E-04	4.37E-04	4.37E-04	4.37E-04	3.92E-04
Ca	ET	SAP	2.13E-04	2.13E-04	2.13E-04	6.90E-05	2.21E-04	2.21E-04	2.21E-04	5.22E-05
Ca	LF	BK	2.19E-03	2.19E-03	2.19E-03	2.31E-04	1.63E-03	1.63E-03	1.63E-03	3.79E-04
Ca	LF	DEAD	1.83E-03	1.83E-03	1.83E-03	2.50E-04	1.44E-03	1.44E-03	1.44E-03	4.17E-04
Ca	LF	FOL1	2.59E-03	2.59E-03	2.59E-03	2.93E-04	2.67E-03	2.67E-03	2.67E-03	1.12E-04
Ca	LF	FOL2	3.39E-03	3.39E-03	3.39E-03	3.59E-04	3.57E-03	3.57E-03	3.57E-03	1.23E-04
Ca	LF	FOL3	4.36E-03	4.36E-03	4.36E-03	4.07E-04	4.39E-03	4.39E-03	4.39E-03	2.86E-04
Ca	LF	HRT	2.94E-04	2.94E-04	2.94E-04	8.45E-05	6.12E-04	6.12E-04	6.12E-04	2.83E-04
Ca	LF	LIVE BR	1.12E-03	1.12E-03	1.12E-03	7.88E-05	1.22E-03	1.22E-03	1.22E-03	1.80E-04

Table A4.Continued…

Nutrient	Site	Component	Mean	Min	Max	SE	Mean	Min	Max	SE
			Fertilized				*Unfertilized*			
Ca	LF	SAP	0.00042	0.00042	0.00042	3.6E-05	0.00069	0.00069	0.00069	0.00021
Ca	PC	BK	0.00174	0.00174	0.00174	0.00022	0.00167	0.00167	0.00167	0.0002
Ca	PC	DEAD	0.00194	0.00194	0.00194	0.00026	0.00151	0.00151	0.00151	0.00027
Ca	PC	FOL1	0.00185	0.00185	0.00185	0.00011	0.00153	0.00153	0.00153	0.00017
Ca	PC	FOL2	0.00249	0.00249	0.00249	0.00015	0.00233	0.00233	0.00233	0.00023
Ca	PC	FOL3	0.00303	0.00303	0.00303	0.00026	0.00258	0.00258	0.00258	0.00029
Ca	PC	HRT	0.00052	0.00052	0.00052	0.00013	0.0005	0.0005	0.0005	8.9E-05
Ca	PC	LIVE BR	0.00135	0.00135	0.00135	0.00025	0.00175	0.00175	0.00175	0.00029
Ca	PC	SAP	0.00046	0.00046	0.00046	8.3E-05	0.00058	0.00058	0.00058	0.00011
Ca	RR	BK	0.00247	0.00247	0.00247	0.00034	0.00203	0.00203	0.00203	0.00017
Ca	RR	DEAD	0.00117	0.00117	0.00117	0.00023	0.00162	0.00162	0.00162	0.00066
Ca	RR	FOL1	0.00378	0.00378	0.00378	0.00035	0.00266	0.00266	0.00266	0.00015
Ca	RR	FOL2	0.00478	0.00478	0.00478	0.00035	0.00352	0.00352	0.00352	0.00027
Ca	RR	FOL3	0.0061	0.0061	0.0061	0.00048	0.00528	0.00528	0.00528	0.00043
Ca	RR	HRT	0.00044	0.00044	0.00044	0.00019	0.00031	0.00031	0.00031	0.00014
Ca	RR	LIVE BR	0.00105	0.00105	0.00105	0.00011	0.00093	0.00093	0.00093	0.00015
Ca	RR	SAP	0.00036	0.00036	0.00036	1.4E-05	0.00044	0.00044	0.00044	6.6E-05
Cu	ET	BK	3.8E-06	3.8E-06	3.8E-06	5.3E-07	4.2E-06	4.2E-06	4.2E-06	5.5E-07
Cu	ET	DEAD	3E-06	3E-06	3E-06	7.8E-07	3.9E-06	3.9E-06	3.9E-06	7.3E-07
Cu	ET	FOL1	3.7E-06	3.7E-06	3.7E-06	3.3E-07	3.9E-06	3.9E-06	3.9E-06	2.5E-07
Cu	ET	FOL2	4.7E-06	4.7E-06	4.7E-06	2.8E-06	3.5E-06	3.5E-06	3.5E-06	2.3E-07
Cu	ET	FOL3	6.4E-06	6.4E-06	6.4E-06	1.8E-06	3.5E-06	3.5E-06	3.5E-06	1.9E-07
Cu	ET	HRT	2.2E-06	2.2E-06	2.2E-06	6.8E-07	2.4E-06	2.4E-06	2.4E-06	2.4E-07
Cu	ET	LIVE BR	4.4E-06	4.4E-06	4.4E-06	6.8E-07	3.1E-06	3.1E-06	3.1E-06	5.7E-07
Cu	ET	SAP	1.9E-06	1.9E-06	1.9E-06	6.3E-07	2.3E-06	2.3E-06	2.3E-06	4.4E-07
Cu	LF	BK	4.3E-06	4.3E-06	4.3E-06	4.6E-07	3.7E-06	3.7E-06	3.7E-06	2.6E-07
Cu	LF	DEAD	4.5E-06	4.5E-06	4.5E-06	1.3E-06	2.1E-06	2.1E-06	2.1E-06	6.2E-07
Cu	LF	FOL1	4.8E-06	4.8E-06	4.8E-06	4.7E-07	1.3E-05	1.3E-05	1.3E-05	8.9E-06
Cu	LF	FOL2	3.5E-06	3.5E-06	3.5E-06	7.7E-08	3.8E-06	3.8E-06	3.8E-06	1.8E-07
Cu	LF	FOL3	4.9E-06	4.9E-06	4.9E-06	2.1E-07	4E-06	4E-06	4E-06	2.1E-07
Cu	LF	HRT	8.3E-07	8.3E-07	8.3E-07	4.1E-07	7.7E-07	7.7E-07	7.7E-07	2.9E-07
Cu	LF	LIVE BR	2.6E-06	2.6E-06	2.6E-06	3.4E-07	3.4E-06	3.4E-06	3.4E-06	3.8E-07
Cu	LF	SAP	1.4E-06	1.4E-06	1.4E-06	3.7E-07	1.3E-06	1.3E-06	1.3E-06	3E-07
Cu	PC	BK	5.1E-06	5.1E-06	5.1E-06	2.9E-07	4.1E-06	4.1E-06	4.1E-06	5E-07
Cu	PC	DEAD	4.3E-06	4.3E-06	4.3E-06	2.7E-07	3.4E-06	3.4E-06	3.4E-06	3.5E-07
Cu	PC	FOL1	2.9E-06	2.9E-06	2.9E-06	2.2E-07	3.3E-06	3.3E-06	3.3E-06	3.9E-07
Cu	PC	FOL2	5.9E-06	5.9E-06	5.9E-06	2.2E-06	2.6E-06	2.6E-06	2.6E-06	1.7E-07
Cu	PC	FOL3	2.8E-06	2.8E-06	2.8E-06	2.4E-07	2.9E-06	2.9E-06	2.9E-06	1.9E-07
Cu	PC	HRT	3.3E-06	3.3E-06	3.3E-06	4.2E-07	1.9E-06	1.9E-06	1.9E-06	2.2E-07
Cu	PC	LIVE BR	5.1E-06	5.1E-06	5.1E-06	4.3E-07	4.7E-06	4.7E-06	4.7E-06	5.2E-07
Cu	PC	SAP	2.9E-06	2.9E-06	2.9E-06	2.1E-07	1.8E-06	1.8E-06	1.8E-06	2.7E-07
Cu	RR	BK	3.7E-06	3.7E-06	3.7E-06	1.5E-07	4E-06	4E-06	4E-06	6.3E-07
Cu	RR	DEAD	1.5E-06	1.5E-06	1.5E-06	3.2E-07	1.9E-06	1.9E-06	1.9E-06	2.7E-07
Cu	RR	FOL1	4E-06	4E-06	4E-06	8.7E-08	3.7E-06	3.7E-06	3.7E-06	1.9E-07
Cu	RR	FOL2	4.2E-06	4.2E-06	4.2E-06	1.7E-07	4.1E-06	4.1E-06	4.1E-06	2.2E-07
Cu	RR	FOL3	4E-06	4E-06	4E-06	2.5E-07	4.4E-06	4.4E-06	4.4E-06	2.2E-07
Cu	RR	HRT	7.8E-07	7.8E-07	7.8E-07	1.4E-07	2.5E-07	2.5E-07	2.5E-07	1.7E-07

Table A4.Continued…

Nutrient	Site	Component	Mean	Min	Max	SE	Mean	Min	Max	SE
			Fertilized				*Unfertilized*			
Cu	RR	LIVE BR	2.2E-06	2.2E-06	2.2E-06	3.6E-07	2.5E-06	2.5E-06	2.5E-06	2.1E-07
Cu	RR	SAP	8.4E-07	8.4E-07	8.4E-07	1.1E-07	2E-07	2E-07	2E-07	4.1E-08
Fe	ET	BK	0.00067	0.00067	0.00067	0.00029	0.00073	0.00073	0.00073	0.00034
Fe	ET	DEAD	0.00053	0.00053	0.00053	0.00028	0.00072	0.00072	0.00072	0.00032
Fe	ET	FOL1	3.6E-05	3.6E-05	3.6E-05	7.2E-06	5E-05	5E-05	5E-05	5.3E-06
Fe	ET	FOL2	5.3E-05	5.3E-05	5.3E-05	5.6E-06	7.1E-05	7.1E-05	7.1E-05	2.3E-05
Fe	ET	FOL3	6.8E-05	6.8E-05	6.8E-05	6.7E-06	6.9E-05	6.9E-05	6.9E-05	9.6E-06
Fe	ET	HRT	3.2E-05	3.2E-05	3.2E-05	2.2E-05	5.4E-05	5.4E-05	5.4E-05	2.4E-05
Fe	ET	LIVE BR	0.00026	0.00026	0.00026	0.00016	0.00104	0.00104	0.00104	0.00031
Fe	ET	SAP	0.00016	0.00016	0.00016	5.6E-05	0.00012	0.00012	0.00012	4.6E-05
Fe	LF	BK	2.3E-05	2.3E-05	2.3E-05	9.1E-06	0.00051	0.00051	0.00051	0.00031
Fe	LF	DEAD	7.7E-05	7.7E-05	7.7E-05	3.5E-05	0.00016	0.00016	0.00016	0.00013
Fe	LF	FOL1	5.7E-05	5.7E-05	5.7E-05	7.6E-06	4.7E-05	4.7E-05	4.7E-05	5E-06
Fe	LF	FOL2	7.3E-05	7.3E-05	7.3E-05	6.1E-06	6.4E-05	6.4E-05	6.4E-05	6.9E-06
Fe	LF	FOL3	9E-05	9E-05	9E-05	9.1E-06	7.8E-05	7.8E-05	7.8E-05	9E-06
Fe	LF	HRT	1.1E-05	1.1E-05	1.1E-05	5.8E-06	5.3E-05	5.3E-05	5.3E-05	3.1E-05
Fe	LF	LIVE BR	6.3E-06	6.3E-06	6.3E-06	1.8E-06	2E-05	2E-05	2E-05	5.1E-06
Fe	LF	SAP	5.7E-06	5.7E-06	5.7E-06	2.8E-06	7.5E-05	7.5E-05	7.5E-05	4.2E-05
Fe	PC	BK	2.3E-05	2.3E-05	2.3E-05	2.3E-06	2.7E-05	2.7E-05	2.7E-05	3.8E-06
Fe	PC	DEAD	3.1E-05	3.1E-05	3.1E-05	9.1E-06	3.9E-05	3.9E-05	3.9E-05	1.2E-05
Fe	PC	FOL1	3.5E-05	3.5E-05	3.5E-05	4.7E-06	5.1E-05	5.1E-05	5.1E-05	1.1E-05
Fe	PC	FOL2	3.5E-05	3.5E-05	3.5E-05	2.4E-06	6.3E-05	6.3E-05	6.3E-05	1.7E-05
Fe	PC	FOL3	3.6E-05	3.6E-05	3.6E-05	2E-06	8.8E-05	8.8E-05	8.8E-05	3.8E-05
Fe	PC	HRT	1.3E-05	1.3E-05	1.3E-05	3.1E-06	1.5E-05	1.5E-05	1.5E-05	2.1E-06
Fe	PC	LIVE BR	9.9E-06	9.9E-06	9.9E-06	2.2E-06	1.2E-05	1.2E-05	1.2E-05	1.8E-06
Fe	PC	SAP	1.2E-05	1.2E-05	1.2E-05	2.4E-06	1.9E-05	1.9E-05	1.9E-05	3.4E-06
Fe	RR	BK	6E-05	6E-05	6E-05	1.3E-05	3.1E-05	3.1E-05	3.1E-05	5.8E-06
Fe	RR	DEAD	4.5E-05	4.5E-05	4.5E-05	2.7E-05	8.4E-05	8.4E-05	8.4E-05	4.9E-05
Fe	RR	FOL1	5E-05	5E-05	5E-05	6.8E-06	6.3E-05	6.3E-05	6.3E-05	5.5E-06
Fe	RR	FOL2	6.2E-05	6.2E-05	6.2E-05	7E-06	9.5E-05	9.5E-05	9.5E-05	1.8E-05
Fe	RR	FOL3	7.4E-05	7.4E-05	7.4E-05	1.1E-05	0.00012	0.00012	0.00012	3.2E-05
Fe	RR	HRT	1.4E-05	1.4E-05	1.4E-05	4.8E-06	2.2E-05	2.2E-05	2.2E-05	3E-05
Fe	RR	LIVE BR	1.2E-05	1.2E-05	1.2E-05	3.2E-06	9E-06	9E-06	9E-06	3.9E-06
Fe	RR	SAP	2.5E-05	2.5E-05	2.5E-05	1E-05	1.3E-05	1.3E-05	1.3E-05	8.9E-06
K	ET	BK	0.00202	0.00202	0.00202	9.1E-05	0.00263	0.00263	0.00263	0.00014
K	ET	DEAD	0.00029	0.00029	0.00029	0.00015	0.00024	0.00024	0.00024	9.1E-05
K	ET	FOL1	0.00508	0.00508	0.00508	0.00053	0.00593	0.00593	0.00593	0.0004
K	ET	FOL2	0.00396	0.00396	0.00396	0.00027	0.00475	0.00475	0.00475	0.0002
K	ET	FOL3	0.00389	0.00389	0.00389	0.00027	0.00407	0.00407	0.00407	0.00011
K	ET	HRT					5.4E-06	5.4E-06	5.4E-06	
K	ET	LIVE BR	0.00077	0.00077	0.00077	6E-05	0.00095	0.00095	0.00095	8.5E-05
K	ET	SAP	0.00029	0.00029	0.00029	2.1E-05	0.00033	0.00033	0.00033	1.7E-05
K	LF	BK	0.0018	0.0018	0.0018	0.00018	0.00194	0.00194	0.00194	0.0001
K	LF	DEAD	0.00025	0.00025	0.00025	6.2E-05	5.8E-05	5.8E-05	5.8E-05	3.1E-05
K	LF	FOL1	0.00347	0.00347	0.00347	0.00025	0.0037	0.0037	0.0037	0.00048
K	LF	FOL2	0.0035	0.0035	0.0035	0.00027	0.00364	0.00364	0.00364	0.00026
K	LF	FOL3	0.00301	0.00301	0.00301	0.00021	0.00315	0.00315	0.00315	0.00025

Table A4.Continued…

Nutrient	Site	Component	Mean	Min	Max	SE	Mean	Min	Max	SE
			Fertilized				*Unfertilized*			
K	LF	HRT	2.1E-06	2.1E-06	2.1E-06	NA				
K	LF	LIVE BR	0.00078	0.00078	0.00078	8.1E-05	0.00082	0.00082	0.00082	5.9E-05
K	LF	SAP	0.00027	0.00027	0.00027	4.1E-05	0.00029	0.00029	0.00029	2.5E-05
K	PC	BK	0.00158	0.00158	0.00158	0.00013	0.002	0.002	0.002	0.00013
K	PC	DEAD	0.00026	0.00026	0.00026	0.00014	0.00021	0.00021	0.00021	8.4E-05
K	PC	FOL1	0.00516	0.00516	0.00516	0.0002	0.00565	0.00565	0.00565	0.00034
K	PC	FOL2	0.00476	0.00476	0.00476	0.00026	0.00519	0.00519	0.00519	0.00045
K	PC	FOL3	0.00379	0.00379	0.00379	0.00027	0.00447	0.00447	0.00447	0.00032
K	PC	HRT	2E-06	2E-06	2E-06		8.2E-07	8.2E-07	8.2E-07	
K	PC	LIVE BR	0.0008	0.0008	0.0008	0.00012	0.00115	0.00115	0.00115	9.2E-05
K	PC	SAP	0.00029	0.00029	0.00029	3.9E-05	0.00033	0.00033	0.00033	3.5E-05
K	RR	BK	0.00148	0.00148	0.00148	0.00016	0.00144	0.00144	0.00144	0.00013
K	RR	DEAD	0.00016	0.00016	0.00016	4.2E-05	0.00038	0.00038	0.00038	0.00016
K	RR	FOL1	0.00365	0.00365	0.00365	0.00026	0.00429	0.00429	0.00429	0.00026
K	RR	FOL2	0.00335	0.00335	0.00335	0.00033	0.00406	0.00406	0.00406	0.00027
K	RR	FOL3	0.00319	0.00319	0.00319	0.00029	0.00346	0.00346	0.00346	0.00027
K	RR	HRT	3.6E-06	3.6E-06	3.6E-06	5.2E-06	2.2E-06	2.2E-06	2.2E-06	
K	RR	LIVE BR	0.00081	0.00081	0.00081	0.00015	0.0008	0.0008	0.0008	8E-05
K	RR	SAP	0.0003	0.0003	0.0003	2E-05	0.00022	0.00022	0.00022	2.4E-05
Mg	ET	BK	0.00032	0.00032	0.00032	2.1E-05	0.00032	0.00032	0.00032	3.5E-05
Mg	ET	DEAD	0.00019	0.00019	0.00019	2.2E-05	0.00026	0.00026	0.00026	4.5E-05
Mg	ET	FOL1	0.00107	0.00107	0.00107	7.5E-05	0.00113	0.00113	0.00113	7.7E-05
Mg	ET	FOL2	0.00091	0.00091	0.00091	6.1E-05	0.00096	0.00096	0.00096	4.8E-05
Mg	ET	FOL3	0.00078	0.00078	0.00078	6.8E-05	0.00084	0.00084	0.00084	5.6E-05
Mg	ET	HRT	2.3E-05	2.3E-05	2.3E-05	3.1E-06	1.6E-05	1.6E-05	1.6E-05	3.8E-06
Mg	ET	LIVE BR	0.0002	0.0002	0.0002	1.2E-05	0.00024	0.00024	0.00024	2E-05
Mg	ET	SAP	7.6E-05	7.6E-05	7.6E-05	5.4E-06	6.4E-05	6.4E-05	6.4E-05	5E-06
Mg	LF	BK	0.00028	0.00028	0.00028	3.7E-05	0.00032	0.00032	0.00032	2.3E-05
Mg	LF	DEAD	0.00022	0.00022	0.00022	3.8E-05	0.00017	0.00017	0.00017	1.7E-05
Mg	LF	FOL1	0.00098	0.00098	0.00098	3.9E-05	0.00107	0.00107	0.00107	5.1E-05
Mg	LF	FOL2	0.00091	0.00091	0.00091	5.8E-05	0.00099	0.00099	0.00099	6.9E-05
Mg	LF	FOL3	0.00073	0.00073	0.00073	3.7E-05	0.00087	0.00087	0.00087	0.0001
Mg	LF	HRT	1.4E-05	1.4E-05	1.4E-05	3.9E-06	2.9E-05	2.9E-05	2.9E-05	6.2E-06
Mg	LF	LIVE BR	0.00017	0.00017	0.00017	1.8E-05	0.00019	0.00019	0.00019	1.4E-05
Mg	LF	SAP	6.5E-05	6.5E-05	6.5E-05	4.5E-06	9.4E-05	9.4E-05	9.4E-05	6.7E-06
Mg	PC	BK	0.00036	0.00036	0.00036	3.1E-05	0.00037	0.00037	0.00037	0.00005
Mg	PC	DEAD	0.00039	0.00039	0.00039	4.1E-05	0.00037	0.00037	0.00037	3.9E-05
Mg	PC	FOL1	0.0008	0.0008	0.0008	4.8E-05	0.00086	0.00086	0.00086	4E-05
Mg	PC	FOL2	0.00082	0.00082	0.00082	6.4E-05	0.0009	0.0009	0.0009	8.6E-05
Mg	PC	FOL3	0.00096	0.00096	0.00096	0.00012	0.00104	0.00104	0.00104	0.00012
Mg	PC	HRT	3.1E-05	3.1E-05	3.1E-05	7.3E-06	1.9E-05	1.9E-05	1.9E-05	3.3E-06
Mg	PC	LIVE BR	0.00026	0.00026	0.00026	1.9E-05	0.00032	0.00032	0.00032	5.1E-05
Mg	PC	SAP	6.6E-05	6.6E-05	6.6E-05	2.2E-06	7.3E-05	7.3E-05	7.3E-05	6.8E-06
Mg	RR	BK	0.00034	0.00034	0.00034	5.1E-05	0.00033	0.00033	0.00033	3.5E-05
Mg	RR	DEAD	0.00019	0.00019	0.00019	1.3E-05	0.00021	0.00021	0.00021	3.1E-05
Mg	RR	FOL1	0.00118	0.00118	0.00118	6.6E-05	0.00125	0.00125	0.00125	8.4E-05
Mg	RR	FOL2	0.00109	0.00109	0.00109	7.5E-05	0.00113	0.00113	0.00113	0.00013

Table A4. Continued…

Nutrient	Site	Component	Mean	Min	Max	SE	Mean	Min	Max	SE
			Fertilized				*Unfertilized*			
Mg	RR	FOL3	0.00112	0.00112	0.00112	8.2E-05	0.00124	0.00124	0.00124	0.00017
Mg	RR	HRT	1.2E-05	1.2E-05	1.2E-05	2.5E-06	2.8E-06	2.8E-06	2.8E-06	6.4E-06
Mg	RR	LIVE BR	0.00017	0.00017	0.00017	0.00003	0.00018	0.00018	0.00018	1.2E-05
Mg	RR	SAP	6.7E-05	6.7E-05	6.7E-05	8.8E-06	5.9E-05	5.9E-05	5.9E-05	5E-06
Mn	ET	BK	6.2E-05	6.2E-05	6.2E-05	8.3E-06	7.9E-05	7.9E-05	7.9E-05	1.5E-05
Mn	ET	DEAD	7.4E-05	7.4E-05	7.4E-05	2.5E-05	0.0001	0.0001	0.0001	1.9E-05
Mn	ET	FOL1	0.00019	0.00019	0.00019	2.8E-05	0.00024	0.00024	0.00024	3.6E-05
Mn	ET	FOL2	0.00025	0.00025	0.00025	3.7E-05	0.00032	0.00032	0.00032	5.8E-05
Mn	ET	FOL3	0.00029	0.00029	0.00029	5.4E-05	0.00035	0.00035	0.00035	5.8E-05
Mn	ET	HRT	1.1E-05	1.1E-05	1.1E-05	2E-06	9.9E-06	9.9E-06	9.9E-06	1.8E-06
Mn	ET	LIVE BR	3.8E-05	3.8E-05	3.8E-05	4.3E-06	4.7E-05	4.7E-05	4.7E-05	1.1E-05
Mn	ET	SAP	1.5E-05	1.5E-05	1.5E-05	2.4E-06	1.7E-05	1.7E-05	1.7E-05	2.8E-06
Mn	LF	BK	5.9E-05	5.9E-05	5.9E-05	5.3E-06	5.4E-05	5.4E-05	5.4E-05	5.9E-06
Mn	LF	DEAD	7.3E-05	7.3E-05	7.3E-05	2.3E-05	5.5E-05	5.5E-05	5.5E-05	1.7E-05
Mn	LF	FOL1	0.00022	0.00022	0.00022	2.9E-05	0.00021	0.00021	0.00021	2E-05
Mn	LF	FOL2	0.00024	0.00024	0.00024	2.7E-05	0.00025	0.00025	0.00025	3.1E-05
Mn	LF	FOL3	0.00028	0.00028	0.00028	3.8E-05	0.00027	0.00027	0.00027	3.8E-05
Mn	LF	HRT	5.5E-06	5.5E-06	5.5E-06	1.1E-06	8.7E-06	8.7E-06	8.7E-06	9.5E-07
Mn	LF	LIVE BR	4.5E-05	4.5E-05	4.5E-05	4.8E-06	4.2E-05	4.2E-05	4.2E-05	2.3E-06
Mn	LF	SAP	1.5E-05	1.5E-05	1.5E-05	2.2E-06	1.9E-05	1.9E-05	1.9E-05	1.7E-06
Mn	PC	BK	5.2E-05	5.2E-05	5.2E-05	7.5E-06	4.4E-05	4.4E-05	4.4E-05	9.9E-06
Mn	PC	DEAD	6.4E-05	6.4E-05	6.4E-05	1.4E-05	3.1E-05	3.1E-05	3.1E-05	6.5E-06
Mn	PC	FOL1	0.00016	0.00016	0.00016	1.1E-05	0.0001	0.0001	0.0001	1.3E-05
Mn	PC	FOL2	0.00018	0.00018	0.00018	2.1E-05	0.00013	0.00013	0.00013	1.9E-05
Mn	PC	FOL3	0.00018	0.00018	0.00018	3.1E-05	0.00012	0.00012	0.00012	2.2E-05
Mn	PC	HRT	8.4E-06	8.4E-06	8.4E-06	1E-06	5.7E-06	5.7E-06	5.7E-06	6.4E-07
Mn	PC	LIVE BR	4.8E-05	4.8E-05	4.8E-05	5.8E-06	4.1E-05	4.1E-05	4.1E-05	9.9E-06
Mn	PC	SAP	1.3E-05	1.3E-05	1.3E-05	1.2E-06	1E-05	1E-05	1E-05	1.4E-06
Mn	RR	BK	4.8E-05	4.8E-05	4.8E-05	5.1E-06	5.9E-05	5.9E-05	5.9E-05	8.9E-06
Mn	RR	DEAD	3.1E-05	3.1E-05	3.1E-05	5.8E-06	6E-05	6E-05	6E-05	2.4E-05
Mn	RR	FOL1	0.00017	0.00017	0.00017	1.2E-05	0.00019	0.00019	0.00019	2.2E-05
Mn	RR	FOL2	0.00019	0.00019	0.00019	1.7E-05	0.00021	0.00021	0.00021	2.6E-05
Mn	RR	FOL3	0.00022	0.00022	0.00022	2.4E-05	0.00027	0.00027	0.00027	3E-05
Mn	RR	HRT	3.8E-06	3.8E-06	3.8E-06	4E-07	4.9E-06	4.9E-06	4.9E-06	7.1E-07
Mn	RR	LIVE BR	2.8E-05	2.8E-05	2.8E-05	2.9E-06	3.3E-05	3.3E-05	3.3E-05	5E-06
Mn	RR	SAP	8.9E-06	8.9E-06	8.9E-06	1E-06	1.2E-05	1.2E-05	1.2E-05	1.4E-06
N	ET	BK	0.00258	0.00258	0.00258	0.00015	0.00252	0.00252	0.00252	0.00013
N	ET	DEAD	0.00135	0.00135	0.00135	0.00023	0.00156	0.00156	0.00156	0.00041
N	ET	FOL1	0.01291	0.01291	0.01291	0.00038	0.01226	0.01226	0.01226	0.00038
N	ET	FOL2	0.01457	0.01457	0.01457	0.00042	0.01306	0.01306	0.01306	0.00041
N	ET	FOL3	0.01385	0.01385	0.01385	0.00022	0.01245	0.01245	0.01245	0.00075
N	ET	HRT	0.00025	0.00025	0.00025	2.5E-05	0.00025	0.00025	0.00025	2.2E-05
N	ET	LIVE BR	0.0013	0.0013	0.0013	0.00015	0.00124	0.00124	0.00124	0.00019
N	ET	SAP	0.00034	0.00034	0.00034	2.7E-05	0.00033	0.00033	0.00033	2.1E-05
N	LF	BK	0.0022	0.0022	0.0022	0.00014	0.00221	0.00221	0.00221	9.2E-05
N	LF	DEAD	0.00319	0.00319	0.00319	0.00176	0.0011	0.0011	0.0011	0.00028
N	LF	FOL1	0.01583	0.01583	0.01583	0.00031	0.01341	0.01341	0.01341	0.0004

Table A4. Continued…

Nutrient	Site	Component	Mean	Min	Max	SE	Mean	Min	Max	SE
			Fertilized				*Unfertilized*			
N	LF	FOL2	0.01463	0.01463	0.01463	0.00062	0.01284	0.01284	0.01284	0.00031
N	LF	FOL3	0.01558	0.01558	0.01558	0.00061	0.01327	0.01327	0.01327	0.00042
N	LF	HRT	0.00026	0.00026	0.00026	1.9E-05	0.00027	0.00027	0.00027	2.2E-05
N	LF	LIVE BR	0.00136	0.00136	0.00136	0.00018	0.00119	0.00119	0.00119	0.00017
N	LF	SAP	0.00026	0.00026	0.00026	2.3E-05	0.00026	0.00026	0.00026	2.3E-05
N	PC	BK	0.00223	0.00223	0.00223	0.0001	0.00213	0.00213	0.00213	9.6E-05
N	PC	DEAD	0.00189	0.00189	0.00189	0.00023	0.00145	0.00145	0.00145	0.00031
N	PC	FOL1	0.01425	0.01425	0.01425	0.00034	0.01393	0.01393	0.01393	0.00018
N	PC	FOL2	0.01394	0.01394	0.01394	0.00059	0.01323	0.01323	0.01323	0.00048
N	PC	FOL3	0.01241	0.01241	0.01241	0.00039	0.01241	0.01241	0.01241	0.00051
N	PC	HRT	0.00033	0.00033	0.00033	3.8E-05	0.0003	0.0003	0.0003	3.6E-05
N	PC	LIVE BR	0.00155	0.00155	0.00155	0.00015	0.00178	0.00178	0.00178	0.00011
N	PC	SAP	0.00035	0.00035	0.00035	2.9E-05	0.00038	0.00038	0.00038	1.4E-05
N	RR	BK	0.00241	0.00241	0.00241	9.5E-05	0.00235	0.00235	0.00235	0.00015
N	RR	DEAD	0.00205	0.00205	0.00205	0.00074	0.00123	0.00123	0.00123	0.00026
N	RR	FOL1	0.01411	0.01411	0.01411	0.00032	0.01368	0.01368	0.01368	0.00042
N	RR	FOL2	0.01413	0.01413	0.01413	0.00061	0.0143	0.0143	0.0143	0.0005
N	RR	FOL3	0.01342	0.01342	0.01342	0.00089	0.01296	0.01296	0.01296	0.00067
N	RR	HRT	0.0003	0.0003	0.0003	2.4E-05	0.00023	0.00023	0.00023	2.3E-05
N	RR	LIVE BR	0.00134	0.00134	0.00134	0.00011	0.00181	0.00181	0.00181	0.00027
N	RR	SAP	0.00035	0.00035	0.00035	2.2E-05	0.00035	0.00035	0.00035	3.1E-05
P	ET	BK	0.00047	0.00047	0.00047	3.1E-05	0.00055	0.00055	0.00055	2.4E-05
P	ET	DEAD	0.00013	0.00013	0.00013	3.1E-05	0.00017	0.00017	0.00017	5E-05
P	ET	FOL1	0.00155	0.00155	0.00155	9.1E-05	0.00166	0.00166	0.00166	0.00012
P	ET	FOL2	0.00121	0.00121	0.00121	4E-05	0.00155	0.00155	0.00155	0.00015
P	ET	FOL3	0.00104	0.00104	0.00104	5.5E-05	0.00131	0.00131	0.00131	0.00011
P	ET	HRT	1.2E-05	1.2E-05	1.2E-05	5.7E-07	1.4E-05	1.4E-05	1.4E-05	1E-06
P	ET	LIVE BR	0.00017	0.00017	0.00017	1.3E-05	0.00021	0.00021	0.00021	2.3E-05
P	ET	SAP	5.5E-05	5.5E-05	5.5E-05	4.3E-06	5.9E-05	5.9E-05	5.9E-05	2.7E-06
P	LF	BK	0.00033	0.00033	0.00033	2.6E-05	0.00043	0.00043	0.00043	2.7E-05
P	LF	DEAD	0.00018	0.00018	0.00018	7.6E-05	7.5E-05	7.5E-05	7.5E-05	2.7E-05
P	LF	FOL1	0.00096	0.00096	0.00096	3.8E-05	0.00112	0.00112	0.00112	4.4E-05
P	LF	FOL2	0.00084	0.00084	0.00084	1.6E-05	0.00101	0.00101	0.00101	6.8E-05
P	LF	FOL3	0.00082	0.00082	0.00082	1.1E-05	0.00096	0.00096	0.00096	7.1E-05
P	LF	HRT	4.9E-06	4.9E-06	4.9E-06	1E-06	5.7E-06	5.7E-06	5.7E-06	1E-06
P	LF	LIVE BR	0.00013	0.00013	0.00013	1.7E-05	0.00016	0.00016	0.00016	1.5E-05
P	LF	SAP	4.5E-05	4.5E-05	4.5E-05	2.6E-06	4.7E-05	4.7E-05	4.7E-05	3.3E-06
P	PC	BK	0.00039	0.00039	0.00039	3.4E-05	0.00053	0.00053	0.00053	3.2E-05
P	PC	DEAD	0.00015	0.00015	0.00015	2.1E-05	0.00012	0.00012	0.00012	2.3E-05
P	PC	FOL1	0.00122	0.00122	0.00122	9.1E-05	0.00128	0.00128	0.00128	3.6E-05
P	PC	FOL2	0.00118	0.00118	0.00118	0.00011	0.00122	0.00122	0.00122	8.8E-05
P	PC	FOL3	0.00111	0.00111	0.00111	0.00014	0.00118	0.00118	0.00118	0.00013
P	PC	HRT	2E-05	2E-05	2E-05	4.4E-06	1.8E-05	1.8E-05	1.8E-05	1.5E-06
P	PC	LIVE BR	0.00024	0.00024	0.00024	3.2E-05	0.0003	0.0003	0.0003	2.8E-05
P	PC	SAP	6.8E-05	6.8E-05	6.8E-05	5.7E-06	7.7E-05	7.7E-05	7.7E-05	4.5E-06
P	RR	BK	0.00038	0.00038	0.00038	2.5E-05	0.00039	0.00039	0.00039	3E-05
P	RR	DEAD	0.0001	0.0001	0.0001	3.4E-05	0.00011	0.00011	0.00011	3.1E-05

Table A4. Continued…

Nutrient	Site	Component	Mean	Min	Max	SE	Mean	Min	Max	SE
			Fertilized				*Unfertilized*			
P	RR	FOL1	0.00117	0.00117	0.00117	5.9E-05	0.00121	0.00121	0.00121	5.7E-05
P	RR	FOL2	0.00098	0.00098	0.00098	3.8E-05	0.00108	0.00108	0.00108	4.7E-05
P	RR	FOL3	0.00097	0.00097	0.00097	4.9E-05	0.00101	0.00101	0.00101	4.9E-05
P	RR	HRT	9.1E-06	9.1E-06	9.1E-06	1.7E-06	2.8E-06	2.8E-06	2.8E-06	1.3E-06
P	RR	LIVE BR	0.00014	0.00014	0.00014	2.6E-05	0.00013	0.00013	0.00013	1.9E-05
P	RR	SAP	6E-05	6E-05	6E-05	4.2E-06	5.1E-05	5.1E-05	5.1E-05	3.6E-06
S	ET	BK	0.0002	0.0002	0.0002	9.9E-06	0.00021	0.00021	0.00021	9.6E-06
S	ET	DEAD	0.00015	0.00015	0.00015	4.3E-05	0.0002	0.0002	0.0002	5.4E-05
S	ET	FOL1	0.00067	0.00067	0.00067	2.8E-05	0.00075	0.00075	0.00075	3.9E-05
S	ET	FOL2	0.00069	0.00069	0.00069	8.7E-06	0.0008	0.0008	0.0008	5.6E-05
S	ET	FOL3	0.00072	0.00072	0.00072	1.7E-05	0.00077	0.00077	0.00077	3.7E-05
S	ET	HRT	3.9E-05	3.9E-05	3.9E-05	2.2E-06	3.3E-05	3.3E-05	3.3E-05	2E-06
S	ET	LIVE BR	7.7E-05	7.7E-05	7.7E-05	3.3E-06	0.0001	0.0001	0.0001	9.9E-06
S	ET	SAP	3.9E-05	3.9E-05	3.9E-05	1.4E-06	4E-05	4E-05	4E-05	1.9E-06
S	LF	BK	0.00019	0.00019	0.00019	7E-06	0.0002	0.0002	0.0002	7.7E-06
S	LF	DEAD	0.00027	0.00027	0.00027	0.00012	0.00015	0.00015	0.00015	3.9E-05
S	LF	FOL1	0.00068	0.00068	0.00068	2.7E-05	0.00066	0.00066	0.00066	2.4E-05
S	LF	FOL2	0.00077	0.00077	0.00077	3E-05	0.00079	0.00079	0.00079	3.5E-05
S	LF	FOL3	0.00081	0.00081	0.00081	3.7E-05	0.00076	0.00076	0.00076	1.8E-05
S	LF	HRT	3.7E-05	3.7E-05	3.7E-05	2.3E-06	4E-05	4E-05	4E-05	2.6E-06
S	LF	LIVE BR	8.2E-05	8.2E-05	8.2E-05	7.5E-06	9.2E-05	9.2E-05	9.2E-05	8.5E-06
S	LF	SAP	3.6E-05	3.6E-05	3.6E-05	2.8E-06	4E-05	4E-05	4E-05	2.3E-06
S	PC	BK	0.00019	0.00019	0.00019	7.9E-06	0.00019	0.00019	0.00019	7.4E-06
S	PC	DEAD	0.00019	0.00019	0.00019	3.3E-05	0.00016	0.00016	0.00016	3.4E-05
S	PC	FOL1	0.00072	0.00072	0.00072	3.2E-05	0.00068	0.00068	0.00068	1.9E-05
S	PC	FOL2	0.0008	0.0008	0.0008	3E-05	0.00075	0.00075	0.00075	3.2E-05
S	PC	FOL3	0.00083	0.00083	0.00083	2.7E-05	0.00076	0.00076	0.00076	4E-05
S	PC	HRT	4.2E-05	4.2E-05	4.2E-05	2.6E-06	4.2E-05	4.2E-05	4.2E-05	2.5E-06
S	PC	LIVE BR	0.00013	0.00013	0.00013	1.4E-05	0.00013	0.00013	0.00013	1.1E-05
S	RR	BK	0.00018	0.00018	0.00018	6.2E-06	0.00017	0.00017	0.00017	9.1E-06
S	RR	DEAD	0.00012	0.00012	0.00012	3.4E-05	0.00012	0.00012	0.00012	3.3E-05
S	RR	FOL1	0.00075	0.00075	0.00075	3.5E-05	0.00076	0.00076	0.00076	9.9E-06
S	RR	FOL2	0.00081	0.00081	0.00081	3.3E-05	0.00082	0.00082	0.00082	1.9E-05
S	RR	FOL3	0.0008	0.0008	0.0008	3.8E-05	0.00084	0.00084	0.00084	2.4E-05
S	RR	HRT	3.6E-05	3.6E-05	3.6E-05	2.8E-06	3.1E-05	3.1E-05	3.1E-05	3.3E-06
S	RR	LIVE BR	8.7E-05	8.7E-05	8.7E-05	1.4E-05	8.9E-05	8.9E-05	8.9E-05	8.1E-06
S	RR	SAP	3.7E-05	3.7E-05	3.7E-05	1.5E-06	3.5E-05	3.5E-05	3.5E-05	1.9E-06
Zn	ET	BK	1.6E-05	1.6E-05	1.6E-05	1E-06	2E-05	2E-05	2E-05	2.1E-06
Zn	ET	DEAD	1.1E-05	1.1E-05	1.1E-05	2.9E-06	1.7E-05	1.7E-05	1.7E-05	3.1E-06
Zn	ET	FOL1	1.1E-05	1.1E-05	1.1E-05	7.3E-07	1.3E-05	1.3E-05	1.3E-05	1.1E-06
Zn	ET	FOL2	9.5E-06	9.5E-06	9.5E-06	1.5E-06	1.2E-05	1.2E-05	1.2E-05	9E-07
Zn	ET	FOL3	0.00001	0.00001	0.00001	1.1E-06	1.1E-05	1.1E-05	1.1E-05	5.7E-07
Zn	ET	HRT	2.5E-06	2.5E-06	2.5E-06	5.1E-07	3.4E-06	3.4E-06	3.4E-06	5.5E-07
Zn	ET	LIVE BR	8E-06	8E-06	8E-06	8.8E-07	9.7E-06	9.7E-06	9.7E-06	8.5E-07
Zn	ET	SAP	2.7E-06	2.7E-06	2.7E-06	5.7E-07	2.9E-06	2.9E-06	2.9E-06	3.7E-07
Zn	LF	BK	1.4E-05	1.4E-05	1.4E-05	1.6E-06	1.1E-05	1.1E-05	1.1E-05	1.6E-06
Zn	LF	DEAD	1.8E-05	1.8E-05	1.8E-05	4.1E-06	8.4E-06	8.4E-06	8.4E-06	2.1E-06

Table A4. Continued…

Nutrient	Site	Component	Mean	Min	Max	SE	Mean	Min	Max	SE
			Fertilized				*Unfertilized*			
Zn	LF	FOL1	1.1E-05	1.1E-05	1.1E-05	1E-06	1.6E-05	1.6E-05	1.6E-05	3.9E-06
Zn	LF	FOL2	9.9E-06	9.9E-06	9.9E-06	1.1E-06	1.1E-05	1.1E-05	1.1E-05	8.9E-07
Zn	LF	FOL3	1.1E-05	1.1E-05	1.1E-05	8.2E-07	1.1E-05	1.1E-05	1.1E-05	9E-07
Zn	LF	HRT	1.4E-06	1.4E-06	1.4E-06	3.1E-07	1.3E-06	1.3E-06	1.3E-06	2.3E-07
Zn	LF	LIVE BR	6.7E-06	6.7E-06	6.7E-06	9.2E-07	7.2E-06	7.2E-06	7.2E-06	6.6E-07
Zn	LF	SAP	1.5E-06	1.5E-06	1.5E-06	3E-07	2.2E-06	2.2E-06	2.2E-06	2E-07
Zn	PC	BK	1.5E-05	1.5E-05	1.5E-05	1.8E-06	1.4E-05	1.4E-05	1.4E-05	1.2E-06
Zn	PC	DEAD	1.7E-05	1.7E-05	1.7E-05	3.3E-06	1.3E-05	1.3E-05	1.3E-05	2.7E-06
Zn	PC	FOL1	9E-06	9E-06	9E-06	4.2E-07	1E-05	1E-05	1E-05	8.1E-07
Zn	PC	FOL2	8.3E-06	8.3E-06	8.3E-06	5.1E-07	8.3E-06	8.3E-06	8.3E-06	5.3E-07
Zn	PC	FOL3	8.2E-06	8.2E-06	8.2E-06	4.2E-07	1.1E-05	1.1E-05	1.1E-05	3.3E-06
Zn	PC	HRT	3.9E-06	3.9E-06	3.9E-06	6.2E-07	2.9E-06	2.9E-06	2.9E-06	2.7E-07
Zn	PC	LIVE BR	1.4E-05	1.4E-05	1.4E-05	1.6E-06	1.3E-05	1.3E-05	1.3E-05	1.5E-06
Zn	PC	SAP	3.6E-06	3.6E-06	3.6E-06	3.1E-07	2.9E-06	2.9E-06	2.9E-06	4.4E-07
Zn	RR	BK	1.6E-05	1.6E-05	1.6E-05	1.1E-06	1.4E-05	1.4E-05	1.4E-05	1.7E-06
Zn	RR	DEAD	9.8E-06	9.8E-06	9.8E-06	2.4E-06	1.2E-05	1.2E-05	1.2E-05	3.6E-06
Zn	RR	FOL1	1.2E-05	1.2E-05	1.2E-05	7.2E-07	1.3E-05	1.3E-05	1.3E-05	8.7E-07
Zn	RR	FOL2	1E-05	1E-05	1E-05	7.8E-07	1.3E-05	1.3E-05	1.3E-05	1.6E-06
Zn	RR	FOL3	0.00001	0.00001	0.00001	7.9E-07	1.3E-05	1.3E-05	1.3E-05	8.6E-07
Zn	RR	HRT	1.2E-06	1.2E-06	1.2E-06	1.6E-07	9.2E-07	9.2E-07	9.2E-07	3.5E-07
Zn	RR	LIVE BR	6.5E-06	6.5E-06	6.5E-06	8.2E-07	6.5E-06	6.5E-06	6.5E-06	8E-07
Zn	RR	SAP	2.1E-06	2.1E-06	2.1E-06	2.8E-07	1.8E-06	1.8E-06	1.8E-06	1.5E-07

Table A5. Stand level nutrient content by component for each SMC Type I site sampled in 2011. 1-year-old foliage (FOL1), 2-year-old foliage (FOL2), ≥3-year-old foliage (FOL1), live branches (LIVE BR), bark (BK), sapwood (SAP) and heartwood (HRT), are presented for each of the four sites.

Site	Component	Nutrient	Content (kg/ha)	SE
ET	HRT	B	0.055	0.002
ET	HRT	Ca	6.726	0.418
ET	HRT	Cu	0.078	0.002
ET	HRT	Fe	1.529	0.037
ET	HRT	K	0.110	0.007
ET	HRT	Mg	0.636	0.019
ET	HRT	Mn	0.340	0.007
ET	HRT	N	8.342	0.175
ET	HRT	P	0.434	0.008
ET	HRT	S	1.186	0.029
ET	HRT	Zn	0.102	0.002
LF	HRT	B	0.022	0.000
LF	HRT	Ca	22.906	0.685
LF	HRT	Cu	0.036	0.000
LF	HRT	Fe	1.769	0.082
LF	HRT	K	0.032	0.004
LF	HRT	Mg	1.086	0.031
LF	HRT	Mn	0.347	0.008
LF	HRT	N	12.228	0.145
LF	HRT	P	0.249	0.004
LF	HRT	S	1.766	0.022
LF	HRT	Zn	0.060	0.001
PC	HRT	B	0.052	0.001
PC	HRT	Ca	11.652	0.138
PC	HRT	Cu	0.055	0.001
PC	HRT	Fe	0.328	0.004
PC	HRT	K	0.028	0.001
PC	HRT	Mg	0.528	0.011
PC	HRT	Mn	0.151	0.003
PC	HRT	N	7.056	0.083
PC	HRT	P	0.424	0.005
PC	HRT	S	0.953	0.011
PC	HRT	Zn	0.074	0.001
RR	HRT	B	0.047	0.001
RR	HRT	Ca	8.788	0.152
RR	HRT	Cu	0.010	0.000
RR	HRT	Fe	0.480	0.013
RR	HRT	K	0.066	0.001
RR	HRT	Mg	0.149	0.009
RR	HRT	Mn	0.114	0.002
RR	HRT	N	6.238	0.100
RR	HRT	P	0.121	0.006
RR	HRT	S	0.806	0.012

Table A5. Continued..

Site	Component	Nutrient	Content (kg/ha)	SE
RR	HRT	Zn	0.025	0.000
ET	SAP	B	0.022	0.000
ET	SAP	Ca	8.444	0.178
ET	SAP	Cu	0.083	0.002
ET	SAP	Fe	5.097	0.121
ET	SAP	K	12.090	0.263
ET	SAP	Mg	2.637	0.057
ET	SAP	Mn	0.632	0.014
ET	SAP	N	12.900	0.269
ET	SAP	P	2.227	0.048
ET	SAP	S	1.528	0.032
ET	SAP	Zn	0.109	0.002
LF	SAP	B	0.032	0.001
LF	SAP	Ca	27.012	0.778
LF	SAP	Cu	0.061	0.001
LF	SAP	Fe	2.340	0.140
LF	SAP	K	12.786	0.234
LF	SAP	Mg	3.795	0.096
LF	SAP	Mn	0.784	0.017
LF	SAP	N	11.797	0.203
LF	SAP	P	2.098	0.038
LF	SAP	S	1.737	0.033
LF	SAP	Zn	0.088	0.002
PC	SAP	B	0.071	0.001
PC	SAP	Ca	17.357	0.308
PC	SAP	Cu	0.071	0.001
PC	SAP	Fe	0.530	0.012
PC	SAP	K	10.153	0.161
PC	SAP	Mg	2.274	0.033
PC	SAP	Mn	0.360	0.005
PC	SAP	N	11.952	0.176
PC	SAP	P	2.382	0.037
PC	SAP	S	1.747	0.022
PC	SAP	Zn	0.101	0.001
RR	SAP	B	0.057	0.001
RR	SAP	Ca	13.840	0.295
RR	SAP	Cu	0.014	0.001
RR	SAP	Fe	0.560	0.015
RR	SAP	K	8.150	0.148
RR	SAP	Mg	2.053	0.035
RR	SAP	Mn	0.371	0.009
RR	SAP	N	11.563	0.204
RR	SAP	P	1.796	0.030
RR	SAP	S	1.175	0.020
RR	SAP	Zn	0.063	0.001

Table A5. Continued…

Site	Component	Nutrient	Content (kg/ha)	SE
ET	BK	B	0.060	0.001
ET	BK	Ca	14.263	0.355
ET	BK	Cu	0.047	0.001
ET	BK	Fe	8.195	0.183
ET	BK	K	27.901	0.675
ET	BK	Mg	3.705	0.083
ET	BK	Mn	0.849	0.020
ET	BK	N	29.664	0.662
ET	BK	P	6.044	0.138
ET	BK	S	2.393	0.053
ET	BK	Zn	0.211	0.005
LF	BK	B	0.085	0.002
LF	BK	Ca	28.597	0.465
LF	BK	Cu	0.061	0.001
LF	BK	Fe	5.513	0.339
LF	BK	K	29.820	0.515
LF	BK	Mg	4.830	0.089
LF	BK	Mn	0.875	0.013
LF	BK	N	34.756	0.560
LF	BK	P	6.243	0.136
LF	BK	S	3.072	0.051
LF	BK	Zn	0.190	0.003
PC	BK	B	0.057	0.001
PC	BK	Ca	16.050	0.189
PC	BK	Cu	0.042	0.001
PC	BK	Fe	0.241	0.004
PC	BK	K	17.622	0.297
PC	BK	Mg	3.483	0.045
PC	BK	Mn	0.444	0.005
PC	BK	N	20.514	0.242
PC	BK	P	4.572	0.085
PC	BK	S	1.844	0.022
PC	BK	Zn	0.133	0.002
RR	BK	B	0.061	0.001
RR	BK	Ca	23.212	0.356
RR	BK	Cu	0.041	0.001
RR	BK	Fe	0.432	0.012
RR	BK	K	15.505	0.237
RR	BK	Mg	3.509	0.054
RR	BK	Mn	0.593	0.011
RR	BK	N	25.240	0.386
RR	BK	P	4.124	0.065
RR	BK	S	1.876	0.029
RR	BK	Zn	0.156	0.002
ET	LIVE BR	B	0.006	0.000

Table A5. Continued..

Site	Component	Nutrient	Content (kg/ha)	SE
ET	LIVE BR	Ca	2.282	0.131
ET	LIVE BR	Cu	0.011	0.000
ET	LIVE BR	Fe	1.743	0.109
ET	LIVE BR	K	2.476	0.044
ET	LIVE BR	Mg	0.639	0.012
ET	LIVE BR	Mn	0.121	0.002
ET	LIVE BR	N	3.725	0.086
ET	LIVE BR	P	0.543	0.010
ET	LIVE BR	S	0.257	0.005
ET	LIVE BR	Zn	0.026	0.000
LF	LIVE BR	B	0.008	0.000
LF	LIVE BR	Ca	3.896	0.031
LF	LIVE BR	Cu	0.010	0.000
LF	LIVE BR	Fe	0.046	0.002
LF	LIVE BR	K	2.651	0.020
LF	LIVE BR	Mg	0.595	0.005
LF	LIVE BR	Mn	0.143	0.001
LF	LIVE BR	N	4.169	0.044
LF	LIVE BR	P	0.473	0.005
LF	LIVE BR	S	0.289	0.002
LF	LIVE BR	Zn	0.023	0.000
PC	LIVE BR	B	0.010	0.000
PC	LIVE BR	Ca	3.636	0.044
PC	LIVE BR	Cu	0.011	0.000
PC	LIVE BR	Fe	0.026	0.000
PC	LIVE BR	K	2.312	0.038
PC	LIVE BR	Mg	0.670	0.007
PC	LIVE BR	Mn	0.100	0.001
PC	LIVE BR	N	3.856	0.031
PC	LIVE BR	P	0.633	0.007
PC	LIVE BR	S	0.296	0.002
PC	LIVE BR	Zn	0.030	0.000
RR	LIVE BR	B	0.005	0.000
RR	LIVE BR	Ca	2.029	0.022
RR	LIVE BR	Cu	0.005	0.000
RR	LIVE BR	Fe	0.021	0.000
RR	LIVE BR	K	1.656	0.018
RR	LIVE BR	Mg	0.363	0.004
RR	LIVE BR	Mn	0.063	0.001
RR	LIVE BR	N	3.304	0.066
RR	LIVE BR	P	0.279	0.003
RR	LIVE BR	S	0.181	0.002
RR	LIVE BR	Zn	0.013	0.000
ET	FOL3	B	0.007	0.000
ET	FOL3	Ca	6.166	0.113

Table A5. Continued..

Site	Component	Nutrient	Content (kg/ha)	SE
ET	FOL3	cu	0.443	0.016
ET	FOL3	fe	0.695	0.044
ET	FOL3	k	0.484	0.020
ET	FOL3	mg	0.726	0.026
ET	FOL3	mn	0.490	0.017
ET	FOL3	n	20.081	1.174
ET	FOL3	p	0.273	0.051
ET	FOL3	s	0.710	0.029
ET	FOL3	zn	0.441	0.050
LF	FOL3	b	0.349	0.010
LF	FOL3	ca	5.667	0.164
LF	FOL3	cu	0.539	0.026
LF	FOL3	fe	0.478	0.015
LF	FOL3	k	0.294	0.008
LF	FOL3	mg	0.587	0.019
LF	FOL3	mn	0.361	0.011
LF	FOL3	n	18.541	0.803
LF	FOL3	p	0.584	0.030
LF	FOL3	s	0.636	0.019
LF	FOL3	zn	0.353	0.014
PC	FOL3	b	0.348	0.013
PC	FOL3	ca	2.463	0.122
PC	FOL3	cu	0.190	0.007
PC	FOL3	fe	0.276	0.010
PC	FOL3	k	0.286	0.011
PC	FOL3	mg	0.265	0.030
PC	FOL3	mn	0.131	0.010
PC	FOL3	n	10.989	0.423
PC	FOL3	p	0.298	0.022
PC	FOL3	s	0.446	0.020
PC	FOL3	zn	0.381	0.026
RR	FOL3	b	0.358	0.009
RR	FOL3	ca	4.852	0.124
RR	FOL3	cu	0.353	0.011
RR	FOL3	fe	0.275	0.032
RR	FOL3	k	0.218	0.007
RR	FOL3	mg	0.161	0.022
RR	FOL3	mn	0.214	0.009
RR	FOL3	n	11.363	0.271
RR	FOL3	p	0.195	0.026
RR	FOL3	s	0.453	0.013
RR	FOL3	zn	0.272	0.012
ET	FOL2	b	0.285	0.015
ET	FOL2	ca	3.281	0.203
ET	FOL2	cu	0.256	0.013

Table A5. Continued..

Site	Component	Nutrient	Content (kg/ha)	SE
ET	FOL2	Fe	0.057	0.001
ET	FOL2	K	3.995	0.076
ET	FOL2	Mg	0.851	0.018
ET	FOL2	Mn	0.261	0.005
ET	FOL2	N	12.382	0.324
ET	FOL2	P	1.269	0.024
ET	FOL2	S	0.679	0.013
ET	FOL2	Zn	0.010	0.000
LF	FOL2	B	0.004	0.000
LF	FOL2	Ca	3.312	0.034
LF	FOL2	Cu	0.004	0.000
LF	FOL2	Fe	0.064	0.001
LF	FOL2	K	3.394	0.035
LF	FOL2	Mg	0.909	0.009
LF	FOL2	Mn	0.232	0.002
LF	FOL2	N	12.789	0.186
LF	FOL2	P	0.891	0.010
LF	FOL2	S	0.739	0.008
LF	FOL2	Zn	0.010	0.000
PC	FOL2	B	0.008	0.000
PC	FOL2	Ca	2.002	0.019
PC	FOL2	Cu	0.003	0.000
PC	FOL2	Fe	0.044	0.001
PC	FOL2	K	4.224	0.037
PC	FOL2	Mg	0.730	0.006
PC	FOL2	Mn	0.124	0.002
PC	FOL2	N	11.308	0.106
PC	FOL2	P	1.012	0.009
PC	FOL2	S	0.647	0.006
PC	FOL2	Zn	0.007	0.000
RR	FOL2	B	0.008	0.000
RR	FOL2	Ca	2.998	0.046
RR	FOL2	Cu	0.003	0.000
RR	FOL2	Fe	0.063	0.001
RR	FOL2	K	2.887	0.043
RR	FOL2	Mg	0.845	0.009
RR	FOL2	Mn	0.152	0.002
RR	FOL2	N	10.779	0.107
RR	FOL2	P	0.790	0.009
RR	FOL2	S	0.617	0.006
RR	FOL2	Zn	0.009	0.000
ET	FOL1	B	0.008	0.000
ET	FOL1	Ca	3.498	0.114
ET	FOL1	Cu	0.005	0.000
ET	FOL1	Fe	0.059	0.002
ET	FOL1	K	7.511	0.236

Table A5. Continued…

Site	Component	Nutrient	Content (kg/ha)	SE
ET	FOL1	Mg	1.487	0.048
ET	FOL1	Mn	0.295	0.009
ET	FOL1	N	16.860	0.575
ET	FOL1	P	2.171	0.070
ET	FOL1	S	0.960	0.030
ET	FOL1	Zn	0.016	0.001
LF	FOL1	B	0.011	0.000
LF	FOL1	Ca	4.063	0.036
LF	FOL1	Cu	0.016	0.001
LF	FOL1	Fe	0.077	0.001
LF	FOL1	K	5.560	0.049
LF	FOL1	Mg	1.591	0.015
LF	FOL1	Mn	0.327	0.003
LF	FOL1	N	21.860	0.279
LF	FOL1	P	1.639	0.017
LF	FOL1	S	1.020	0.010
LF	FOL1	Zn	0.022	0.000
PC	FOL1	B	0.018	0.000
PC	FOL1	Ca	3.017	0.033
PC	FOL1	Cu	0.006	0.000
PC	FOL1	Fe	0.082	0.001
PC	FOL1	K	9.987	0.077
PC	FOL1	Mg	1.531	0.011
PC	FOL1	Mn	0.226	0.004
PC	FOL1	N	25.694	0.184
PC	FOL1	P	2.301	0.016
PC	FOL1	S	1.275	0.009
PC	FOL1	Zn	0.018	0.000
RR	FOL1	B	0.024	0.000
RR	FOL1	Ca	4.761	0.083
RR	FOL1	Cu	0.006	0.000
RR	FOL1	Fe	0.092	0.001
RR	FOL1	K	6.434	0.086
RR	FOL1	Mg	1.939	0.021
RR	FOL1	Mn	0.290	0.004
RR	FOL1	N	21.782	0.211
RR	FOL1	P	1.885	0.020
RR	FOL1	S	1.192	0.012
RR	FOL1	Zn	0.019	0.000

Table A6. Relative Nutrients Harvested by site for each harvest scenario and fertilization treatment.

Site	Nutrient	Harvesting and Treatment	Mean (%)	Min (%)	Max (%)
ET	B	BO.f	26.9	25.7	29.2
ET	B	BO.o	22.4	22.0	22.7
ET	B	BT.f	29.9	27.8	33.9
ET	B	BT.o	27.9	25.0	33.1
ET	B	VC.f	47.0	46.5	47.5
ET	B	VC.o	47.3	45.3	48.1
ET	Ca	BO.f	20.3	19.2	22.3
ET	Ca	BO.o	17.4	16.7	17.9
ET	Ca	BT.f	29.5	25.6	36.8
ET	Ca	BT.o	28.5	23.6	36.8
ET	Ca	VC.f	40.8	40.4	41.2
ET	Ca	VC.o	42.4	39.6	43.5
ET	Cu	BO.f	29.1	27.6	32.1
ET	Cu	BO.o	32.4	31.7	33.6
ET	Cu	BT.f	32.9	30.2	38.0
ET	Cu	BT.o	35.1	33.1	38.7
ET	Cu	VC.f	45.5	45.2	45.7
ET	Cu	VC.o	48.0	46.8	48.4
ET	Fe	BO.f	22.5	21.3	24.8
ET	Fe	BO.o	19.7	19.5	19.9
ET	Fe	BT.f	23.9	22.3	27.0
ET	Fe	BT.o	24.6	22.2	29.0
ET	Fe	VC.f	43.3	42.6	43.9
ET	Fe	VC.o	43.8	42.1	44.5
ET	K	BO.f	14.3	13.5	15.7
ET	K	BO.o	15.6	14.7	16.1
ET	K	BT.f	23.7	20.1	30.5
ET	K	BT.o	26.1	21.5	34.0
ET	K	VC.f	40.5	39.7	41.2
ET	K	VC.o	45.2	42.2	46.4
ET	Mg	BO.f	17.7	16.6	19.5
ET	Mg	BO.o	17.0	16.2	17.6
ET	Mg	BT.f	26.9	23.1	34.1
ET	Mg	BT.o	29.3	23.9	38.3
ET	Mg	VC.f	40.3	39.8	40.7
ET	Mg	VC.o	42.2	39.8	43.2
ET	Mn	BO.f	17.4	16.4	19.2
ET	Mn	BO.o	17.6	16.7	18.2
ET	Mn	BT.f	27.8	23.6	35.7

Table A6. Continued...

Site	Nutrient	Harvesting and Treatment	Mean (%)	Min (%)	Max (%)
ET	Mn	BT.o	30.6	24.9	39.9
ET	Mn	VC.f	38.5	38.0	38.9
ET	Mn	VC.o	40.6	38.1	41.6
ET	N	BO.f	12.4	11.6	13.6
ET	N	BO.o	13.6	12.5	14.2
ET	N	BT.f	27.2	21.9	37.0
ET	N	BT.o	30.5	23.3	42.2
ET	N	VC.f	37.4	36.8	37.8
ET	N	VC.o	40.2	37.6	41.3
ET	P	BO.f	13.2	12.4	14.3
ET	P	BO.o	13.8	12.9	14.4
ET	P	BT.f	23.7	19.8	31.0
ET	P	BT.o	27.0	21.3	36.7
ET	P	VC.f	39.5	38.8	40.2
ET	P	VC.o	43.0	40.1	44.2
ET	S	BO.f	18.5	17.4	20.3
ET	S	BO.o	18.2	17.4	18.7
ET	S	BT.f	28.1	24.2	35.5
ET	S	BT.o	30.5	25.1	39.6
ET	S	VC.f	40.3	39.8	40.8
ET	S	VC.o	42.0	39.6	42.9
ET	Zn	BO.f	21.8	20.8	23.8
ET	Zn	BO.o	23.0	22.6	23.5
ET	Zn	BT.f	25.3	23.3	29.4
ET	Zn	BT.o	27.0	24.8	31.1
ET	Zn	VC.f	43.3	42.7	43.9
ET	Zn	VC.o	46.5	44.5	47.2
LF	B	BO.f	19.8	19.2	20.8
LF	B	BO.o	18.8	16.7	20.2
LF	B	BT.f	23.4	21.2	27.1
LF	B	BT.o	23.7	18.8	28.4
LF	B	VC.f	46.9	46.7	47.3
LF	B	VC.o	47.9	47.0	48.7
LF	Ca	BO.f	19.5	18.9	20.4
LF	Ca	BO.o	26.6	23.1	29.1
LF	Ca	BT.f	23.9	21.4	28.1
LF	Ca	BT.o	31.8	25.3	37.4
LF	Ca	VC.f	45.9	45.7	46.3
LF	Ca	VC.o	46.7	46.1	47.1
LF	Cu	BO.f	23.5	22.7	24.9

Table A6. Continued...

Site	Nutrient	Harvesting and Treatment	Mean (%)	Min (%)	Max (%)
LF	Cu	BO.o	24.1	20.9	26.3
LF	Cu	BT.f	26.5	24.3	29.9
LF	Cu	BT.o	30.1	23.4	35.9
LF	Cu	VC.f	46.3	46.0	46.7
LF	Cu	VC.o	45.9	45.2	46.5
LF	Fe	BO.f	22.3	21.6	23.5
LF	Fe	BO.o	23.4	20.6	25.5
LF	Fe	BT.f	26.7	24.1	31.1
LF	Fe	BT.o	24.0	20.9	26.6
LF	Fe	VC.f	44.4	44.4	44.5
LF	Fe	VC.o	50.5	49.6	51.4
LF	K	BO.f	14.9	14.6	15.4
LF	K	BO.o	16.1	14.3	17.3
LF	K	BT.f	21.0	18.1	26.0
LF	K	BT.o	24.4	17.8	30.7
LF	K	VC.f	46.0	45.7	46.4
LF	K	VC.o	47.0	45.8	48.1
LF	Mg	BO.f	16.2	15.9	16.8
LF	Mg	BO.o	20.1	17.5	21.9
LF	Mg	BT.f	23.4	20.1	29.2
LF	Mg	BT.o	28.9	21.2	35.9
LF	Mg	VC.f	44.2	44.1	44.6
LF	Mg	VC.o	45.3	44.4	46.1
LF	Mn	BO.f	16.1	15.7	16.6
LF	Mn	BO.o	20.0	17.3	21.7
LF	Mn	BT.f	24.4	20.7	30.8
LF	Mn	BT.o	30.3	21.8	38.1
LF	Mn	VC.f	43.4	43.3	43.7
LF	Mn	VC.o	44.0	43.2	44.6
LF	N	BO.f	10.9	10.7	11.1
LF	N	BO.o	13.1	11.7	14.0
LF	N	BT.f	22.4	17.6	30.7
LF	N	BT.o	28.2	18.1	38.2
LF	N	VC.f	40.9	40.8	41.1
LF	N	VC.o	42.7	42.3	43.0
LF	P	BO.f	13.5	13.2	13.9
LF	P	BO.o	13.9	12.5	14.8
LF	P	BT.f	21.0	17.6	26.8
LF	P	BT.o	24.0	16.7	31.2
LF	P	VC.f	44.5	44.2	44.8

Table A6. Continued...

Site	Nutrient	Harvesting and Treatment	Mean (%)	Min (%)	Max (%)
LF	P	VC.o	45.7	44.6	46.6
LF	S	BO.f	17.0	16.7	17.7
LF	S	BO.o	19.2	16.9	20.7
LF	S	BT.f	24.3	20.9	30.2
LF	S	BT.o	28.8	21.0	36.3
LF	S	VC.f	43.8	43.7	44.0
LF	S	VC.o	44.9	44.4	45.3
LF	Zn	BO.f	17.6	17.1	18.6
LF	Zn	BO.o	20.4	17.9	22.1
LF	Zn	BT.f	20.9	18.9	24.2
LF	Zn	BT.o	25.6	20.1	30.5
LF	Zn	VC.f	45.0	44.8	45.4
LF	Zn	VC.o	45.5	44.7	46.2
PC	B	BO.f	26.2	25.1	26.8
PC	B	BO.o	28.8	28.2	29.5
PC	B	BT.f	34.6	32.9	37.0
PC	B	BT.o	35.5	33.8	37.3
PC	B	VC.f	45.5	45.5	45.5
PC	B	VC.o	46.6	46.6	46.7
PC	Ca	BO.f	23.9	22.9	24.4
PC	Ca	BO.o	26.9	26.3	27.5
PC	Ca	BT.f	32.3	30.6	34.8
PC	Ca	BT.o	34.0	32.2	36.0
PC	Ca	VC.f	44.0	43.8	44.2
PC	Ca	VC.o	45.7	45.6	45.8
PC	Cu	BO.f	33.6	32.7	34.1
PC	Cu	BO.o	30.9	30.4	31.4
PC	Cu	BT.f	38.0	37.2	38.9
PC	Cu	BT.o	35.6	34.5	36.9
PC	Cu	VC.f	47.7	47.3	47.9
PC	Cu	VC.o	46.1	45.9	46.4
PC	Fe	BO.f	30.7	29.7	31.2
PC	Fe	BO.o	30.7	29.8	31.5
PC	Fe	BT.f	36.5	35.4	37.9
PC	Fe	BT.o	37.0	35.6	38.6
PC	Fe	VC.f	45.8	45.6	45.9
PC	Fe	VC.o	45.8	45.7	45.9
PC	K	BO.f	14.5	13.6	15.0
PC	K	BO.o	15.2	14.7	15.8
PC	K	BT.f	32.6	28.6	38.4

Table A6. Continued...

Site	Nutrient	Harvesting and Treatment	Mean (%)	Min (%)	Max (%)
PC	K	BT.o	30.9	26.4	35.7
PC	K	VC.f	44.0	43.1	45.3
PC	K	VC.o	44.8	44.1	45.9
PC	Mg	BO.f	16.1	15.2	16.6
PC	Mg	BO.o	16.1	15.6	16.8
PC	Mg	BT.f	30.6	27.4	35.2
PC	Mg	BT.o	29.8	25.9	33.9
PC	Mg	VC.f	41.7	41.0	42.8
PC	Mg	VC.o	42.0	41.3	43.0
PC	Mn	BO.f	17.4	16.2	18.0
PC	Mn	BO.o	18.7	18.1	19.5
PC	Mn	BT.f	32.9	29.6	37.6
PC	Mn	BT.o	31.9	28.3	35.7
PC	Mn	VC.f	41.9	41.1	43.0
PC	Mn	VC.o	43.8	43.2	44.7
PC	N	BO.f	11.2	10.1	11.8
PC	N	BO.o	12.3	11.5	13.1
PC	N	BT.f	33.6	28.9	40.5
PC	N	BT.o	33.0	27.3	38.8
PC	N	VC.f	40.8	39.5	42.7
PC	N	VC.o	41.8	40.4	43.6
PC	P	BO.f	14.8	13.8	15.4
PC	P	BO.o	15.5	15.0	16.1
PC	P	BT.f	32.6	28.8	38.2
PC	P	BT.o	30.1	25.9	34.7
PC	P	VC.f	43.7	42.8	45.0
PC	P	VC.o	44.7	44.1	45.7
PC	S	BO.f	18.6	17.3	19.3
PC	S	BO.o	19.3	18.4	20.2
PC	S	BT.f	34.6	31.3	39.4
PC	S	BT.o	33.4	29.7	37.4
PC	S	VC.f	43.3	42.5	44.3
PC	S	VC.o	44.0	43.3	45.0
PC	Zn	BO.f	24.7	24.0	25.1
PC	Zn	BO.o	23.5	23.2	23.8
PC	Zn	BT.f	30.8	29.6	32.6
PC	Zn	BT.o	29.9	28.1	31.9
PC	Zn	VC.f	43.2	43.1	43.3
PC	Zn	VC.o	43.6	43.6	43.7
RR	B	BO.f	25.6	24.8	26.9

Table A6. Continued...

Site	Nutrient	Harvesting and Treatment	Mean (%)	Min (%)	Max (%)
RR	B	BO.o	25.5	24.6	26.0
RR	B	BT.f	32.0	29.7	33.8
RR	B	BT.o	32.1	29.5	36.4
RR	B	VC.f	48.6	48.6	48.6
RR	B	VC.o	48.4	48.3	48.6
RR	Ca	BO.f	19.4	18.6	20.3
RR	Ca	BO.o	21.5	20.8	22.1
RR	Ca	BT.f	28.2	25.4	30.9
RR	Ca	BT.o	29.1	26.3	33.7
RR	Ca	VC.f	48.6	48.4	49.0
RR	Ca	VC.o	48.0	47.9	48.3
RR	Cu	BO.f	24.0	23.3	25.1
RR	Cu	BO.o	14.2	14.0	14.3
RR	Cu	BT.f	29.6	27.6	31.2
RR	Cu	BT.o	21.9	19.6	26.8
RR	Cu	VC.f	48.5	48.4	48.6
RR	Cu	VC.o	47.8	47.6	48.0
RR	Fe	BO.f	29.2	28.4	30.6
RR	Fe	BO.o	26.4	25.6	26.8
RR	Fe	BT.f	32.9	31.1	33.9
RR	Fe	BT.o	31.9	29.6	35.7
RR	Fe	VC.f	49.6	49.5	49.8
RR	Fe	VC.o	45.0	45.0	45.1
RR	K	BO.f	17.3	16.4	18.5
RR	K	BO.o	15.1	14.5	15.8
RR	K	BT.f	28.7	25.2	32.0
RR	K	BT.o	28.2	24.1	35.5
RR	K	VC.f	49.0	48.8	49.4
RR	K	VC.o	49.5	49.2	49.9
RR	Mg	BO.f	15.7	14.7	16.9
RR	Mg	BO.o	14.4	13.8	15.2
RR	Mg	BT.f	29.1	25.1	33.1
RR	Mg	BT.o	28.8	24.3	36.7
RR	Mg	VC.f	47.6	47.3	48.1
RR	Mg	VC.o	47.4	47.2	47.7
RR	Mn	BO.f	15.2	14.2	16.3
RR	Mn	BO.o	16.6	15.9	17.3
RR	Mn	BT.f	29.6	25.3	33.9
RR	Mn	BT.o	29.5	25.4	36.8
RR	Mn	VC.f	47.6	47.3	48.2

Table A6. Continued...

Site	Nutrient	Harvesting and Treatment	Mean (%)	Min (%)	Max (%)
RR	Mn	VC.o	47.3	47.1	47.5
RR	N	BO.f	12.5	11.6	13.4
RR	N	BO.o	12.7	12.2	13.3
RR	N	BT.f	29.9	24.9	35.2
RR	N	BT.o	30.5	25.2	40.2
RR	N	VC.f	46.7	46.2	47.5
RR	N	VC.o	47.7	47.4	47.9
RR	P	BO.f	15.3	14.5	16.3
RR	P	BO.o	14.3	13.7	14.9
RR	P	BT.f	28.0	24.2	31.9
RR	P	BT.o	27.4	23.4	34.9
RR	P	VC.f	48.5	48.3	49.0
RR	P	VC.o	49.3	49.0	49.6
RR	S	BO.f	17.4	16.3	18.5
RR	S	BO.o	17.0	16.4	17.7
RR	S	BT.f	30.9	26.9	34.9
RR	S	BT.o	31.0	26.6	38.8
RR	S	VC.f	47.9	47.6	48.4
RR	S	VC.o	48.1	47.9	48.3
RR	Zn	BO.f	19.4	18.9	20.1
RR	Zn	BO.o	18.3	17.8	18.6
RR	Zn	BT.f	24.2	22.5	25.8
RR	Zn	BT.o	24.0	22.0	27.7
RR	Zn	VC.f	47.6	47.5	47.9
RR	Zn	VC.o	46.8	46.6	47.1

8.2 Harvest Scenario Mass

Table A7. Total biomass per hectare and percentage of total aboveground biomass removed harvested under each of the four harvesting scenarios at each of the four SMC Type I installations.

Harvest Scenario	Model	Site	Harvested Biomass (Mg/Ha)	Min. Harvested Biomass (Mg/Ha)	Max. Harvested Biomass (Mg/Ha)	Relative Tree Biomass Removed (%)	Min. Relative Tree Biomass Removed (%)	Max. Relative Tree Biomass Removed (%)
BO	*SMC site-specific*	ET	61.3	35.6	81.0	69.9	63.4	74.7
		LF	76.1	60.9	100.4	66.5	59.2	75.4
		PC	52.6	40.9	70.3	74.9	73.5	75.5
		RR	51.5	33.7	65.2	71.3	69.8	75.2
BT		ET	64.5	39.4	84.7	74.0	66.5	81.4
		LF	79.8	62.6	103.9	69.9	60.9	81.6
		PC	57.1	46.7	74.0	81.5	80.1	83
		RR	54.5	36.9	68.4	75.9	73.0	81.6
VC		ET	84.9	45.8	112.0	96.2	94.5	97.3
		LF	111.3	95.8	151.1	97.2	96.4	98
		PC	68.3	54.0	90.5	97.2	96.3	97.6
		RR	70.4	46.5	89.9	97.5	96.4	97.7
WT		ET	88.1	48.4	115.5	100.0	-	-
		LF	114.5	99.1	154.2	100.0	-	-
		PC	70.2	56.3	92.2	100.0	-	-
		RR	72.1	48.2	91.6	100.0	-	-
BO	*SMC general*	ET	64.7	36.3	87.3	68.4	65.4	76.5
		LF	74.2	59.7	98.5	66.9	58.8	75
		PC	52.3	43.5	66.4	74.6	72.7	76.2
		RR	53.9	35.0	68.4	72.4	68.9	74.4
BT		ET	68.7	41.1	91.6	73.0	68.1	82.3
		LF	78.0	61.3	102.1	70.4	60.4	81.2
		PC	56.9	49.1	70.5	81.3	80.3	83
		RR	57.1	38.2	71.8	77.0	72.1	80.2
VC		ET	91.8	48.8	122.7	96.5	94.6	97
		LF	108.0	92.7	147.0	97.2	96.4	98
		PC	68.0	57.0	85.9	97.1	95.9	98.1
		RR	72.5	46.9	93.2	97.2	96.5	98.1
WT		ET	95.0	51.6	126.1	100	-	-
		LF	111.1	95.9	150.1	100	-	-
		PC	70.0	59.2	87.9	100	-	-
		RR	74.5	48.7	95.4	100	-	-

8.4 Stability Ratio

Table A8. .2011 Stability Ratio (SRc) and 50 year Stability Ratio (SR50) by site, fertilization treatment, nutrient and harvest scenario for all nutrients. Treatment types include fertilized (F) and unfertilized (O) plots.

Site	Harvest scenario	Nutrient	Fertilization Treatment	Aboveground Nutrient Content (Kg/ha)	Total Soil Nutrient (kg/ha)	SRc	SR50
ET	BO	Ca	F	20.09	7208.52	0.0028	0.0037
ET	BO	Ca	O	12.49	7208.52	0.0017	0.0023
ET	BT	Ca	F	28.95	7208.52	0.0040	0.0053
ET	BT	Ca	O	19.61	7208.52	0.0027	0.0036
ET	VC	Ca	F	40.56	7208.52	0.0056	0.0074
ET	VC	Ca	O	30.41	7208.52	0.0042	0.0055
ET	WT	Ca	F	99.30	7208.52	0.0136	0.0179
ET	WT	Ca	O	71.16	7208.52	0.0098	0.0129
LF	BO	Ca	F	31.22	4089.89	0.0076	0.0100
LF	BO	Ca	O	56.66	4089.89	0.0137	0.0180
LF	BT	Ca	F	38.32	4089.89	0.0093	0.0122
LF	BT	Ca	O	67.33	4089.89	0.0162	0.0213
LF	VC	Ca	F	73.79	4089.89	0.0177	0.0233
LF	VC	Ca	O	99.51	4089.89	0.0238	0.0313
LF	WT	Ca	F	160.56	4089.89	0.0378	0.0497
LF	WT	Ca	O	213.00	4089.89	0.0495	0.0651
PC	BO	Ca	F	26.95	4298.59	0.0062	0.0115
PC	BO	Ca	O	32.61	4298.59	0.0075	0.0139
PC	BT	Ca	F	36.18	4298.59	0.0083	0.0155
PC	BT	Ca	O	40.91	4298.59	0.0094	0.0175
PC	VC	Ca	F	49.44	4298.59	0.0114	0.0211
PC	VC	Ca	O	55.20	4298.59	0.0127	0.0235
PC	WT	Ca	F	112.42	4298.59	0.0255	0.0472
PC	WT	Ca	O	120.91	4298.59	0.0274	0.0507
RR	BO	Ca	F	23.35	5581.82	0.0042	0.0065
RR	BO	Ca	O	25.51	5581.82	0.0045	0.0071
RR	BT	Ca	F	33.42	5581.82	0.0060	0.0093
RR	BT	Ca	O	34.05	5581.82	0.0061	0.0095
RR	VC	Ca	F	58.20	5581.82	0.0103	0.0161
RR	VC	Ca	O	56.95	5581.82	0.0101	0.0158
RR	WT	Ca	F	119.79	5581.82	0.0210	0.0328
RR	WT	Ca	O	118.58	5581.82	0.0208	0.0325
ET	BO	K	F	15.06	4162.84	0.0036	0.0047
ET	BO	K	O	16.15	4162.84	0.0039	0.0051
ET	BT	K	F	24.67	4162.84	0.0059	0.0078
ET	BT	K	O	25.79	4162.84	0.0062	0.0081
ET	VC	K	F	42.77	4162.84	0.0102	0.0134
ET	VC	K	O	46.80	4162.84	0.0111	0.0146
ET	WT	K	F	105.69	4162.84	0.0248	0.0326

Table A8. Continued...

Site	Harvest scenario	Nutrient	Fertilization Treatment	Aboveground nutrient content (Kg/ha)	Total soil nutrient (kg/ha)	SRc	SR50
ET	WT	K	O	102.69	4162.84	0.0241	0.0317
LF	BO	K	F	15.54	347.15	0.0428	0.0564
LF	BO	K	O	19.31	347.15	0.0527	0.0693
LF	BT	K	F	21.83	347.15	0.0592	0.0778
LF	BT	K	O	28.85	347.15	0.0767	0.1010
LF	VC	K	F	47.87	347.15	0.1212	0.1595
LF	VC	K	O	56.31	347.15	0.1396	0.1836
LF	WT	K	F	104.07	347.15	0.2306	0.3035
LF	WT	K	O	119.51	347.15	0.2561	0.3370
PC	BO	K	F	12.08	4959.96	0.0024	0.0045
PC	BO	K	O	15.54	4959.96	0.0031	0.0058
PC	BT	K	F	26.91	4959.96	0.0054	0.0100
PC	BT	K	O	31.12	4959.96	0.0062	0.0115
PC	VC	K	F	36.56	4959.96	0.0073	0.0136
PC	VC	K	O	45.68	4959.96	0.0091	0.0169
PC	WT	K	F	83.17	4959.96	0.0165	0.0305
PC	WT	K	O	102.05	4959.96	0.0202	0.0373
RR	BO	K	F	11.71	1190.65	0.0097	0.0152
RR	BO	K	O	10.67	1190.65	0.0089	0.0139
RR	BT	K	F	18.97	1190.65	0.0157	0.0245
RR	BT	K	O	19.44	1190.65	0.0161	0.0251
RR	VC	K	F	32.85	1190.65	0.0268	0.0420
RR	VC	K	O	34.77	1190.65	0.0284	0.0443
RR	WT	K	F	67.04	1190.65	0.0533	0.0833
RR	WT	K	O	70.31	1190.65	0.0558	0.0871
ET	BO	Mg	F	4.08	42772.00	0.0001	0.0001
ET	BO	Mg	O	3.10	42772.00	0.0001	0.0001
ET	BT	Mg	F	6.17	42772.00	0.0001	0.0002
ET	BT	Mg	O	5.09	42772.00	0.0001	0.0002
ET	VC	Mg	F	9.36	42772.00	0.0002	0.0003
ET	VC	Mg	O	7.66	42772.00	0.0002	0.0002
ET	WT	Mg	F	23.23	42772.00	0.0005	0.0007
ET	WT	Mg	O	18.02	42772.00	0.0004	0.0006
LF	BO	Mg	F	3.63	15222.48	0.0002	0.0003
LF	BO	Mg	O	6.12	15222.48	0.0004	0.0005
LF	BT	Mg	F	5.22	15222.48	0.0003	0.0005
LF	BT	Mg	O	8.72	15222.48	0.0006	0.0008
LF	VC	Mg	F	9.88	15222.48	0.0006	0.0009
LF	VC	Mg	O	13.81	15222.48	0.0009	0.0012

Table A8. Continued...

Site	Harvest scenario	Nutrient	Fertilization Treatment	Aboveground nutrient content (Kg/ha)	Total soil nutrient (kg/ha)	SRc	SR50
LF	WT	Mg	F	22.33	15222.48	0.0015	0.0019
LF	WT	Mg	O	30.44	15222.48	0.0020	0.0026
PC	BO	Mg	F	3.33	9931.27	0.0003	0.0006
PC	BO	Mg	O	3.62	9931.27	0.0004	0.0007
PC	BT	Mg	F	6.25	9931.27	0.0006	0.0012
PC	BT	Mg	O	6.58	9931.27	0.0007	0.0012
PC	VC	Mg	F	8.59	9931.27	0.0009	0.0016
PC	VC	Mg	O	9.39	9931.27	0.0009	0.0017
PC	WT	Mg	F	20.62	9931.27	0.0021	0.0038
PC	WT	Mg	O	22.37	9931.27	0.0022	0.0042
RR	BO	Mg	F	2.85	13246.28	0.0002	0.0003
RR	BO	Mg	O	2.76	13246.28	0.0002	0.0003
RR	BT	Mg	F	5.16	13246.28	0.0004	0.0006
RR	BT	Mg	O	5.39	13246.28	0.0004	0.0006
RR	VC	Mg	F	8.54	13246.28	0.0006	0.0010
RR	VC	Mg	O	9.04	13246.28	0.0007	0.0011
RR	WT	Mg	F	17.98	13246.28	0.0014	0.0021
RR	WT	Mg	O	19.07	13246.28	0.0014	0.0022
ET	BO	N	F	25.72	10154.04	0.0025	0.0033
ET	BO	N	O	21.64	10154.04	0.0021	0.0028
ET	BT	N	F	55.39	10154.04	0.0054	0.0071
ET	BT	N	O	45.99	10154.04	0.0045	0.0059
ET	VC	N	F	77.58	10154.04	0.0076	0.0100
ET	VC	N	O	63.83	10154.04	0.0062	0.0082
ET	WT	N	F	207.70	10154.04	0.0200	0.0264
ET	WT	N	O	157.42	10154.04	0.0153	0.0201
LF	BO	N	F	24.90	9958.75	0.0025	0.0033
LF	BO	N	O	29.00	9958.75	0.0029	0.0038
LF	BT	N	F	51.07	9958.75	0.0051	0.0067
LF	BT	N	O	61.51	9958.75	0.0061	0.0081
LF	VC	N	F	93.14	9958.75	0.0093	0.0122
LF	VC	N	O	94.38	9958.75	0.0094	0.0124
LF	WT	N	F	227.65	9958.75	0.0223	0.0294
LF	WT	N	O	220.70	9958.75	0.0217	0.0285
PC	BO	N	F	21.17	21632.45	0.0010	0.0018
PC	BO	N	O	23.26	21632.45	0.0011	0.0020
PC	BT	N	F	63.12	21632.45	0.0029	0.0054
PC	BT	N	O	61.19	21632.45	0.0028	0.0052
PC	VC	N	F	76.95	21632.45	0.0035	0.0066

Table A8. Continued….

Site	Harvest scenario	Nutrient	Fertilization Treatment	Aboveground nutrient content (Kg/ha)	Total soil nutrient (kg/ha)	SRc	SR50
PC	VC	N	O	78.27	21632.45	0.0036	0.0067
PC	WT	N	F	189.06	21632.45	0.0087	0.0160
PC	WT	N	O	187.88	21632.45	0.0086	0.0159
RR	BO	N	F	20.47	14021.98	0.0015	0.0023
RR	BO	N	O	21.52	14021.98	0.0015	0.0024
RR	BT	N	F	47.72	14021.98	0.0034	0.0053
RR	BT	N	O	50.53	14021.98	0.0036	0.0056
RR	VC	N	F	75.87	14021.98	0.0054	0.0084
RR	VC	N	O	80.67	14021.98	0.0057	0.0089
RR	WT	N	F	162.73	14021.98	0.0115	0.0179
RR	WT	N	O	169.19	14021.98	0.0119	0.0186
ET	BO	P	F	3.43	14879.97	0.0002	0.0003
ET	BO	P	O	3.38	14879.97	0.0002	0.0003
ET	BT	P	F	6.10	14879.97	0.0004	0.0005
ET	BT	P	O	6.26	14879.97	0.0004	0.0006
ET	VC	P	F	10.34	14879.97	0.0007	0.0009
ET	VC	P	O	10.49	14879.97	0.0007	0.0009
ET	WT	P	F	26.15	14879.97	0.0018	0.0023
ET	WT	P	O	24.16	14879.97	0.0016	0.0021
LF	BO	P	F	2.82	3246.95	0.0009	0.0011
LF	BO	P	O	3.80	3246.95	0.0012	0.0015
LF	BT	P	F	4.37	3246.95	0.0013	0.0018
LF	BT	P	O	6.45	3246.95	0.0020	0.0026
LF	VC	P	F	9.29	3246.95	0.0029	0.0038
LF	VC	P	O	12.48	3246.95	**0.0038**	0.0050
LF	WT	P	F	20.88	3246.95	**0.0064**	0.0084
LF	WT	P	O	27.27	3246.95	**0.0083**	0.0110
PC	BO	P	F	3.25	7857.84	0.0004	0.0008
PC	BO	P	O	4.11	7857.84	0.0005	0.0010
PC	BT	P	F	7.07	7857.84	0.0009	0.0017
PC	BT	P	O	7.87	7857.84	0.0010	0.0019
PC	VC	P	F	9.54	7857.84	0.0012	0.0022
PC	VC	P	O	11.81	7857.84	0.0015	0.0028
PC	WT	P	F	21.84	7857.84	0.0028	0.0051
PC	WT	P	O	26.46	7857.84	0.0034	0.0062
RR	BO	P	F	2.70	9455.12	0.0003	0.0004
RR	BO	P	O	2.66	9455.12	0.0003	0.0004
RR	BT	P	F	4.83	9455.12	0.0005	0.0008
RR	BT	P	O	5.01	9455.12	0.0005	0.0008

Table A8. Continued...

Site	Harvest scenario	Nutrient	Fertilization Treatment	Aboveground nutrient content (Kg/ha)	Total soil nutrient (kg/ha)	SRc	SR50
RR	VC	P	F	8.48	9455.12	0.0009	0.0014
RR	VC	P	O	9.17	9455.12	0.0010	0.0015
RR	WT	P	F	17.51	9455.12	0.0018	0.0029
RR	WT	P	O	18.63	9455.12	0.0020	0.0031
ET	BO	S	F	2.99	1484.68	0.0020	0.0026
ET	BO	S	O	2.50	1484.68	0.0017	0.0022
ET	BT	S	F	4.50	1484.68	0.0030	0.0040
ET	BT	S	O	4.03	1484.68	0.0027	0.0036
ET	VC	S	F	6.54	1484.68	0.0044	0.0058
ET	VC	S	O	5.78	1484.68	0.0039	0.0051
ET	WT	S	F	16.23	1484.68	0.0108	0.0142
ET	WT	S	O	13.67	1484.68	0.0091	0.0120
LF	BO	S	F	3.08	1041.59	0.0029	0.0039
LF	BO	S	O	3.82	1041.59	0.0036	0.0048
LF	BT	S	F	4.38	1041.59	0.0042	0.0055
LF	BT	S	O	5.67	1041.59	0.0054	0.0071
LF	VC	S	F	7.91	1041.59	0.0075	0.0099
LF	VC	S	O	8.93	1041.59	0.0085	0.0112
LF	WT	S	F	18.05	1041.59	0.0170	0.0224
LF	WT	S	O	19.87	1041.59	0.0187	0.0246
PC	BO	S	F	2.91	2201.71	0.0013	0.0024
PC	BO	S	O	2.98	2201.71	0.0013	0.0025
PC	BT	S	F	5.36	2201.71	0.0024	0.0045
PC	BT	S	O	5.09	2201.71	0.0023	0.0043
PC	VC	S	F	6.74	2201.71	0.0031	0.0057
PC	VC	S	O	6.75	2201.71	0.0031	0.0057
PC	WT	S	F	15.59	2201.71	0.0070	0.0130
PC	WT	S	O	15.37	2201.71	0.0069	0.0128
RR	BO	S	F	2.08	2644.31	0.0008	0.0010
RR	BO	S	O	2.15	2644.31	0.0008	0.0011
RR	BT	S	F	3.62	2644.31	0.0014	0.0018
RR	BT	S	O	3.84	2644.31	0.0014	0.0019
RR	VC	S	F	5.69	2644.31	0.0021	0.0028
RR	VC	S	O	6.07	2644.31	0.0023	0.0030
RR	WT	S	F	11.89	2644.31	0.0045	0.0059
RR	WT	S	O	12.61	2644.31	0.0047	0.0062