AN ABSTRACT OF THE THESIS OF

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Concentration of carbon dioxide (CO_2) in the atmosphere has increased over the past 150 years. Because CO_2 is one of a number of radiatively active gases, there is concern that global temperatures will rise and climatic conditions will change. Recent research indicates northern hemisphere forests may currently be accumulating carbon (C) from the atmosphere. Live trees hold a large proportion of forest C, however, live-tree C can only be measured indirectly and therefore estimates of live-tree C are subject to numerous uncertainties.

The objectives of this research were to estimate how live-tree C stores changed in the Pacific Northwest (Oregon and Washington west of the Cascade crest) between 1963-91 and to assess the factors introducing uncertainty into the estimate of live-tree C storage.

The first objective was accomplished by using data from the Forest Service Forest Inventory and Analysis Program (FIA), combined with western Oregon and western Washington annual timber harvest data. The study produced live-tree C estimates for all timberland by land-ownership group. Between 1963-91, C on all timberland in the Pacific Northwest decreased from 1636 to 1392 Tg, or by 15% of the 1963 total. National forest, other public (other federal, state, and local government), forest

industry, and miscellaneous private land lost 15, 5 (non-significant), 24, and 18% of their 1963 total timberland live-tree C by 1991, respectively. All landowners except industry experienced significant declines in total timberland area. C density (live-tree C per area) on all timberland dropped by 13% on national forests and by 30% on forest industry, but rose by 1% (non-significant) on other public and 26% on miscellaneous private land. For the Pacific Northwest as a whole, C density on all timberland decreased by 8% over the 28-year study period. C density declined most dramatically between 1963 and 1974. Since 1974, increasing C density on other public and miscellaneous private land balanced declining C density on national forest and forest industry land, resulting a C density ranging between 135-136 Mg C ha^{-1} on all timberland.

The live-tree C estimate is subject to uncertainty arising from sampling, regression, measurement, and model error. We created and implemented a method for assessing uncertainty arising from model error. Volume equations, densities, biomass equations, and C:biomass ratios were compiled for the five major tree species in northwest Oregon: *Picea sitchensis, Pseudotsuga menziesii, Tsuga heterophylla, Acer macrophyllum*, and *Alnus rubra*. Volume equations were transformed into biomass by multiplying predicted volume with a range of species-specific measured densities. Biomass derived from volume equations multiplied by densities or from biomass equations was converted to C using a range of C:biomass ratios. For each tree component, species, and diameter at breast height, the maximum and minimum C predicted by equations was captured and stored as lookup tables. Component lookup tables were summed to create estimates of tree total C under three assumptions about within-dbh class correlation between components: perfect positive, zero, or perfect negative correlation. Application of lookup table bounds to individual tree data from the FIA program produced estimates of minimum and maximum C for the five target species in northwest Oregon.

The above methods resulted in a base-case live-tree C estimate for northwest Oregon ranging from 28-210 Tg C (±76% uncertainty) assuming perfect positive correlation, and 67-154 Tg C (±40% uncertainty) for perfect negative correlation. When height variation was incorporated, C storage uncertainty rose to ±91% for

positive and ±51% for negative correlation. A gain in precision was realized when species-specific equations were applied. Replacement of diameter-distribution data by quadratic mean diameter for each species reduced the absolute value of uncertainty, but created a bias when compared to the base case. Our attempt to incorporate regression standard error produced extremely large uncertainties for some equations and therefore was not pursued further. Results indicate that the most substantial reductions in uncertainty could be obtained by accurately assigning individual trees to suitable equations.

The magnitude of model error produced by our methods currently precludes determination of significant differences between live-tree C stores of most landowners in the Pacific Northwest, and renders impossible the precise determination of the amount of live-tree C in a given forest area. Nevertheless, this does not necessarily preclude meaningful comparisons of C flux.

Results of this study indicate uncertainty from model error in live-tree C could be extremely large. However, by accurately assigning appropriate volume or biomass prediction equations to trees, uncertainty could be greatly reduced.

Live-Tree Carbon in the Pacific Northwest: Estimates and Uncertainties

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LIVE-TREE CARBON IN THE PACIFIC NORTHWEST: ESTIMATES AND UNCERTAINTIES

1 INTRODUCTION

1.1 Climate Change

It has long been suggested that buildup of various anthropogenically-emitted radiatively-active gases in the atmosphere will bring about global climate change through the greenhouse effect (Fleming 1998). This effect results from the behavior of these greenhouse gases, such as water vapor, carbon dioxide (CO_2), methane, chlorofluorocarbons, and nitrous oxides, which capture heat and re-radiate it within the atmosphere (Albritton et al. 2001). The greenhouse effect maintains the surface temperature of much of the earth within a range suitable for life, but enhancement of this effect has been predicted to cause a rise in air temperature, regional alterations in frequency and intensity of precipitation, changes in ocean circulation, rise in sea-levels, and increase in catastrophic weather events. Although human activities have increased the atmospheric concentration of numerous greenhouse gases, firm evidence for associated climate change was lacking for many years owing to insufficient or unreliable data. Recent research indicates that globally averaged temperatures have risen since the late 1800s, and minimum daily temperatures increased almost twice as fast as maximum temperatures (Easterling et al. 1997). Precipitation has increased in some regions and declined in others. Sea levels reportedly rose by 1-2 mm year^{-1} between 1900-2000, and large oceanic cycles have been more irregular in recent years. The frequency and intensity of extreme weather events are so variable that changes are still difficult to gauge, but there is evidence that they are increasing in some regions (Albritton et al. 2001).

There remains a great deal to be learned about what the effects and magnitudes of global climate changes will be. Some have suggested a warmer, CO_2-enriched atmosphere will improve forestry, because plants require CO_2 for growth. However, some experimenters believe CO_2 growth enhancement might be short-lived (Schafer et al. 2003). Increased temperatures may counteract any CO_2 fertilization effect by increasing fire frequency or intensity, or both (Bachelet et al. 2001), and even with

abundant CO_2, other necessary compounds may become limiting for vegetation growth (Schafer et al. 2003). Because of the likelihood of various climate changes persisting or even increasing for many years after greenhouse gas levels have stabilized (Albritton et al. 2001), it is generally thought that greenhouse gas emissions should be reduced. To that end, the Kyoto Protocol (United Nations Framework Convention on Climate Change 2003) was negotiated in 1997. This international agreement required industrialized nations to meet country-specific goals of emissions reductions for numerous greenhouse gases within a set timeframe. The Protocol also provided for the possibility of emissions trading, in which countries with more sinks (processes that remove the gas from the atmosphere) than sources (process that release the gas into the atmosphere) can sell credits to countries that have more sources than sinks. Emissions trading is already practiced in the power-generating industry, and sinks of various compounds are now traded in financial markets Chicago Climate Exchange 2004; CO2e.com 2002).

For each country to demonstrate it has met its Protocol agreements for each target greenhouse gas, nation-wide inventories of sources and sinks are required. Although the United States (US) Congress has not ratified the Kyoto Protocol, the government is still interested in inventorying various greenhouse gases, and CO_2 is a main focus.

1.2   The Carbon Cycle

CO_2 is the greenhouse gas that has received the most attention over the past decades. Weathering and vulcanism release carbon (C) from rocks over the course of millions of years. Once freed from the lithosphere, much of it is eventually released as CO_2 into the atmosphere (Berner and Lasaga 1989) where it is then exchanged between the atmosphere (which holds approximately 748 P, 1 Petagram = 10^{15} grams), ocean (38,000 Pg), and terrestrial systems (2,000 Pg) (Post et al. 1990). Eventually C is returned to the lithosphere through oceanic sedimentation. An additional 4,000 Pg resides in fossil fuel deposits (Post et al. 1990). Exchange between vegetation, atmosphere, and upper ocean layers is relatively rapid and these pools can equilibrate fairly quickly to changes in free CO_2 (Post et al. 1990). Human activities affect the carbon cycle by releasing C into the atmosphere that was previously stored in fossil fuel deposits and forests. Because the largest pool of free

CO_2, the deep ocean, has a long exchange time, much of this anthropogenically-emitted CO_2 will remain in the atmosphere for decades or even centuries (Post et al. 1990). Besides natural changes in atmospheric concentrations of CO_2 annually due to vegetational growth, atmospheric CO_2 fluctuates over longer timespans in response to changes in solar radiation, the earth's orbit (Albritton et al. 2001), volcanic activity, and the rate at which organic material is buried (Berner and Lasaga 1989). Ice core research and geochemical studies suggest present CO_2 levels are the highest they have been in 420 thousand, and possibly 20 million, years (Albritton et al. 2001). Measurements at Mauna Loa, Hawaii indicate that in 2003, CO_2 reached 376 parts per million in the atmosphere (Keeling and Whorf 2004), a 16% increase from 1959, and a 25% increase from the estimated CO_2 concentration in 1750 (Albritton et al. 2001).

1.3   Forest Carbon Stores

C is captured by vegetation during photosynthesis and released during respiration. Net uptake of C results in plant growth, and live trees represent a significant C sink. After the death of a tree, C incorporated into tissues is released through decomposition. At the level of an individual tree, the tree death results in an eventual return of C to the atmosphere. At the level of a stand or a forest, however, tree death leads to the accumulation of a woody debris pool (Harmon 2001). Non-woody debris results from litterfall, and at the level of a forest a considerable amount of C can build up in the litter layer. Decomposition of both types of detritus and fine roots transfer some C into the soil, where it may be sequestered for many years.

A mature forest unaffected by humans or major natural disturbances is assumed to be at "equilibrium", with C taken from the atmosphere balanced by C leaving the forest through decomposition and respiration. However, most if not all of the forest area in the US has been affected at some time both by harvest operations and by natural disturbances such as fire, insects, disease, and extreme weather. The amount of C stored is a function of forest area, management practices, and disturbance. Forest area is diminished through land-clearing for urban or agricultural expansion and construction of roads and dams, but is increased when any of those land-uses is allowed to revert to forest. The harvest process releases about 58% of the harvested

C to the atmosphere within a few years of harvest, though some C is sequestered in long-lived wood products (Harmon et al. 1990). After harvest, forest C first declines as harvest residue decays, then accumulates as young trees reclaim the site. Fires can return large quantities of C to the atmosphere, though a fraction of C is converted to charcoal, which persists for many years. Tree mortality from insects, disease, or weather transfers C from the live to the detrital pools, where it is gradually released to the atmosphere and transferred to the soil layer. Increased intensity or frequency, or both, of any disturbance may result in less C stored in a forest.

Recent evidence suggests that northern hemisphere forests are a significant C sink (Dixon et al. 1994; Goodale et al. 2002). Many countries, the US included, are interested in exploring forest C sequestration as a possible way to offset their anthropogenic CO_2 emissions and profit through the sale of any excess carbon credits to other entities. Turner et al. (1995) estimated that timberland in the lower 48 US states stored 36.7 Pg C, or 183 Mg ha^{-1} (timberland is forest that can produce 1.4 m^{3}ha^{-1}yr^{-1} of merchantable wood). Birdsey and Heath (1995) calculated 34.2 Pg C (168 Mg ha^{-1}) for timberland in the same area for 1992. Soils stored 50%, the live tree store comprised 33%, woody debris accounted for 10%, litter held 6%, and understory vegetation was 1% of C in US timberland (Turner et al. 1995). Forest re-growth on old agricultural sites in much of the nation created a net sink of almost 0.26 Pg C yr^{-1} between 1952-92 on US timberland, although this C sequestration rate was expected to decline between 1992 and 2040 (Birdsey and Heath 1995).

This level of C sequestration by US forests cannot balance current US CO_2 emissions (Birdsey and Heath 1995, Marland and Marland 1992). However, reforestation can help reduce atmospheric CO_2 when combined with emissions-reduction measures. For the US to use these sinks to offset anthropogenic CO_2 emissions, sink magnitude and variability must be better understood. Regional forest C dynamics result from the interaction of climate and the land-use histories of individual forest parcels, both of which are regionally variable.

1.4   Uncertainty

A great deal of uncertainty surrounds the global climate change issue. Firstly, is it happening? Recent measurements reduce the uncertainty of the analysis and indicate the answer is more and more likely to be "yes" (Albritton et al. 2001). Secondly, what will the exact climate changes be? Computer models, called general circulation models (GCMs) attempt to predict this by simulating interacting processes occurring in the oceans, continents, and atmosphere to create predictions of climate patterns at low (100s of km) or high (50 km) resolutions (Met Office 2002). Although GCMs have become much more sophisticated, they still lack integration of all influential inputs. Even when all inputs are present, lack of knowledge about system behavior may limit output reliability. For example, clouds can warm or cool the earth's surface, depending on their individual properties. Predicting these properties is a complex undertaking, and models parameterize influential variables differently, resulting in different model outputs (Albritton et al. 2001).

Computer modeling is also used to predict the effect of climate change on global vegetation. Vegetation models use climate predictions from GCMs, and may require additional inputs such as the effect of CO_2 on vegetation, the impact of global warming on the nitrogen cycle, wildfire frequency and intensity, and so on. Variation of input assumptions can cause large differences in predictions, and different models with the same inputs still generate different predictions, although they often agree on the same general patterns of change. For example, Bachelet et al. (2001) determined that two types of models concurred that moderate global temperature increases would enhance US forest C sequestration, and a more extreme temperature rise would produce declines in forest C. However, the models differed in their predictions of the magnitude of vegetation distribution change, and occasionally even in whether such changes would be positive or negative for a given vegetation type.

This level of uncertainty about future climate changes and the response of vegetation complicates decision-making. For policymakers to determine which predictions to react to and how strongly to react, estimates of the likelihood of each outcome are required. An estimate of uncertainty is as important as the estimate of the quantity itself.

Besides the uncertainty surrounding the effect of climate change on various C pools, uncertainty exists in the past and present magnitudes of these pools. Uncertainty introduced into a forest C storage estimate has many sources. Partly it originates from the sampling error of the forest inventories which must be employed because there is no practical way of measuring forest C directly. C estimate uncertainty may arise from measurement error in the forest inventory dataset. Uncertainty also arises from using regression relationships to convert individual tree data to C. In many cases, numerous regression relationships are available, and many may appear equally applicable to the target dataset. Uncertainty in the final C estimate that arises from application of different sets of equations to the same data is termed model error.

1.5   Thesis Overview

Determination of forest C store magnitude and flux is an issue of global importance with implications for policy and economics. To assist in assessing C flux, we estimate change in PNW live-tree C stores over almost three decades. Because these live-tree C store estimates are constructed from forest inventory data using regression relationships and conversion factors, uncertainty is introduced in numerous ways. It enters through the sampling error of the inventory, measurement error of the inventory data, regression error of the equations used to convert inventory data to C, and model error that arises from choosing one set of equations and conversion factors from all applicable equations and conversion factors. We therefore explore uncertainties in live-tree C store estimates in northwest Oregon stemming from model error.

In Chapter 2, we estimate change in forest live-tree C stores by major landowner class in the Pacific Northwest (PNW) region. We apply a simplified version of the methods used in Turner et al. (1995) to forest inventory data for 1963-97 to create yearly estimates of C storage. To examine the effect of management practices in the PNW, we also calculate C storage for four landowner classes: national forest, other public, forest industry, and miscellaneous private.

Between 1963-91, the PNW lost 13% of its 1963 live-tree C store of 1636 Tg. C density (C per area) declined from 146 to 138 Mg C ha^{-1}. National forest timberland

lost 15% of its 1963 live-tree C and 13% of its C density. The other public land category experienced little significant change in live-tree C stores. Forest industry showed the highest percentage C loss, 24%, and C density declined by 29% of its 1963 value. Live-tree C on miscellaneous private land declined by 18% between 1963 and 1991, but the loss of timberland area over the same time period resulted in a C density increase of 26%.

In 1991, national forest held by far the most live-tree C, miscellaneous private the least, and other public and forest industry an intermediate amount. C density on national forest and other public was approximately equal. This was almost double the C density of forest industry and miscellaneous private lands, which were not significantly different from one another.

Chapter 3 contributes an estimate of uncertainty of forest live-tree C store arising mainly from model error. We produce this estimate by collecting all applicable volume and biomass equations for the five major tree species in northwest Oregon. We then develop a method to apply each combination of equations to every tree to determine a range of possible forest C values for that region. Along with estimated model error, we suggest where future research should be concentrated to most effectively reduce uncertainty.

Our estimate of live-tree C uncertainty from model error in Northwest Oregon (NW OR) was very large. Under positive correlation of tree parts, NW OR live-tree C storage ranged from 28-210 Tg C, or ±119 Tg with ±70% uncertainty. Negative correlation of tree parts resulted in the narrowest bounds of 67-154 Tg, or 110 Tg with ±40% uncertainty.

Replacement of species-specific total tree C uncertainty with a generic uncertainty encompassing total tree uncertainty from all species increased uncertainty for NW OR. Removing information about distribution reduced midpoint estimates and the absolute uncertainty, but not percent uncertainty. Incorporating estimated variation from heights increased uncertainty to ±92 and ±53% under positive and negative correlation, respectively. We attempted to incorporate the variation around each equation introduced by regression error. Standard errors of regression were so great

for some equations that we decided this procedure was not useful currently. Regression errors nevertheless contribute to total uncertainty and eventually they should be incorporated into uncertainty estimates.

Our investigations suggested that the most effective way to reduce uncertainty from model error would be to partition the model error among groups of trees. Researchers using volume and biomass equations have essentially been partitioning trees among equations, sometimes based on geographic regions and sometimes on site characteristics. The problem with these partitions is there is often no way to tell whether they were appropriate. The most effective use of research time and money might best be focused on determining accurate ways to assign volume and biomass equations to trees.

2 CHANGES IN LIVE-TREE CARBON: THE PACIFIC NORTHWEST 1963-91

2.1 Introduction

Interest in the fate of the greenhouse gas carbon dioxide (CO_2) has increased focus on identifying and quantifying terrestrial pools of carbon (C). Release of CO_2 by anthropogenic activities, such as burning fossil fuel and clearing land, could increase the surface temperature of the planet and lead to other climatic alterations (Albritton et al. 2001), including a rise in sea-level and changes in variability and amount of precipitation. Oceans are the largest sink for CO_2 outside of carbonate rocks, yet the slow transfer of CO_2 to deep water layers means oceans cannot offset yearly anthropogenic emissions. Thus, atmospheric CO_2 concentration continues to climb (Albritton et al. 2001). Vegetation stores lesser amounts of CO_2 through photosynthesis, but emits it during respiration. Recent data suggest that terrestrial biomass acted as a C sink in the 1990s (Battle et al. 2000), especially in the northern hemisphere (Gurney et al. 2002); sequestration by northern temperate forests accounts for a portion of this sink (Goodale et al. 2002).

The amount of C stored in live trees depends on regional history. Because C is roughly half the mass of a living tree, it follows that accumulation of biomass will increase live-tree C stores. Trees in the Pacific Northwest (PNW) of the United States (US) can attain large volumes and thus store great amounts of C per hectare if undisturbed (Smithwick et al. 2002). At the landscape level, available area, site potential, and disturbance regime all contribute to total forest biomass (and, by extension, C). Available forest area in the PNW is controlled largely by human actions, whereas C storage potentials across the landscape are a complex interaction of climatic and geologic factors. Disturbance, either natural or anthropogenic, prevents a site from achieving its maximum C storage potential. Humans act to both disturb and restore the forest – most directly by clearing land, planting trees, and managing fire regimes, but also by polluting, fertilizing, and possibly changing climate. Any of these actions might alter stand composition and structure, and thereby change forest C storage. The greater the area or intensity of a disturbance, the greater the change in C stores on a landscape scale.

This chapter provides estimates of C stored in live trees on total and nonreserved timberland in the PNW between 1963-91. Timberland is defined here as forest land capable of producing 1.4 m^3 ha^{-1} year^{-1} or more of industrial-quality wood (MacLean et al. 1992). Nonreserved lands are areas open to commercial production; reserved lands are removed from such production by ordinance or statute (MacLean et al. 1992). Impacts of land-use history on live-tree C storage trends for the different landowners in the PNW are discussed. Lastly, some speculations about future live-tree C storage are considered.

2.2   Methods

2.2.1   Study Area

As used here, the PNW refers to the region of Oregon (OR) and Washington (WA) between the Pacific Ocean and the crest of the Cascade Range (Figure 2.1). The PNW covers 14.2 million ha, 11 million ha of which are forested. Ninety-three percent of the forest, or 10.3 million ha, are composed of timberland. The climate is generally mild, with cool wet winters and warm dry summers that foster growth of conifer-dominated forests. Forested areas are primarily located in the four PNW mountain ranges: the Coast Range that parallels the OR and part of the WA coast; the Olympic Range that follows the Olympic Peninsula in WA; the Cascade Range that runs north/south inland of the Coast Range in OR and continues through WA; and the Klamath range that is found in southwest OR. *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) and *Tsuga heterophylla* (Raf.) Sarg. (western hemlock) are the dominant tree species of the low- to mid-elevations (Franklin and Dyrness 1988).

Timberland ownership is almost evenly divided between public and private holdings. Two public ownership categories were recognized in this analysis: National Forest (NF) and Other Public (OP). NF lands are administered by the US Department of Agriculture (USDA) Forest Service (FS). OP holdings consist of US Department of Interior (USDI) Bureau of Land Management (BLM) and various other federal, state, and local government properties. Private landowners are also divided into two categories: Forest Industry (FI), owned by timber corporations; and Miscellaneous Private (MP), which includes those nonpublic lands in nonindustrial ownership.
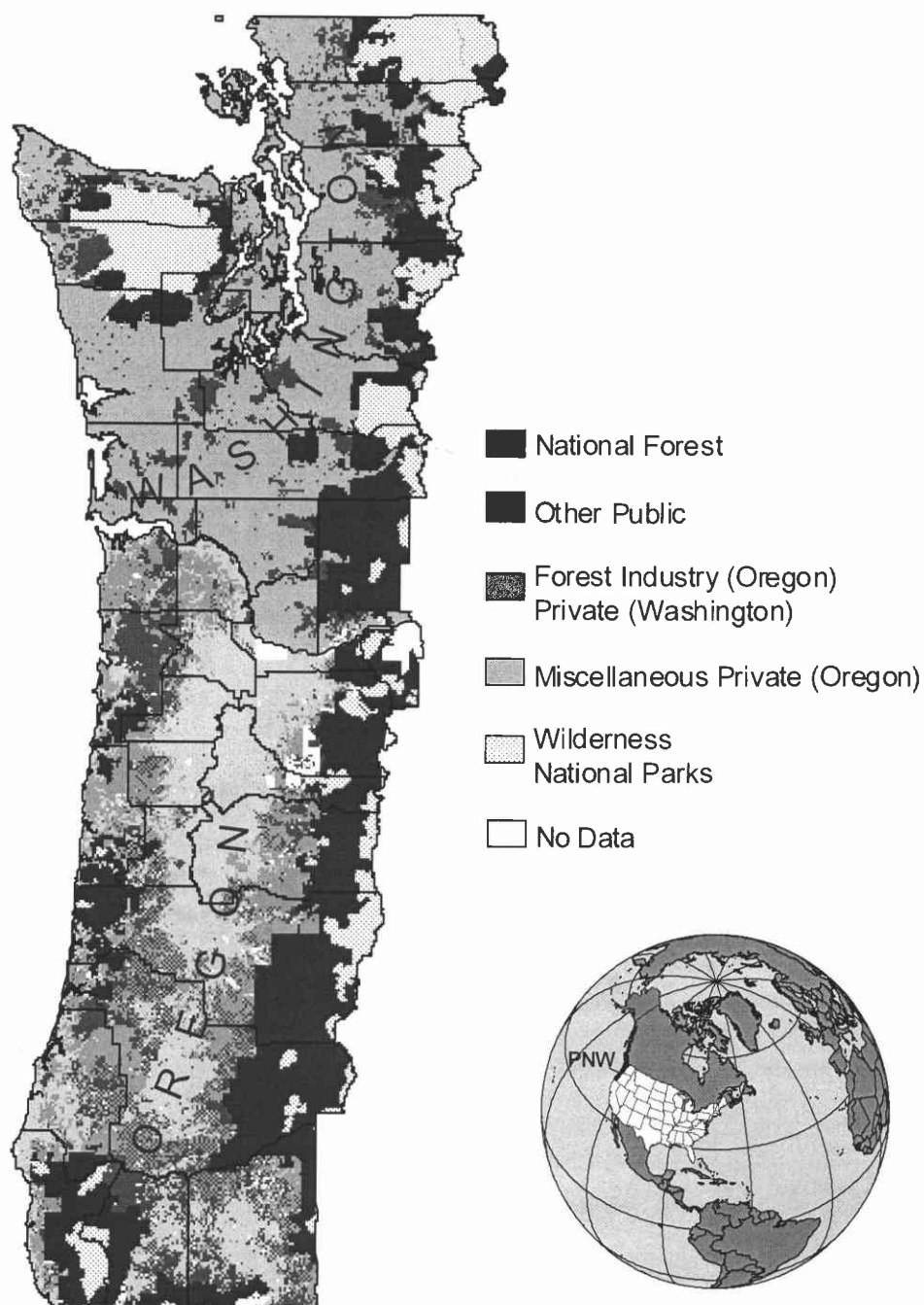
Figure 2.1. PNW study area by landowner class. WA landowner data was obtained in 2001 through the FIA program in Portland, OR; OR data from Kagan et al. (1999) and Sollins (1994). WA landownership was not separated into FI and MP. Not all areas shown contain timberland.

2.2.2 *Inventory Design and Data*

Forest inventory data were collected and compiled by individual NFs, the FS PNW Research Station, and the BLM between 1957-97. NF personnel conducted inventories on NF land from the 1960s to 2000. The research station program, currently known as Forest Inventory and Analysis (FIA), inventoried private and public lands excluding NF and BLM lands in western OR (WOR) from the 1960s to 2000. The BLM directed inventories on its own lands. No inventory during this period included the national park (NP) system. Sampling procedures differed between agencies and years; nevertheless, similar base data (to produce estimates of timberland volume, growth, and mortality) were always taken. Data from the various inventories were presented in FIA reports (e.g., Bassett and Oswald 1982; Mei 1979). However, no wilderness timberland volumes were included. Data were summarized by the aforementioned land ownership categories: NF, OP, FI, and MP.

To simplify calculation of PNW C, conversion factors from the two predominate forest types were used to convert all data. The *Pseudotsuga menziesii* forest type covered approximately 5.3 million ha in the early 1990s. The second most abundant type, *Tsuga heterophylla-Picea sitchensis* (Bong.) Carr (Sitka spruce), accounted for 1.2 million ha. Together, these forest types represented an estimated 70% of total nonreserved timberland area and held 76% of total cubic volume on nonreserved timberland in the mid-1990s (Hiserote and Waddell 2003).

2.2.2.1 Forest Inventory and Analysis Program Inventory Design

The FIA program has inventoried WOR and western WA (WWA) at roughly 10-year intervals since 1930. Inventories were not based on a permanent plot system until the late 1950s; thus, data gathered with those methods were largely excluded from this analysis. The exceptions were 1933 inventory figures used for historical comparison (Andrews and Cowlin 1940; Table 2.1). Beginning in the 1950s, the FIA installed a network of permanent inventory plots on an approximately 5.5-km grid across OR and WA to estimate forest area, volume, growth, and mortality. Field plots were augmented by a more intense grid of points established on aerial photographs to create a stratified double-sampling design (Cochran, 1977). These photo points are

the primary sample and delineate the secondary sample field plots into strata by owner and forest type. This stratification scheme minimizes variance among sampled plots in each stratum, leading to more precise population estimates.

Data collected on field plots included tree species, diameter at breast height (dbh), height, age, and radial growth of individual trees. Four plot designs were employed: a 3-point plot in the late 1950s, followed by a 10-point design implemented around 1960, and two versions of a 5-point plot in the late 1970s and mid-1990s (Gedney 1982; Hazard 1965; MacLean et al. 1992; Table 2.1). Data for this analysis came directly from FIA summaries of forest statistics, except in the case of the 1995-97 WOR inventory, which was partially drawn from the FIA database (Hiserote and Waddell 2003). Sampling errors for area and volume estimates were published by FIA for their data, but were not always reported for other inventories.

2.2.2.2 National Forest and Bureau of Land Management Inventory Design

Historically, inventory design varied by NF. Often, estimates of NF land area were obtained from maps or aerial photos, so there was no calculated sampling error for area. Estimates of volume, growth, and mortality were determined from a series of plots on a 2.7-km grid across each NF, except on the Klamath (random sampling in 1967), Gifford Pinchot (random sampling in 1981), and Olympic (1.9-km grid in 1974) NFs (Bassett 1977; Bassett and Oswald 1981b; MacLean et al. 1992). During the 1950s-1970s, generally, plots were not measured in recently cut stands; instead, data for cleared areas were taken from stand exams (e.g., MacLean et al. 1992; Mei 1979). Plot design generally corresponded to the FIA design of the time, but, because some NFs were on a longer inventory cycle than the FIA, data from some old plot designs were reported along with those from newer FIA layouts (Bassett and Oswald 1981a, b; Bassett and Oswald 1982; Jacobs 1978). On BLM lands in southwestern OR, plots were established every 1.4, 1.9, or 2.7 km on a regular grid system, depending on the BLM administrative unit and inventory cycle (Bassett 1977; Jacobs 1978; Mei 1979). Summary data for FS and BLM lands were included in FIA publications through the 1970s for WOR and 1990s for WWA. Current

Table 2.1. FIA publications used in this analysis, inventoried areas, and sampling information. Date column indicates the year the data were intended to represent (data from old inventories were sometimes updated). In some cases, data taken in more than 1 year were combined in the FIA reports to create estimates for just 1 year. OP does not include NP data.

Report	State	Land owner	Date	Sampling design
Andrews & Cowlin (1940)	WOR & WWA	All forest lands outside of city limits	1933	Private lands: data from owners, modified by FIA. All other lands: data from type maps and timber cruises taken by FIA.
Newport (1965)	WOR & WWA	FI, MP, & OP	1950s-63	Systematic double sampling for stratification.
		NF	1950s-63	Systematic or random.
Bassett (1977) Jacobs (1978) Mei (1979)	WOR	FI, MP, & OP excluding BLM	1973-76	Systematic double sampling for stratification.
		NF	1967-75	Systematic samples. Many NF did not sample recent clearcuts; data obtained from stand exams. Klamath NF: double random sampling.
		BLM	1973-76	Systematic sampling.
Bassett and Oswald (1981a) Bassett and Oswald (1981b) Bassett and Oswald (1982)	WWA	FI, MP & OP	1978-79	Systematic double sampling for stratification.
		NF	1974-77	Systematic sampling.
Gedney et al. (1986a) Gedney et al. (1986b) Gedney et al. (1987)	WOR	FI, MP, & OP excluding BLM	1984-86	Systematic double sampling for stratification.
MacLean et al. (1992)	WWA	FI, MP & OP	1988-89	Systematic double sampling for stratification.
		NF	1981-89	Systematic sampling. NF did not sample recent clearcuts; data obtained from stand exams. Gifford Pinchot NF: stratified random sample.
Azuma et al. (2002) Hiserote and Waddell (2003)	WOR	FI, MP & OP excluding BLM	1995-97	Systematic double sampling for stratification.
		NF	1993-96	Systematic sampling.
		BLM	1997	Systematic sampling.

data for WOR NF and BLM lands were obtained through the FIA Program in Portland, OR (Hiserote and Waddell 2003).

2.2.3 Calculation Methods and Determination of Significance

Timber-volume data were converted to C using simple assumptions modified from Turner et al. (1995). In concordance with their method, net growing stock volume of sound bole wood (from a 30.5-cm stump to a 10.1-cm top) from FIA reports was first converted from cubic feet to cubic meters; volume of noncommercial species was included by multiplying net growing stock bole volume with a correction factor of 1.01. Specific gravities of the wood of the three most common species in *Pseudotsuga menziesii* and *Tsuga heterophylla-Picea sitchensis* forest types were averaged to produce a generic specific gravity of 453 kg m^{-3}, which was multiplied by bole cubic volume to give an estimate of bole biomass. Because C is roughly half the bole biomass (Janisch and Harmon 2002), dividing bole biomass by 2 produced an estimate of bole C. C in nonmerchantable tree components (i.e., tops, stumps, branches, roots, and cull trees) was added by multiplying bole C with a correction factor of 1.73, the average for the two predominant PNW forest types (Turner et al. 1995). Sapling C was calculated with the ratio of sapling to tree biomass, 0.057, given in Cost et al. (1990) for OR, WA, and California (CA) and added to the C stored by mature trees.

This analysis extended to 1991, the date of the most recent published data for WWA. Because NF volumes were not reported by the FIA for WOR in the 1980s (Gedney et al. 1986a,b; Gedney et al. 1987), 1978 and 1995-97 data were used to estimate C totals between those years for WOR NF land, using the non-linear interpolation procedure described below.

Numerous wilderness areas were designated between 1964 and 1991 (USDA FS 1963-76; USDA FS 1977-91). FIA reports generally omit volume estimates for these areas because wilderness is reserved land, defined by the FIA as land removed from timber production by statute, ordinance, or administrative order (MacLean et al. 1992). Statistics were reported for commercial forestland (now called timberland) on NF in 1963 (Newport 1965). Although not specifically mentioned by Newport, some

wilderness areas were already withdrawn in 1963 by the FS pending legislative approval of their reserved status (Gilligan 1953; US Congress 1961; USDA FS 1932). However, because the timberland area in each reserved area was not reported, it was impossible to determine how much timberland had been converted to designated wilderness since 1963 using FIA periodic reports. Therefore, vegetation layers from the Gap Analysis Project (GAP) (Cassidy 1997; Northwest Habitat Institute 2001) were overlaid with state ownership grids (Kagan et al. 1999) to estimate the timberland area within wilderness. In OR, GAP vegetation classes of barren, subalpine meadow, shrubland, and parkland were considered to be non-timberland; in WA, any polygon with a primary cover of bare, developed, agricultural, water (excluding hardwood and softwood-dominated riparian areas), or undisturbed nonforest was similarly assigned non-timberland status. The present percent timberland area in the PNW portion of each wilderness was then applied to that wilderness acreage for each year of its existence to obtain an estimate of timberland area. Average C density (C stored in live trees per area) on NF or OP lands between 1963-91 was applied as appropriate to wilderness timberland area to produce an estimate of live-tree C.

NPs are also classified as reserved land. Although comprising approximately 4% of PNW timberland, they contain areas of old forest that store considerable C in live trees (Smithwick et al. 2002). A rough estimate of their live-tree C storage was obtained by assuming that park land classified as closed-canopy forest by the GAP held 300 Mg C ha^{-1} and that this C density did not change appreciably over the last 40 years. This C density was based on three estimates of mean live-tree C density in PNW old growth stands: 315 Mg C ha^{-1} for boles only, adjusted to 500Mg C ha^{-1} for total trees (Janisch and Harmon 2002), approximately 430 Mg C ha^{-1} (Harmon et al. 1990), and approximately 560 Mg C ha^{-1} (Smithwick et al. 2002), which were then revised downward to account for the presence of high-elevation timberland. NP area estimates for every year were not readily available, so area assumptions were based on references in the literature (Catton 1996; Lien 2000; Louter 1998) and the currently reported park areas (USDI NP Service 2003). Wilderness and NP timberland (hereafter called reserved timberland) area and C estimates were summed by landowner and state for every year.

Inventories were not always undertaken in both states in the same year. Except for 1963 (Newport 1965), volume report publication years were staggered between the states, meaning PNW live-tree timberland C for a given year could not be calculated without first determining values between inventory years separately for each state. The straightforward way to obtain yearly estimates from this data is to use linear interpolation between known points; however, a different approach was followed to account for variation in annual timber harvest. Harvest volume for OR and WA was reported in Scribner board feet (Larsen and Gobroski 1993; OR Department of Forestry 2000b); therefore, regression equations of cubic-foot volume on Scribner board feet were created for each state using FIA data tables that reported volume in both units (Bassett 1977; Bolsinger et al. 1997). Cubic-foot harvest volume was then converted to C by the same method employed for live trees. Sapling C was not included because harvested stands were assumed to contain few small trees. WWA private harvests between 1963-64 were not separated by the WA Department of Natural Resources into FI and MP categories. For calculation purposes, total private harvest was divided between the two ownerships for 1963-64 using the same proportions that were reported for 1965.

For each landowner group within a state, nonreserved timberland C in an inventory year was converted directly from FIA-reported volumes using the method modified from Turner et al. (1995), as described above. Total timberland C by landowner and state in an inventory year was obtained by adding the estimated C in reserved timberland to that in nonreserved timberland. FIA reported net growth (gross growth minus natural mortality) on nonreserved timberland for the year previous to an inventory year. Reserved timberland was assumed to have no net growth. Total C in the year previous to an inventory was calculated as

$$C_{y-1} = C_y - CG_{y-1} + CH_{y-1}$$

where y was the inventory year and C, CG, and CH represented total C, net growth in Mg C, and harvest in Mg C, respectively.

Because net growth for years not directly previous to an inventory year was not reported, it was estimated by the following formula:

$$CG_y = \frac{\left[\left(C_{y-1} - C_p\right) + \sum_{p}^{y-1} CH\right]}{n},$$

where n was the number of years between the prior inventory and the year previous to the current inventory, and p indicated the prior inventory year. Applying this estimated average growth, the reported harvest, and estimated C in the year previous produced a yearly C estimate that fluctuated based on harvest volumes. Estimated live-tree C in both states was combined to produce PNW estimates by landowner group for every year. Once live-tree C on all timberland was estimated, C on nonreserved land was found by subtracting estimated reserved C for every year.

Nonreserved timberland area by state and landowner class in years when there were no inventories was calculated by determining the change in area between inventories, then adding (or subtracting) the average area change per year to the area in the previous year. This produced area estimates for each landowner that changed gradually over the years, when in fact there might have been abrupt changes if large areas were traded between ownerships or left the timberland condition in a single year. Total timberland area by state and landowner for each year was found by adding estimated reserved area in each year to nonreserved area. C in each year was divided by area for that year to produce C density estimates.

C storage in 1933 was obtained from cubic-foot volumes presented in Andrews and Cowlin (1940), and converted to C by the modified method of Turner et al. (1995) described above. Several scenarios were tested to assess the 1933 figure in light of other available information. Scenario 1 assumed that all timberland supported old-growth stands in 1933. Scenario 2 started with the C total from 1963 and worked back to 1933 by adding estimated C harvested each year and assuming no net growth. Scenario 3 used area by size-class data from 1933 and assigned average C density values to each size-class. Scenario 4 employed a C-growth equation from Janisch and Harmon (2002) that predicted C density from stand age and was applied to area by age-class data from 1933.

Results are reported for the entire PNW, as well as by landowner type within the region, for total and nonreserved timberland. All percent changes refer to the 1963–91 period and were calculated with reference to 1963 values. Although results indicate differences among times and landowner categories, small changes may be no more than variation from sampling error. However, PNW-wide standard errors of timberland area and volume were not available. We combined FIA-calculated 68% confidence intervals for area and volume on non-federal land by inventory region and landowner type (Azuma et al. 2002; MacLean et al. 1992) to create PNW-level standard errors by taking the square root of the sum of squared confidence intervals. Doubling the resulting 68% confidence intervals created approximate 95% bounds. Confidence intervals for NF data were calculated from the FIA Integrated Database (IDB) (Hiserote and Waddell 2003) using the method given in Barrett (2004). We applied these confidence intervals, expressed as a percentage of the estimate, to all years since 1963. Because NF area was obtained from maps (in almost all cases), FIA did not present confidence intervals for NF area estimates. To avoid underestimating C density confidence intervals, we calculated bounds by taking the upper limit of C over the lower limit of area and vice versa. Meaningful area and C differences among landowner groups or years were defined to be cases where these rough 95% confidence intervals did not overlap.

2.3   Results

2.3.1   *Changes in Live-Tree Carbon Storage, 1963-91*

Live-tree C stored on all PNW timberland decreased by 13% (1636 to 1430 Tg C), between 1963-91 (Figure 2.2). Seven percent of 11.2 million ha of timberland in 1963 was converted to agriculture, roads, reservoirs, or urban use over the study period (Figure 2.3). C density declined by 5%, from 146 to 138 Mg C ha^{-1} (Figure 2.4).
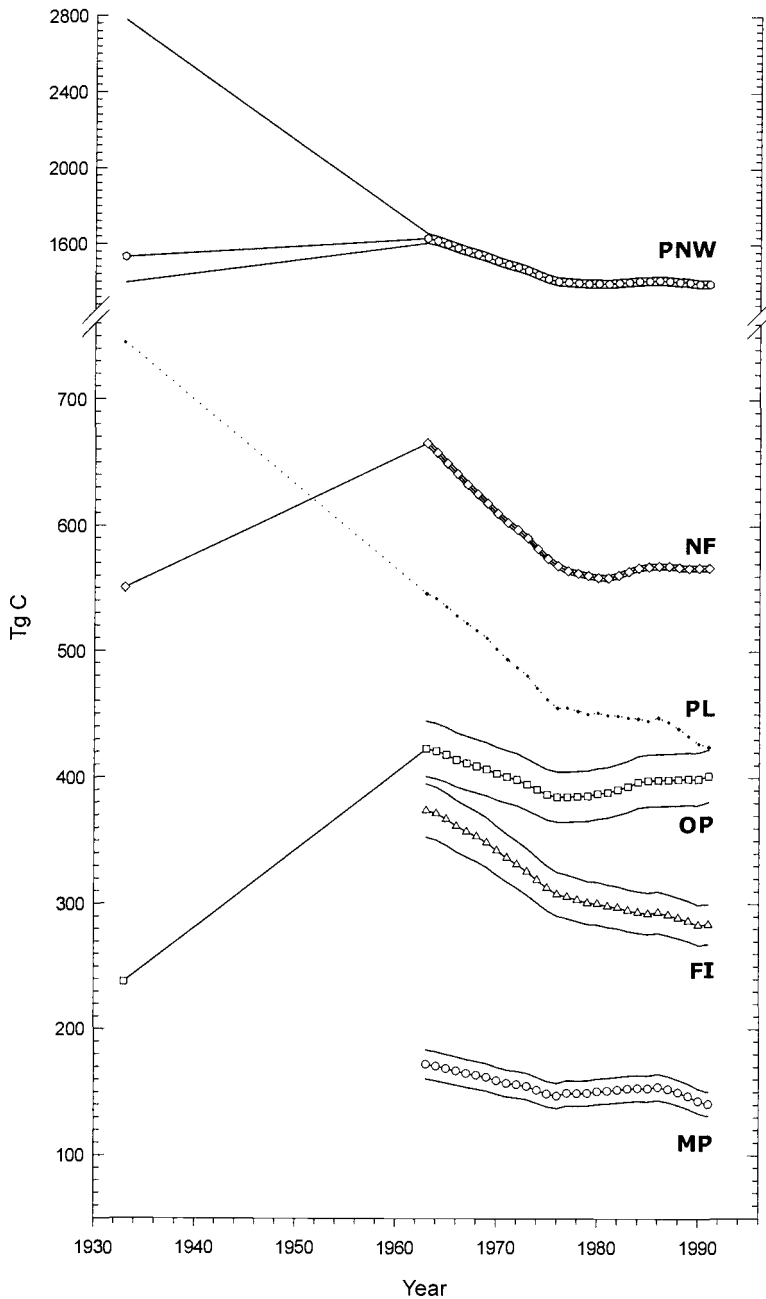
Figure 2.2. Live-tree C on total (reserved and nonreserved) timberland, 1933-91. Solid lines with symbols indicate live-tree C for the four main landownership classes and the PNW total. Solid lines bracketing these totals are approximate 95% confidence intervals, except for the PNW between 1933-63, which was derived from estimates presented in Table 2.2. The dotted line represents all private lands (PL), which is the aggregate of FI and MP. No confidence intervals were calculated for PL.
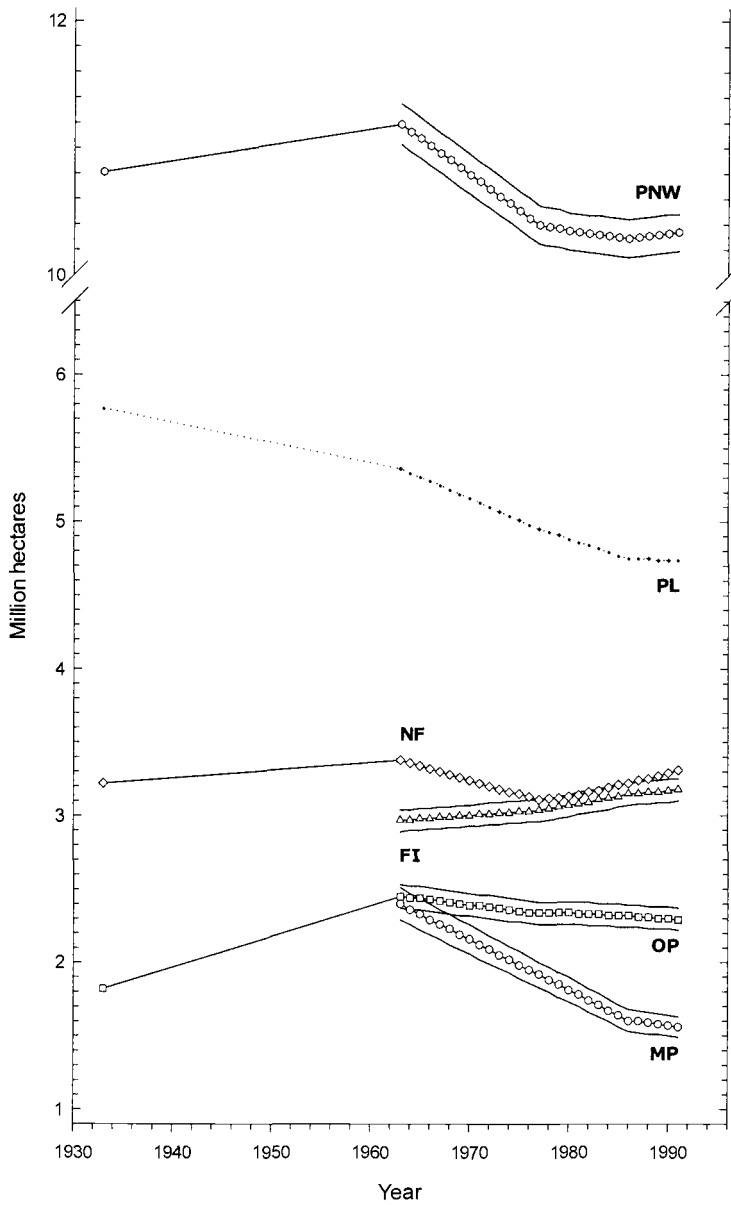
Figure 2.3. Total (reserved and nonreserved) timberland area, 1933-91. Solid lines with symbols represent timberland area by ownership class. Lines bracketing these totals indicate 95% confidence intervals based on the FIA sampling procedure. NF land area is estimated from maps and has no reported sampling error. PL is included for comparison with 1933.
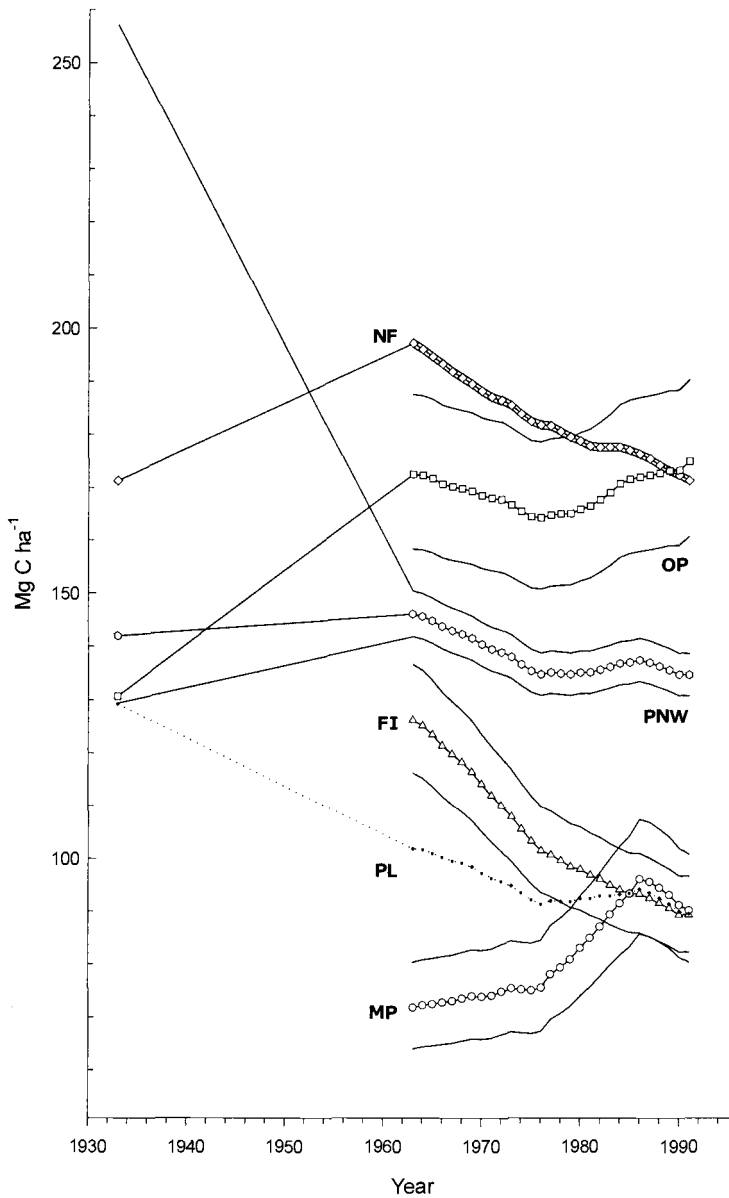
Figure 2.4. C density on total (reserved and nonreserved) timberland, 1933-91. Solid lines with symbols indicate C density for each ownership class and the PNW overall. Lines bracketing these totals indicate rough 95% confidence intervals, where estimates were derived from figures in Table 3.2 divided by the estimated timberland area in 1933.

Between 1963-91 on nonreserved PNW timberland, C in live trees decreased by 19% (1457 to 1179 Tg C). Decline in live-tree C density was less pronounced, though significant; the 1991 total was 8% lower than in 1963. Twelve percent (1.3 million ha) of nonreserved timberland was either incorporated into reserved areas or converted to agriculture, reservoirs, roads, or urban uses over the study period. Total annual net growth increased by 30%, and the corresponding annual net growth intensity (growth per area) rose from 1.7 Mg C ha^{-1} yr^{-1} in 1962 to 2.5 Mg C ha^{-1} yr^{-1} in 1990 (Figure 2.5). Harvest intensity (harvest per area) remained relatively constant over the 28-year period (Larsen and Gobroski 1993; OR Department of Forestry 2000b).

NF nonreserved timberland lost 22% (136 Tg C), of its 1963 live-tree C, 15% of its land area, and 8% of its C density. A good deal of the C and area loss was attributable to the creation of wilderness areas (Figure 2.6). With wilderness timberland included, the live-tree C decline of 9% (62 Tg), combined with a 2% decrease in timberland area, produced a 7% (15 Mg C ha^{-1}) decrease in C density. NF annual net growth and growth intensity rose by over 400% between 1962 and 1990. Harvest levels generally declined, though harvests were temporally variable for all ownerships (Figure 2.5).

The OP land category experienced little significant change in live-tree C stores. Total timberland area decreased from 2.5 million ha in 1963 to 2.3 million ha in 1991. Non-reserved timberland dropped from 2 million ha to 1.85 million ha. Annual net growth increased by 48%, and net growth intensity experienced a 58% rise. Harvest intensity was higher on OP than on NF lands in almost all years.

FI showed the highest percentage C loss, 24%, which equaled a loss of 91 Tg C from the 1963 C store of 374 Tg. FI's timberland base increased by 7%. It also supported the highest percent loss of C density, 29% (126 to 89 Mg C ha^{-1}). Growth on industrial lands showed a moderate increase of 15%, while growth intensity was not significantly different. Harvest intensity was the highest of all ownerships and exhibited a definite decline beginning in the late 1970s.
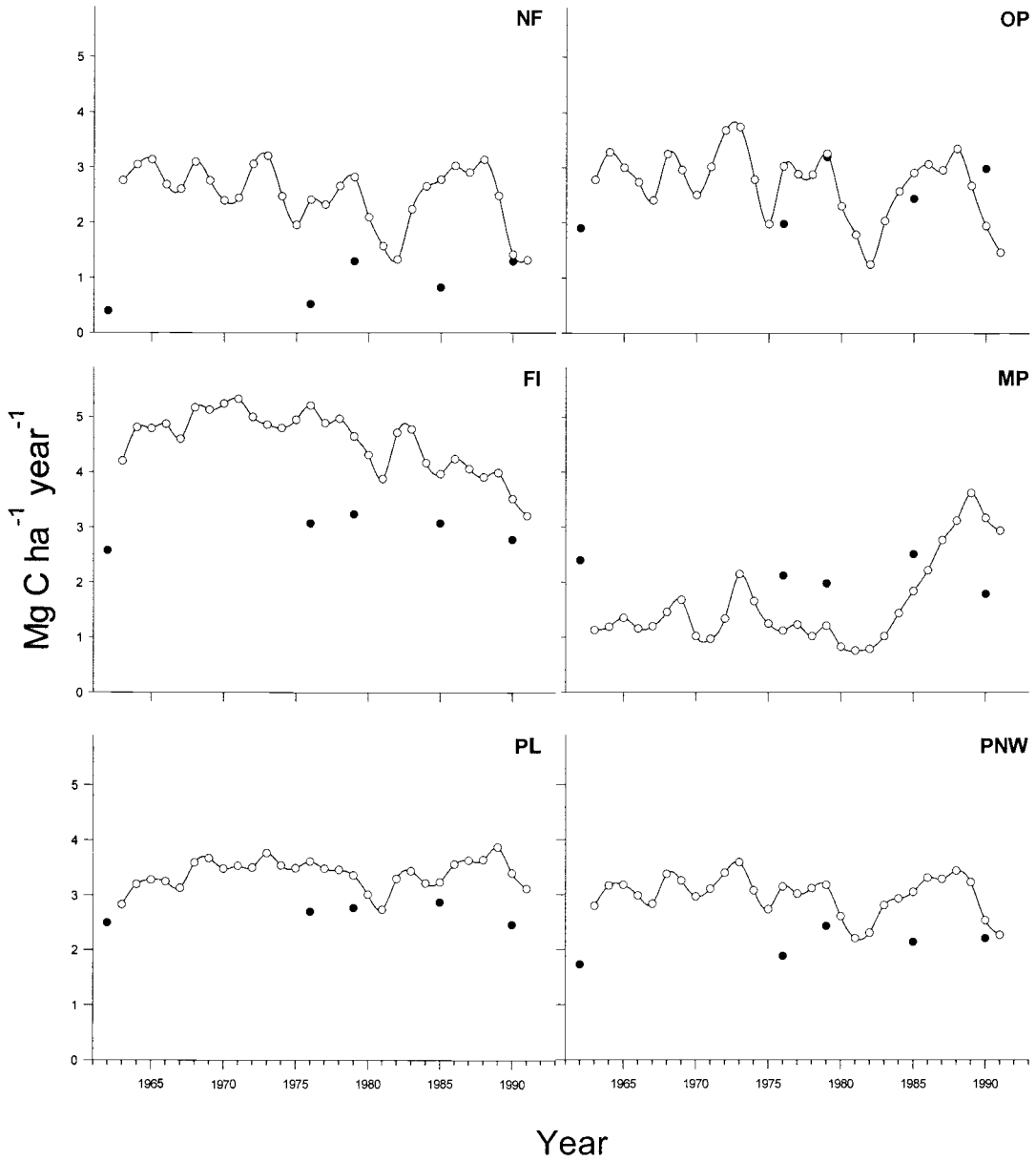
Figure 2.5. Harvest and annual net growth intensity compared for nonreserved timberland. Reserved areas are not harvested and were assumed to have negligible growth. Except for 1963, when net growth was reported for both states, net growth was estimated for one state at the time of an inventory in the other.
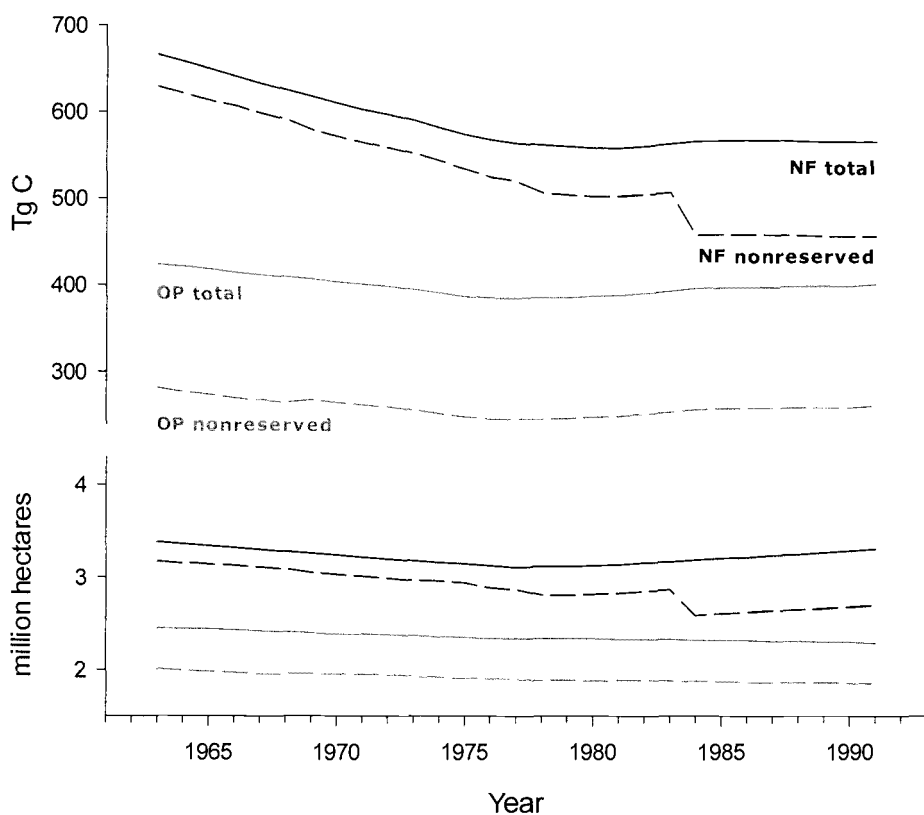
Figure 2.6. Live-tree C and area for total and nonreserved PNW timberland, 1963-91. The sharp drop in C and area in 1984 represents the establishment of numerous wilderness areas. NPs are part of the OP category and were considered reserved land in all years.

Live-tree C on MP land declined by 18% (172 to 141 Tg), but the loss of 35% of 1963 timberland area (0.84 million ha) over the same time period resulted in a C density increase of 26%. This category was the only group to experience a general decline in growth: in 1991, growth was slightly less than half its 1963 value, while growth intensity was three-fourths of its 1963 value. Harvests were the lowest of all landowners until the late 1980s.

When comparing live-tree C held in all landowner categories on all timberland in 1991, NF lands held by far the most live-tree C, MP the least, and OP and FI an intermediate amount (Figure 2.2). C density on NF and OP land was approximately equal. This was almost double the C density of FI and MP lands, which were not significantly different from one another (Figure 2.4).

2.3.2 *Live-Tree Carbon Storage, 1933*

To put the 1963-91 period in perspective, it would be helpful to know C stores before 1963. The earliest forest inventory was conducted in the PNW region in the early 1930s. Although data were collected under an entirely different protocol, comparison of their results with those from later years was of potential interest. The FIA 1933 data (Andrews and Cowlin 1940) for WOR and WWA indicated that 1534 Tg live-tree C was held on 10.8 million ha of commercial forest land, with C density values averaging 142 Mg ha^{-1}. This was unexpectedly low, given that the 1963 inventory yielded 1636 Tg C, 11.2 million ha of timberland, and 147 Mg C ha^{-1} for the same region. If the 1933 calculations were correct, average net annual growth must have been over 28 Tg C yr^{-1} between 1933 and 1963; yet Andrews and Cowlin calculated it to be about 10 Tg C yr^{-1} in 1933 and it was about 19 Tg C yr^{-1} in 1962.

Results of the four alternative scenarios (Table 2.2) suggested that the 1933 inventory value was on the low end of the range of possible values. Although one scenario predicted C stores over 4000 Tg C for 1933, the probable upper live-tree C storage limit for 1933 was assumed to be 2779 Tg C because all areas were obviously not in old-growth condition at the time and several scenarios predicted C stores in that range. The most likely discrepancies between the 1933 and 1963

Table 2.2. Scenarios and associated assumptions used to construct likely 1933 live-tree C storage bounds. The most likely upper bound was estimated at 2779 Tg C, and the lower bound at 1398 Tg C. Assuming the reported area of 10.89 million ha for 1933 was correct, C density was most likely between 127 to 257 Mg ha^{-1}.

Scenario	Assumption	Result (Tg C)
1. Old-growth All forest area in 1933[a] was old-growth.	a. All old-growth stored 400 Mg C ha^{-1} b. All old-growth stored 300 Mg C ha^{-1} c. All old-growth stored 200 Mg C ha^{-1}	4323 3243 2162
2. Harvest Harvest occurred with no growth.[b]	Between 1933 and 1963, harvest occurred with no growth.	2381
3. Size Classes Forest stored C based on tree size. [a]	a. Large trees[c] stored 400 Mg C ha^{-1}; small trees, 100 Mg C ha^{-1}; areas with few or no trees, 10 Mg ha^{-1}	2779
	b. Large trees stored 300 Mg C ha^{-1}; small trees, 75 Mg C ha^{-1}; areas with few or no trees, 10 Mg ha^{-1}	2088
	c. Large trees stored 200 Mg C ha^{-1}; small trees, 50 Mg C ha^{-1}; area with few or no trees, 10 Mg ha^{-1}	1398
4. Age Classes C stored predicted from 1933 area-by-age data using C growth equation.[d] Small tree C was calculated from detailed 1933 area-by-10-year age class data and held constant for each assumption.	a. 25% each of large trees were 150, 200, 250, and 300 years old	3109
	b. all large trees were 150 years old	3054
	c. 10% each of large trees were 150, 175, 200, 225, 250, 275, 300, 325, 350, and 375 years old	3381

[a]Data from Andrews and Cowlin (1940)
[b]Harvest data 1932-1961 from M. E. Harmon, Oregon State University. Data from 1962-1991 from Oregon Department of Forestry (2000b) and Larsen and Gobroski (1993).
[c]The definition of a large tree differed by species but was usually >50.8 cm dbh. For *Pseudotsuga menziesii*, large trees in old-growth areas were >101.6 cm dbh.
[d] Uses C growth equation from Janisch and Harmon (2002) and assumes maximum attainable C density for live tree boles (stem wood plus bark) is 300 Mg C ha^{-1}. Live-tree C totals were multiplied by 1.59 to include C in branches, foliage, and roots.

inventory estimates arise from incompatible techniques. The 1933 data were compiled partly from timber volume records furnished by private land owners and adjusted by the FIA program, and partly from average cubic-foot acre^{-1} estimates from new FIA timber cruises applied to areas from forest type maps. The early inventory had few aerial images to aid in generating these forest type maps or creating a primary sample layer for more precise estimates. Although measurement standards for cubic-foot volume reporting were similar to those used in 1963, Andrews and Cowlin (1940) do not define stump height; it is possible that it was higher than the current 30.5-cm stumps and so led to a downward bias in volume estimates. Recorded methods indicate that on cruises to collect average cubic-foot volumes, all trees with dbhs over 152.4 cm within a plot were measured for dbh and height, while a "considerable percentage" of trees less than that size were similarly measured. Perhaps a significant fraction of volume was ignored by cruisers consistently overlooking or underestimating smaller trees. Nonetheless, a 1963 report for west central OR (Hazard 1965) indicates board-foot volume was relatively constant between the 1933, 1948, and 1963 inventories after adjustment to 1963 reporting standards, so 1534 Tg C may be correct. In that case, C stored in live trees actually increased between 1933 and 1963.

2.4   Discussion

2.4.1   Origins of Differences in Live-Tree Carbon Storage

Explanations for differences in live-tree C stores over time and among landowners lie in tree physiology and the history of land use and forest management in the PNW. At the level of a single tree, a seedling accumulates C slowly as it becomes established, then quickly throughout the middle portion of its life; in maturity, net C uptake is minimal. Even-aged stands show that same C accumulation pattern through time. On the landscape level, with stands of all age classes, live-tree C stored is a function of disturbance and land-use histories. These histories determine stand extent and the proportion of trees in each growth phase, which determine the rate at which a site accumulates live-tree C. Repeated disturbance of an area resets the live-tree C pool to a lower average storage level with magnitude determined by the intensity and frequency of disturbance (Harmon 2001).

Many natural disturbances impacted PNW forests over the 28-year study period. Major natural events of the last century include large wildfires, droughts, windstorms, a volcanic eruption, and various insect and disease outbreaks (Andrews and Cowlin 1940; Backman et al. 1996; Eglitis et al. 1996; MacLean et al. 1992). All these disturbances increase mortality, decrease growth, or both, in the short term, although they may contribute to enhanced future growth of other individuals or species due to release from competition. As a result, live-tree C storage or the rate of live-tree C accumulation decreases immediately. However, as mentioned above, establishment of new trees or accelerated growth in previously competing trees after disturbance may enhance C uptake for many years following the disturbance. Though natural disturbances can have a large impact on C stores, it is unlikely that any one disturbance in the PNW over the 28 years can be definitively visualized at the resolution of the inventory data. The best candidate is the 1980 eruption of Mt. St. Helens, but the estimated loss of 4.5 Tg C (figure converted from board feet given in MacLean et al. 1992) from the live-tree pool that it caused was not discernible against the 1398 Tg C present in the PNW at that time. Theoretically, in the absence of human manipulation, the PNW would remain within an equilibrium C storage range. Occasional major disturbances would cause shifts from normal values, but in general, every year's losses from disturbance would be roughly balanced by gains, assuming the vegetation was not equilibrating to a long-term climate change.

Anthropogenic effects are, however, present; the forests of the PNW are extensively managed for timber production. Almost all stands inventoried by FIA crews have been harvested once, and some are on their third rotation. Short timber rotations of 35-65 years (Lettman 1995) on intensively managed land limit accumulation of C in live trees. Additionally, conversion of forest to nonforest lowers total live-tree C stores and may affect C density if low-C or high-C land is removed from the timberland area. C also seems to disappear from the FIA inventory when reserved areas are set aside, because volume on these reserved lands has not been included in timber statistics publications. Large-scale anthropogenic phenomena, such as climate change or pollutant emission, may also affect tree growth. Diseases introduced or exacerbated by human activities can affect growth, but such impacts are difficult to estimate.

Forests in the PNW have been influenced dramatically by their land-use history. Timber production in OR and WA commenced in the early-1800s (Andrews and Cowlin 1940). Despite the huge timber reserve, intensive logging lagged behind that in other regions because of transport and access difficulties. Initial harvest was limited to the Puget Sound area and along the Pacific coast. Railroad construction and invention of other steam-powered harvesting equipment in the late 1800s extended the reach of harvest, and timber production increased again between 1900 and 1940 with the development of more mobile gasoline-powered machines. During this time, silvicultural practices imported from Europe inspired timberland owners to invest in reforestation, wildfire suppression, and other measures that would promote continuation of the PNW timber supply (Williams 1989). By 1990, most lands outside the NFs and NPs had been harvested or otherwise disturbed; some 94% of their timberland was in stands less than 100 years old (even- and uneven- aged as well as nonstocked areas; Azuma et al. 2002; MacLean et al 1992) at the most recent inventories.

In this study, C density for each landowner class was about as expected from their land-use history. NF lands began to be intensely harvested many decades later than private lands (Wall 1972) and received lower harvest intensity than average (Figure 2.5). Despite wildfires and generally lower site potentials (Azuma et al. 2002; MacLean et al. 1992), they displayed the greatest concentration of live-tree C. NFs in the study area emerged from lands reserved by the federal government in the late 1800s, often in areas that were not productive or accessible enough to attract early timber investors (Andrews and Cowlin 1940). Land in these reserves was generally managed custodially until World War II, with timber harvest limited by adequate private supply and the difficulty of mountain logging. During and after the war, however, rising demand for wood, a depletion of large trees on private holdings, and technological advances moved the FS into a timber-oriented approach (Anderson and Olson 1991). In the late 1980s and early 1990s, timber extraction slowed due to limited demand for exported logs, a weaker economy (Howard 2001; Lettman 1995), and legal challenges over habitat destruction and nonsustainable harvest levels (Anderson and Olson 1991). Timber harvest on NF land in the PNW declined further during the 1990s with the implementation of the Northwest Forest Plan (Haynes

2001). Therefore, even though nonreserved NF acreage was approximately 0.5 million ha less than that of FI, the live-tree C store on nonreserved NF areas was much greater. Although C storage did decline throughout the study period, about 40% of the reduction in nonreserved NF live-tree C since 1963 can be attributed to withdrawal of timberland for wilderness areas.

The more intensive management of OP lands, as indicated by their greater harvest intensity than NF, may account for their lesser C density. The two major components of the OP landowner class are BLM and state land. BLM holdings in WOR arose from lands originally granted to railroad companies, reappropriated by the federal government in 1916, and now managed by the BLM for sustained yield (Richardson 1980). BLM lands in WOR were also governed by the provisions of the Northwest Forest Plan (Haynes 2001). Both OR and WA states own land that was originally granted to them by the federal government (Rakestraw 1955) and that they have acquired over the years. OR and WA legislated state Forest Practices Acts in the 1970s that govern harvest procedures on all timberland within each state (OR Department of Forestry 2001; WA Department of Natural Resources 1992). Both states manage their own lands in a multiple-use framework, with plans for balancing timber production, wildlife management, and other uses (OR Department of Forestry 2000a; WA Department of Natural Resources 1992). Nonreserved OP timberland comprised only 1.85 million ha in 1991, which, when combined with their lower C density, produced a lower live-tree C storage on these lands than on NF.

The lowest C density occurred on privately owned lands. Private harvest was much higher than public throughout the 1950s (Wall 1972) and probably before. The supply of large private timber dwindled after World War II, causing FI owners to adopt new silvicultural practices (Williams 1989). Planting and tending seedlings reduces the generation time of PNW conifer stands, so industry began to reforest cutover areas with nursery-bred stock and manipulate stands to enhance growth. Changing utilization standards, introduction of genetically-selected seedlings, and development of new fertilization technologies may allow industry foresters to continue to reduce rotation ages on many sites. Private lands in WOR are managed with rotation ages currently around 35-65 years (Lettman 1995). These young stands have such a low C

density that total live-tree C storage also diminished, despite increases in the FI timberland base.

Shifting management practices may explain the fluctuating C density observed on MP lands. The original MP lands were areas claimed from the public domain by homesteaders in the 1800s (Rakestraw 1955). Parcels have been subdivided or expanded, and switched ownership categories frequently. Timber management on MP was traditionally less intense than on other ownerships, and low harvest levels (Figure 2.5) combined with steady growth apparently caused a rise in C density from 1963-86. In the latter part of the 1980s, harvests increased in this landownership category as log supplies on FI declined and much of the NF land was withdrawn from timber production. Because MP lands accounted for the least area among the four landowner groups and had low C density, C totals were the lowest of the ownerships.

Growth, harvest, and C storage were associated fairly strongly on a per-hectare basis (Figures 2.4 and 2.5). When net growth was greater than harvest, C density generally rose, and when harvest was greater than net growth, C density fell. The main spurt of net growth appears to have originated in the mid-1970s on public lands, especially NF, pushing net growth intensity to or above the level of harvest intensity and creating a net gain in C density. The growth may have resulted from regenerating stands, because NF lands were not heavily logged until the 1940s. Trees were not included in FIA growth calculations until they were 12.7 cm dbh (MacLean et al. 1992), which would require a decade or more of growth, depending on the site. Therefore, NF net growth should have increased by the 1960s. However, the area in small trees would need to accumulate to a point where its enhanced net growth was large enough to have a discernable effect on the average net growth. According to Figure 2.5, this point was not reached until the mid 1970s. Reported net growth was much higher on OP than on NF. One possible explanation is that OP lands responded to a cutting regime slightly more intense than that on NF, and were on better sites. In the PNW, only 14% of NF timberland was estimated to be on sites where the mean annual increment was greater than or equal to 11.5 m^3 ha^{-1} (165 ft^3 ac^{-1}) compared to 34% of OP, 53% of FI, and 31% of MP (Azuma et al. 2002; MacLean et al. 1992). MP net growth was lower than FI, possibly due to less

intensive management practices by this landowner class or less productive sites. In the mid-1980s on MP timberland, the slight decline in net growth and a jump in harvest intensity combined to reverse the C density gain this landowner class experienced since 1963. MP timberland also lost a large fraction of 1963 area; if this area was of lower than average C density, its loss would contribute to the increasing MP C density between 1963–86.

According to 1933 data, public lands gained C between 1933–63, while C on private lands decreased. C density showed the same trends. Perhaps the gain, if actual, on public lands reflects recovery from many large burns in the 1800s and early 1900s before active fire suppression combined with less intense harvests. Because NF harvest began in earnest in the 1940s, missing data from the 1950s might show that public totals climbed steeply to the mid-1940s and then entered a decline. That would occur only if trees grew very quickly, which may not be reasonable given that NF lands were often on poorer sites. The trend in private land C storage is not surprising, since many of the large old-growth sites were in private ownership (Andrews and Cowlin 1940) and harvest on those lands was heavy (Wall 1972).

2.4.2 Estimate Uncertainties

The accuracy and precision of these results depend on the accuracy and precision of area and volume estimates produced by forest inventories. Ninety-five percent confidence intervals stemming from the PNW FIA sampling design were estimated to be only ±1.4% of the total for area and ±1.5% of the total for volume in 1991. Area 95% confidence intervals were unknown for NF (because area was almost always obtained from maps), 3.3% for OP, 2.4% for FI, and 4.6% for MP. Volume sampling errors were estimated at 0.4%, 5.2%, 5.6% and 6.7% for NF, OP, FI, and MP, respectively.

Volume estimates can differ significantly depending on their source. In the late 1980s in WOR, researchers examined the agreement between 1985-86 FIA FI data and data obtained from a 1986-87 confidential survey wherein industrial landowners reported timber volume on their lands. FIA values were 10% higher than volume estimates from surveyed industry landowners at the WOR level, rising to 40% in

some sub-regions (Sessions et al. 1991). A similar comparison with data from landowners was performed in WWA, where it appeared that FIA and Industry estimates of timberland area and volume were fairly close at the half-state level, but diverged when calculated by forest type or site class (Adams et al. 1992). Comparison of FIA data with WA Department of Natural Resources (DNR) inventories on state-managed lands showed reasonable agreement between area estimates at the half-state level. However, FIA volume estimates were higher by up to 40% for WWA (Adams et al. 1992). The true area and volume figures are unknown. Not all forest industry landowners responded to the surveys, and inventory methods probably differed among landowners, as well as between landowners and the FIA. FIA samples use consistent methodology, at least for inventories in the same year, but the sample is sparse (roughly 1 plot per 1.5-3 thousand ha), depending on the inventory). In OR, investigators assumed data provided by individual landowners were most reliable (Sessions et al. 1991). In WA, Adams et al. (1992) used FIA estimates for their main work but considered industrial and DNR information when performing sensitivity analyses.

This C estimate is subject not only to inventory sampling error but also to errors and biases stemming from measurements, regressions, model selection, and conversions. Inventory measurements cannot possibly have been taken without some error, and perhaps even bias. Because volumes were calculated from dbh and height measurements using regression equations, the error of the regression relationship is also accumulated. Furthermore, the choice of volume equation brings with it model selection error, and biases may be introduced when a volume equation specific to one area is used in another (e.g., Feller 1992). Errors or biases may also creep in during conversions, as from biomass to C. Phillips et al. (2000) report that sampling error was by far the greatest contributor to total variance of FIA volume data of the three errors they studied (sampling, regression, and measurement), so by accounting for that, much of the error may have been expressed. However, model selection and conversion errors remain unknown.

Estimates presented here were derived from the best data available. Where data were unavailable, logical assumptions were employed to generate live-tree C storage

estimates. However, each assumption made increases the uncertainty surrounding the C storage estimate, and the probable effect of these assumptions should be considered when using the conclusions of this study. Major assumptions included: C content and merchantable C:total tree C ratios averaged from two forest types adequately represented these values for the entire PNW; forest growth was constant between inventories; wilderness live-tree C density equaled the average C density of the wilderness landowner group over the study period and no net growth occurred; changes in inventory design made no difference; and the mature tree to sapling biomass ratio was constant.

Although the *Pseudotsuga menziesii* and *Tsuga heterophylla-Picea sitchensis* forest types represent the majority of PNW volume, 24% of timberland volume occurs in other types. Weighted specific gravities of the 3 most common species in each forest type range from 349 to 508 kg m^{-3} (Turner et al. 1995). Of the major forest types found in the PNW, fir-spruce and hardwood types displayed considerably lower specific gravities (349 and 384 kg m^{-3}) than that used here (453 kg m^{-3}). The C proportion of hardwood forest types (49.6%) is slightly lower than that of softwood types (51.2%). This study used 50% as a C conversion factor for all forest types. Ratios of total tree C to merchantable C range from 1.47 for fir-spruce to 2.08 for hardwoods, compared to 1.73 used here. Use of the factors employed in this study probably resulted in an overestimate at the biomass-calculation step, an underestimate when determining bole C, and an overestimate when converting bole C to whole-tree C (because PNW fir-spruce forest types contain slightly more volume than hardwood types). These biases most likely combine to produce an overestimate.

It is unlikely that forests maintained constant growth over decadal spans. This should not introduce great changes in live-tree C values during the years when there was a report for at least one state (1963, 1977, 1980, 1986, and 1991), but it could alter values between inventory years.

The assumption that each wilderness (outside of NPs) contained the average C density of the other lands in the same ownership class between 1963-91 is probably unrealistic. When the PNW 1991 wilderness live-tree C estimate created for this study

was compared with PNW wilderness live-tree C calculated from the FIA IDB (Hiserote and Waddell 2003), which uses NF data collected in the mid-1990s, the IDB predicted 40 Tg C more than this study's estimate. Some of the discrepancy may be due to the no-growth assumption made during our calculations. Turner et al. (1995) assumed wilderness timberland growth intensity was identical to growth intensity on non-reserved timberland and concluded that reserved timberland sequestered 10 Tg yr^{-1} for the entire US, which suggests a positive net growth in PNW wilderness. The IDB indicates in excess of 1 Tg C yr^{-1} net growth in wilderness timberland, not including NPs. The discrepancy also stems from a 26% greater estimate of PNW non-NP wilderness timberland area by the IDB. Our study relied on vegetation classification from remote sensing to determine the percentage of timberland area in the PNW portion of each wilderness; the FIA IDB used plot expansion factors for data. Differences in C and area estimates resulted in the IDB average of 190 Mg C ha^{-1}, compared with this study's average of 172 Mg C ha^{-1} on wilderness timberland outside NPs. No corrections were made to figures used in this study, however.

Including the 1933 inventory, FIA plot design changed four times, although all plots had the same center point from 1963 onwards. Measurement and analysis protocols changed, as well. Because many changes are poorly documented and original data from early inventories are not in computer databases, it proved impossible to correct for them. There are also known peculiarities of certain inventories that are difficult to correct. For example, a small portion of the Gifford Pinchot NF that lies in Eastern WA was incorporated into the 1991 timber statistics report (MacLean et al. 1992) and is therefore included with the PNW. If similar inclusions occurred in other years or other areas, they are not documented. One figure that stands out is the 400% increase in net growth on NF land between 1963 and 1991. It is so dramatic as to be unbelievable and may be an artifact of changing inventory or calculation procedures.

The sapling:mature tree ratio was calculated for data from all of OR, WA, and CA and made no distinction between hardwood and softwood forest types. Applying the ratio only to western OR and WA may have introduced bias. The ratio differs between hardwoods and softwoods, and so would presumably vary based on the proportion of hardwoods and softwoods in each forest type.

2.4.3 Comparison with Other Reports and Regions

The 1392 Tg of live-tree C on all PNW timberland found in this study for 1991 is 17% greater than the approximately 1150 Tg (data read from graph) reported by Turner et al. (1995). They report an average live-tree C density pool of 110 Mg ha^{-1} (data read from graph), 18% lower than the 135 Mg C ha^{-1} calculated here. Estimates produced by Turner et al. would also be affected by inventory sampling error. If 1991 PNW 95% confidence intervals from this study were applied to the Turner et al. estimate, their highest bound is still 15% lower than the lowest bound for this study. It is likely that the simplification of Turner et al.'s calculation method contributed to these differences by causing an overestimate of live-tree C in this study. Furthermore, data used were probably from different inventories: Turner et al. relied on a 1989 FS report, so the latest PNW inventories included may have been the 1980 inventory of WWA and the 1985-86 inventory of WOR. The 1991 estimate from this study relied on the 1988-90 WWA inventory and interpolation between the 1985-86 and 1995-97 WOR inventories. Turner et al.'s data source also projected harvests from the early 1980s to 1990, whereas this study relied on harvest volumes reported by the states through 1996.

Based upon comparisons of C density for different ages of forest, Harmon et al. (1990) suggested that 1500-1800 Tg C were removed from PNW forests since 1890, or 15-18 Tg C yr^{-1}. Between 1963-91, this study indicated a loss of 8.7 Tg C yr^{-1}. However, Harmon et al. included all forest components. Assuming old-growth live trees held 432 Mg C ha^{-1}, 60-year old live trees hold 192 Mg C ha^{-1}, and 5 million ha have been converted from old-growth since 1890, it appears that a loss of 12 Tg C yr^{-1} might be expected from live trees. If old-growth live trees held only 300 Mg C ha^{-1} on average, the loss would still be about 5.4 Tg C yr^{-1}. However, inventory data do not go back to 1890, and the earliest inventory, in 1933, indicated that the PNW gained C between 1933-63, although this is suspect for reasons discussed earlier. If 12 Tg C yr^{-1} were removed between 1933-63, the PNW live-tree C store in 1933 would have been about 2000 Tg.

A modeling approach driven by Landsat data for west central OR (Cohen et al. 1996) indicated that live C stores declined by about 1.3 Mg ha^{-1} yr^{-1} between 1972-91 (data

read from graph), which extrapolates to a 13.5 Tg yr^{-1} loss of live C from all PNW timberland. In contrast, this study suggested a PNW live-tree C loss of 4.8 Tg yr^{-1} during the same time period. Impediments to a direct comparison with the findings of Cohen et al. are differences in calculations of productive forest area and possibly in the forest C pools examined (they estimated live C, which may include understory vegetation). Their PNW-wide figure was extrapolated from a 0.8 million ha forest area, whereas the figures in this study were derived from sampling across the entire PNW. A higher C density loss in their study area could be due to a higher proportion of less-accessible land than average in the PNW. Harvest on such lands could have lagged behind that on much of the PNW, and these relatively recent harvests would have created stands that were still releasing C to the atmosphere during their study period.

Other regions of the US are currently sequestering C as a result of their different land use histories. In the South and Southeast, live-tree C is increasing as previously cleared land is converted to secondary forests (Delcourt and Harris 1980; Turner et al. 1995). Much acreage in the Northeast is also reverting to forest and creating a net C sink, while the Rocky Mountain states show little change (Turner et al. 1995). Eastern forest C accumulation has been so strong since the 1950s that the US as a whole has accumulated forest C, making it one of the many northern hemisphere countries to sequester C during the late 1980s – early 1990s (Goodale et al. 2002).

2.4.4 Future Carbon Storage Prospects in the Pacific Northwest

Timberland live-tree C content has been relatively stable, both total and per area, in the PNW since the mid-1970s. A steady decrease in C density on NF and FI lands over that time period was countered by rising C density on OP, and for a while, MP lands. One policy that probably boosted C density levels on public lands was the Northwest Forest Plan. After its inception, a portion of the available timberland on NF and BLM lands was withdrawn from harvest, and much less volume will be harvested from the remainder (Interagency SEIS Team 1994), assuming acts borne of the Healthy Forest Initiative (Office of the President 2002) do not substantially reverse these changes. The most recent WOR inventory indicates a substantial C density increase occurred in WOR NF after 1990 (when data were input to the yearly

estimation procedure described for this study), possibly due to the effects of the Northwest Forest Plan. The larger the area in older age classes, the higher the average C density (Harmon et al. 1990) and the greater the PNW C total. State forest managers in OR are undertaking structure-based management to create layered or "older forest" structures on a percentage of state forest land while sustaining sufficient harvest income for state programs (OR Department of Forestry 2000a). The WA state management plan indicates there will be less clearcutting on their timberland and more emphasis on alternative harvest measures, where practical (WA Department of Natural Resources 1992). Other policies that may curb live-tree C loss are state Forest Practices Acts that mandate stream and wildlife buffers, green tree retention, and limit organic horizon erosion, all policies that either leave some C on the site or enhance regeneration.

This potential increase in live-tree C on public timberland might be counteracted for a time by the loss of live-tree C from private ownerships, if private lands continue to be managed with rotation ages around 35-65 years. Should rotation age decrease, average C stored in live trees will decrease (Harmon et al. 1990). Current C density figures, applied to the Janisch and Harmon (2002) equation (assuming a maximum potential live-tree stem wood and bark C store of 300 Mg ha^{-1} on all sites), indicate average stand age on private timberland in 1991 was 35 years. Assuming all private lands were managed on a 45-year rotation (average age 22.5 years) and public lands remained in their 1991 condition, PNW live-tree C density would decline from 135 to 113 Mg C ha^{-1}, and PNW live-tree timberland C stores would decrease from 1392 to 1174 Tg (a 15% decline from 1991). However, introduction of genetically-selected stock and improvements in fertilization technology might allow biomass to accumulate in less time so C density might not decrease by this much. Then again, faster growth might result in higher proportions of juvenile wood and therefore in diminished wood density (Haygreen and Bowyer 1996), which could counteract C stored due to gains in growth rate.

Use of partial harvesting instead of clear-cutting may also influence C stores. Simulations performed by Harmon and Marks (2002) suggest that the next best management option for boosting forest C in the PNW, after increasing rotation length,

would be conversion to a partial-harvest rotation system (80% of tree biomass felled, 80% of cut bole biomass taken from the site, rotations greater than 40 years) with no slash burning. Their calculations also indicated such a harvest system would provided more forest products than traditional clearcut-and-burn systems for forests managed on less than 90-year rotations. Thornley and Cannell (2000) found their own modeling system for pine plantations in Scotland predicted the maximum amount of C was stored by an undisturbed forest, but that both forest C storage and yield of products were maximized when 5-25% of woody biomass was removed every year, as opposed to 60-year clearcutting rotations. However, neither study investigated the economic viability of such practices.

Future regulations and harvestability in the PNW may be influenced by forest location. As mentioned in Johnson et al. (1999), MP lands are largely on gently-sloping lands in valleys and foothills. Their greater proximity to population centers and to waterways may result in stricter future harvest regulation compared to other ownership classes and influence how much will be harvested in the future.

The extent of climate change will also determine future live-tree C storage levels. According to biogeochemical model comparisons performed by Bachelet et al. (2001), the severity of temperature increase may determine whether vegetative biomass in the PNW will increase or decrease. A mild to moderate temperature rise may result in biomass gain, whereas more extreme temperature increases may create a loss of biomass through increased stress and risk of fire. If fire risk became great, policies might shift to reduce forest biomass.

On the other hand, C storage itself may become a driving factor in the region. Should financially attractive options for forest C storage appear (such as C sequestration incentive payments), managers could be induced to shift to longer rotation systems, causing C density to rise. In OR, the Forest Resources Trust was established to promote reforestation of nonstocked land in MP ownership, and although it is still a small program, it has attracted the attention of power-generating corporations who appear willing to fund such projects to obtain credits for their emissions offset portfolios (Cathcart 2000).

2.5 Conclusions

Despite the various uncertainties mentioned above, this estimation procedure indicates that live-tree C on PNW timberland declined by 15% between 1963–91. The relative equilibrium seen from 1976-91 appears to result from a balance between rising stores on public land and falling stores on private land. Land-use decisions made in the future will determine whether public and private lands will continue their respective C accumulation or loss patterns and whether this will lead to a greater polarization in live-tree C stores among land ownership classes. As demonstrated here, powerful trends are evident for specific landowner classes but these are masked when results are aggregated to the PNW level. Further analysis could examine C stores by state, by landowner within state, and possibly among sub-state survey units to determine whether local land-use patterns and regulations are linked to C storage values. Data from the new annualized FIA inventory design will soon be available to extend the C storage analysis into the 21st century and determine if Northwest Forest Plan provisions led to further increases in live-tree C on public lands, and whether private live-tree C storage continued to decline. If the PNW is to be a large contributor to future live-tree C sequestration in the US, then land will have to be allocated to older age classes, harvest strategies must change, or both.

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3 UNCERTAINTY ASSOCIATED WITH ESTIMATES OF LIVE-TREE CARBON STORES IN THE PACIFIC NORTHWEST

3.1 Introduction

Rapidly increasing concentrations of atmospheric carbon dioxide (CO_2), a radiatively-active (i.e., greenhouse) gas, have generated concern about atmospheric warming. International agreements such as the Kyoto Protocol require many nations to reduce greenhouse gas emissions in the near future (United Nations Framework Convention on Climate Change 2003). To facilitate verification of the implementation of such commitments, countries are expected to produce nation-wide inventories of greenhouse gas sources and sinks. Though most natural and anthropogenic sources and sinks of CO_2 are well known, the controlling mechanisms and flux magnitudes of the natural carbon (C) processes are not completely understood. Recent evidence suggests that forests of the northern hemisphere are a significant sink (Dixon et al. 1994; Goodale et al. 2002). Many countries, the United States (US) included, are interested in exploring forest C sequestration as a possible way to offset their anthropogenic CO_2 emissions and profit through the sale of any excess "carbon credits" to other entities. However, the existence of such sinks must first be verified, and their magnitude as well as their temporal and regional variability must be assessed.

These tasks have occupied C researchers for some time. At the root of the problem is the difficulty in monitoring fluxes that occur at a variety of temporal and spatial scales. Furthermore, there is no practical way to measure the magnitude of forest C pools directly. Forest C is generally estimated from samples which record such variables as tree species and diameter, woody debris length and diameter, litter layer depth, and so forth. Regression relationships and conversion factors are then applied to estimate C content of each forest C pool. Several types of error are present in the estimates: sampling and measurement error from the inventory process used to gather the data; regression error due to the use of regression relationships; and model error introduced by choosing from a set of applicable regression relationships and conversion factors.

This study deals with estimate uncertainty for one of the two largest segments of the forest C store: live trees. In this chapter we review the calculation methods by which C storage estimates are created, then discuss various uncertainties surrounding the forest live-tree C estimates. The remainder of the chapter is devoted to analyzing uncertainty introduced into the live-tree C storage estimate by model error and exploring ways in which this uncertainty might be most efficiently reduced.

3.1.1 *Live-Tree Carbon Estimation*

Although trees can be harvested and chemically analyzed to determine their C stores, currently we are only able to practically measure C indirectly. Dimensional measurements of key points on the tree are obtained, and these values are entered into equations that predict either volume or biomass. Equations can be either statistical regression models or form factor equations, as discussed below.

3.1.1.1 Volume Equations

Volume equations available for Pacific Northwest (PNW) species generally predict stem wood, stem bark, or both; occasionally they include branch volume as well. Species of commercial importance have many stem wood volume equations (e.g., *Pseudotsuga menziesii* in the Pacific Northwest has at least 18), whereas non-commercial species have few to none.

Equations have been developed in several ways. Most researchers fell trees, section them, and obtain measurements of bole wood and bark thickness at many points along the stem (e.g., Browne 1962; Cochran 1985; Kovats 1977). Diameters at various heights may also be estimated for a standing tree with the aid of a Relaskop or similar instrument (e.g., Pillsbury and Kirkley 1984). When diameters are estimated in this fashion, bark volume is estimated with a regression created from bark thickness samples. Inside-bark diameter measurements are then processed using a standard volume formula. The Smalian volume formula is one of the most commonly used, and is calculated as

$$V = \frac{a_L + a_S}{2} L \, ,$$

where

V = volume of the log section,

a_L and a_S are the areas of the large and small ends of the section, and

L = the length of the section (Bruce and Schumacher, 1950).

This calculated volume is considered to be the actual volume of the tree. Regressions between actual volume and dimensional measurements, such as diameter at breast height (dbh) outside bark or height, or both, are then estimated.

Volume equations may be simple or multiple regressions to obtain volume, or they may be form factor equations. Form factor equations compare the volume of a tree to that of a cylinder of identical height and diameter at the base. Once the equation for the form factor has been developed, volume is estimated by multiplying the value produced by the form factor equation by the formula for the appropriately-sized cylinder. Examples of such equations in the PNW are found in Bruce and DeMars (1974).

The final category of volume equations is the profile equation. They are created by fitting an equation to the diameter of a tree measured at many points along the stem. This taper function is then integrated to produce volume (Spurr, 1952). Once an equation has been developed, accurate predictions of volume require measures of tree height and at least 2 stem diameters (Bruce and Max 1990). Because FIA data only include one stem diameter, profile equations were not included in this study.

Regressions may take a variety of forms. Some of the simplest rely on untransformed variables in unweighted nonlinear regressions. A common form is:

$$V = b_0 d^2 h$$

where
V = volume,
b_0 = regression coefficient,
d = diameter at breast height (dbh), and
h = height.

Other equations raise dbh or height, or both, to different powers, and can be quite complex. A commonly-reported problem with this approach is heteroscedasticity of the regression residuals, because variation commonly increases with larger tree sizes.

Unequal variance has often been corrected by transforming volume and the independent variables using base 10 or natural (base e = 2.71828...) logarithms. Log-transformed equations commonly rely on dbh (Franklin 2002), or various combinations of dbh and height (Brackett 1977; Browne 1962). An equation of

$$V = b_0 d^{b_1} h^{b_2}$$

therefore becomes

$$\ln(V) = \ln(b_0) + b_1 \ln(d) + b_2 \ln(h)$$

when expressed in the natural logarithm (ln) format.

This technique allows a linear regression to be performed at the transformed scale and removes much of the unequal variance, but introduces problems when dependent variables are back-transformed. When mean volume from an approximately normal distribution in the transformed scale is returned to the original scale, this back-transformed mean volume is now the median volume at the original scale (Ramsey and Schafer 1997). In forestry applications, it is assumed that the mean volume is the desired value, especially when individual tree volumes will be multiplied by the number of trees in an area to obtain total volume for all trees in that area. Therefore, volume estimates that were derived from log-log transformed equations (and are therefore estimates of median volume at the original scale) are often multiplied by a correction factor to obtain mean volume. The most common correction factor, given in Baskerville (1972), involves multiplying the back-transformed volume by the correction factor $e^{MSE/2}$, where MSE is the mean squared error on the natural log scale. This is equivalent to adding MSE/2 at the transformed scale, as shown below:

$$\ln(V) = \frac{MSE}{2} + \ln(b_0) + b_1 \ln(d) + b_2 \ln(h).$$

When using base 10 logarithms, the correction factor is

$\ln(10)\frac{MSE}{2}$ (Yandle and Wiant 1981).

Another method for removing heteroscedasticity is weighted regression. Observations are multiplied by the weighting factor, for example, 1/dbh (as in the height equations developed by Garman et al. (1995)), or by other combinations of variables, such as $1/d^2h$ (Farr and LaBau 1976). This technique standardizes residual variance and involves no problematic back-transformation of dependent variables.

Some volume equations were developed many years ago, when it was less common to publish metadata for a study. Therefore it is not unusual to find limited information concerning an equation's effectiveness or its geographic provenance. Measures of equation fit, if any, are often limited to R^2; mean squared error of the regression (MSE) (or its square root (RMSE)) is reported less frequently. Sample sizes may be extremely small, and the range of dbhs is often limited. Equations developed from datasets containing large trees are rare.

3.1.1.2 Density

When volume equations are used to obtain C estimates, they are converted to biomass using the density or specific gravity of wood. Specific gravity is the density of the material expressed as a proportion of the density of water, which is 1 g/cm^3, so specific gravities are easily converted to densities. Density of numerous species has been tested by the US and Canadian forest services (Forest Products Laboratory 1999; Smith 1970; US Forest Service 1965) and many other researchers (see citations in Gonzalez 1990). Often estimates of variability are included with published measurements, but if not, a typical coefficient of variation (CV, the magnitude of the sample standard deviation as a percent of the sample mean) is 10% (Forest Products Laboratory 1999).

3.1.1.3 Biomass Equations

Available biomass equations include extremely general forms that were developed for use on a nation-wide level (Jenkins et al. 2003) as well as equations developed from only a few trees on a single site (see citations in Gholz et al. 1979). Equations may predict entire tree biomass or component biomass. In this study, 'component' is used to mean some part of a tree. It can be very specific, as in the small live branches, or more general, as in total branches (Figure 3.1). To obtain biomass of an entire tree, either an equation specifically developed to predict total tree biomass is applied, or the appropriate component biomass equation output is summed (e.g., live branch and dead branch biomass are summed to produce total branch biomass, which is then added to total foliage biomass to create total crown biomass, and so on). Common timber species have numerous equations for stem wood biomass, and usually have several bark, branch, and foliage biomass equations, but species-specific root biomass relationships are much less common.

Biomass equations are developed by felling trees and sectioning the bole into disks, all of which are weighed fresh and some of which are re-weighed after drying to determine fresh weight:dry weight ratios. These ratios are then applied to the fresh bole weight to achieve dry weight estimates. Branches and foliage are typically weighed fresh in the field and a sample is dried and re-weighed in the same manner as for the bole sections. Depending on the investigator, branches may have been divided into several size classes and foliage may have been separated into new and old. Estimates of these various biomass components for numerous trees are regressed on standard tree measurements such as dbh or height, or both, to produce prediction equations.

As with volume equations, biomass equations may be simple or complex power forms, or various log-log transformations. However, they are not commonly developed from weighted regressions. They tend to be more similar in form and have fewer terms than do the volume equations. Many rely solely on dbh; only a few use height
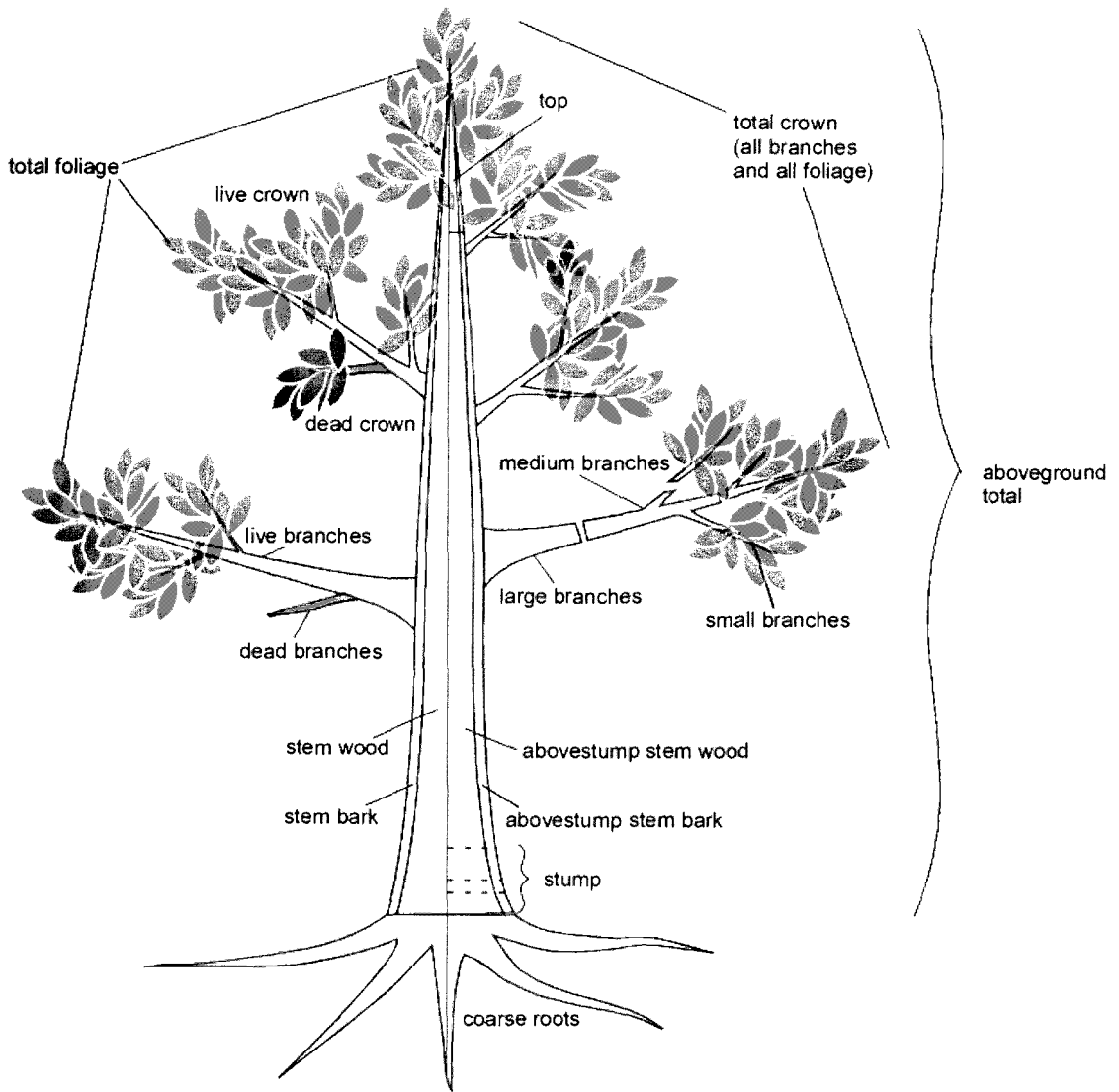
Figure 3.1. Various tree components for which volume or biomass equations, or both, have been developed. Not all possible components are depicted. Stump heights differ between studies, as do dimensions of the large, medium, and small branch classes.

alone (usually height-only equations are used for very small trees (Feller 1992)). One of the most common forms in the biomass literature is the allometric equation:

$$B = b_0 d^{b_1} \text{ or } \ln(B) = \ln(b_0) + b_1 \ln(d),$$

where B = biomass,

d = dbh, and

b_0 and b_1 are regression coefficients.

As with volume equations, measures of precision are sometimes not reported. Occasionally an equation will lack a description of geographic provenance. Sample size may be extremely small, and few datasets contain large trees.

3.1.1.4 Carbon Conversion

Once the biomass of a tree has been estimated, it is converted to C by multiplication with a C:biomass ratio. The most common conversion is simply to multiply biomass by 0.5 (e.g., Janisch and Harmon 2002), but Birdsey (1992) indicates that the average softwood C:biomass ratio for the US is 0.512, whereas the average hardwood ratio is 0.496. No estimate of variability was reported for these ratios.

3.1.1.5 Carbon Estimates from Forest Inventories

The typical approach to obtaining C estimates for large areas begins with data from sampled individual trees and estimated number of similar trees in the area of interest. The main source of this type of data for the US is the US Department of Agriculture (USDA) Forest Service (FS). National forests (NF) and the FS Forest Inventory and Analysis (FIA) Program have inventoried US public and private forests since the late 1920s (Forest Inventory, Economics, and Recreation Research Staff 1992). The Program publishes periodic reports (e.g., Azuma et al. 2002) and maintains databases containing individual tree data such as species, dbh, height, and age; estimates of forest area, volume, growth, and mortality; and per-area estimates of volume, growth, and mortality (e.g., Hiserote and Waddell 2004). Regional net growing stock timber volume published in FIA periodic reports or obtained through FIA databases can be converted to regional C estimates by the method outlined in

Chapter 2. Regional C can also be estimated by first estimating C in each inventoried tree, then expanding to the regional level based on the number of trees represented by the inventoried tree. Individual tree measurements can be converted to forest C in two ways. In the first method, tree data are converted to tree volumes using volume equations, these volumes are multiplied by density to produce biomass, and tree biomass is expressed as C after multiplication with a C:biomass ratio. The second method produces a biomass estimate directly by using a biomass equation, and the resulting biomass is multiplied by a C:biomass ratio to achieve a C estimate. Tree C is then expanded to the area of interest using FIA-calculated expansion factors for each tree and plot.

3.1.2 Sources of Carbon Estimate Uncertainty

Uncertainty has been defined as what is not known about a system that affects outcomes of predictions about the system (Brugnach 2003), or more simply, as lack of confidence in a single value (Heath and Smith 2000). In this chapter we regard uncertainty as the range of possible values estimated for a quantity. Under this definition, a confidence interval is a measure of uncertainty. Uncertainty in live-tree C estimates is introduced through many sources. Some can be modeled statistically, such as error arising from sampling design. Others are not so tractable.

Uncertainty about the final C storage estimate may arise from sampling error. Sampling error results from being unable to measure every individual in a population. The magnitude of sampling error is determined by the sample design, the number of individuals actually measured, and the variability among individuals. Because FS inventory plots sample the tree population, standard errors for forest volume and area totals can be calculated (Barrett 2004). One standard error for volumes on timberland outside NF is generally less than 3% of the estimate at the level of western Oregon (WOR) or western Washington (WWA) (Azuma et al. 2002; Maclean et al. 1992). As the area for which volume is being estimated decreases, the number of samples diminishes and standard errors increase. For example, one standard error equaled 4.7% of the volume estimate for forest industry land in the 6 counties in southwest Washington (WA), but was 2.9% of the volume on forest industry land in all WWA, and 1.8% of the volume on all lands excluding NF in WWA (MacLean et al. 1992).

Examining standard errors contributes to understanding the range of error that might surround the C estimate, but does not explore other areas of uncertainty.

Another form of sampling error, regression error, is introduced when regression equations are employed. At each value of an independent variable used to develop a regression equation, a population exists which exhibits a range of values for the dependent variable, although the sample may only contain one value of the dependent variable. If many independent samples could be taken, each sample would yield different values for the dependent variable at a given independent variable value, and the resulting regression coefficients would vary slightly. The regression standard error (also called the standard error for the estimated mean (Ramsey and Schafer 1997)) expresses this variability. The regression standard error is different for each value of the independent variable because it depends not only on the size of the sample, the magnitude of the residuals, and the variance of the independent variable, but also on the distance of the independent variable of interest from the mean of independent variable values in the sample. Regression error is always present when regression equations are employed, but its contribution to uncertainty depends on how equations are developed and used. The fewest problems would result when regressions were developed from large samples, were a good fit to the data, and were applied to the same population they were developed from, over a range of independent variables close to the mean of the independent variables collected to create the regression. However, if an equation were applied to populations that differed in some respect from those used to fit the regression equations, extra uncertainty would be introduced.

Measurement error also introduces uncertainty. Measurement error occurs when the value recorded is not the "true" value, and it can be decomposed into a random and a systematic component (bias). Random measurement errors are often expected to vary normally and are sometimes considered of little importance because they are assumed to average zero. Bias, on the other hand, is very difficult to model and its effects do not diminish with increasing sample sizes (Cunia 1987a). For example, some hardwood species in the PNW are often encased in a thick moss layer or entwined by vines. FIA inventory rules once called for moss and vine removal before

dbh measurement, but it was often not performed by PNW crews. This can result in recorded diameters above the "true" diameter, and could cause volume and biomass to be over-estimated. If this overestimation were to occur on many trees, reported volumes for the PNW could be inflated.

Yet another uncertainty in forest C storage estimates stems from model error, which arises when there is more than one model to choose from, or in the case of tree C storage, when there are multiple equations and conversion factors that could be applied. In the PNW, many combinations of regression equations and conversion factors are possible, but in many cases, no one combination can be deemed most correct, for there is no absolute C measurement against which to gauge the resulting estimates. Depending on tree species and location, a researcher might have a set of volume or biomass equations at their disposal that covered the entire tree and was clearly applicable to their geographic area. In other cases, it might be necessary to substitute equations from other species or other areas to arrive at total tree C. How much uncertainty this would add to final results has not been adequately explored.

Uncertainty introduced by model error could be substantial. Trees develop different forms based on their location, considering location at both fine and regional scales. Regional differences in form are illustrated by Browne (1962), who gives an example of two trees of the same species, age, dbh, and height, from locations approximately 80 km apart in British Columbia (BC). When both were sectioned and measured, there was a 54% difference in volume between the trees. Browne reports that the trees' forms were typical of their locations – one site consistently produced trees with little taper and thin bark, and the other, trees with strong taper and thick bark. Feller (1992) observed that the difference in live-tree biomass between poor and good sites in the same small area of Vancouver Island was pronounced enough to produce significantly different biomass equations. Broad-leaved species in north-central California are reported to vary in form with local topography and stand density (McDonald 1983), and tree form in general is known to change with stand density (Smith et al. 1997). Trees may also differ in their relative volumes of components based on age (Browne 1962), genetics, or the influence of competition within a stand (St. Clair 1993). Estimates of error (often the residual mean square of the regression)

that accompany some published equations may be thought of as incorporating the variation due to factors not included in the equation, such as age, or height for a dbh-only equation, but they cannot account for forms of trees that were not included in the sample from which equations were estimated.

Available equations for some tree components may be prone to bias based on the original study's scope. It is not uncommon for equations to be developed from a limited area, such as the HJ Andrews Experimental Research Forest (Grier and Logan 1977) or a single clearcut stand (Helgerson et al. 1988). When these equations are applied to areas where trees have different forms, bias is introduced. Equations used in this study range from those based on thousands of trees from a large and diverse area (Browne 1962), to one based on three trees (Santantonio et al. 1977).

Statistical methods are available (Chojnacky 1987; Cunia 1987a; Phillips et al. 2000) to incorporate regression error into sampling error of an inventory, and measurement error may be included as well (Phillips et al. 2000). However, model error is more difficult to handle analytically.

3.1.3 Uncertainty in the Volume, Biomass, and Carbon Literature

Until recently, little attempt was made to gauge the uncertainty surrounding C budgets due to the complexity of the issues and the number and types of errors involved. There is no large-scale inventory designed specifically with C in mind, so data must be assembled from different studies. Most authors report estimates of biomass or C in the study area without confidence intervals or standard errors, as in Birdsey (1992), Turner et al. (1995), and Cost (1990), although some acknowledge the presence of numerous sources of uncertainty (Birdsey 1992). Although FIA typically chooses only one volume and biomass equation per component for trees within a region, they do report error for their calculated volumes based on the analytically determined sampling error (Azuma et al. 2002).

Several studies have compared the results of different equations. For example, Grigal and Kernik (1984) determined that many foliage biomass equations for *Picea mariana*

did not overlap within 2 standard errors, while many total aboveground biomass equations overlapped within 1, and all within 2, standard errors. Tritton and Hornbeck (1982) examined biomass regression equations for *Acer rubrum* in the northeastern US and concluded that most produce similar estimates, but suggested that several equations be used to obtain a range of biomass values. St. Clair (1993) compared published biomass equations for several *Pseudotsuga menziesii* components with his own equations and found significant differences in prediction, even when stands were within the same geographic area and of similar ages. He attributed these discrepancies to differences in age and between-tree competition during stand development. Jenkins et al. (2004) display a plot of several biomass equations for *Pseudotsuga menziesii* that indicates considerable variation among equations. At approximately 90 cm dbh, there was a 3,000 kg difference between the high and the low biomass predictions. Omule et al. (1987) evaluated several volume equations for coastal *Pseudotsuga menziesii* in BC with data from a large BC dataset and determined biases were present that varied by equation and dbh class. However, a detailed dataset with relevant tree measurements must be available for the area of interest to make these types of comparisons. Such detailed information is generally lacking, and when it is present, may not be relevant if it was assembled at a time when conditions, such as climate, stand density, or disturbance regime, for example, were different than they are today (MacLean and Berger 1976). Various researchers have assembled data from many local studies to produce what they hope are regionally-applicable equations. Some studies use data from numerous studies to create a new generic equation suitable for larger geographic regions (e.g., Gholz et al. 1979). Most recently Jenkins et al. (2003) created nationally-applicable equations for species-groups based on numerous equations for individual species.

Some error analysis of C storage figures at a regional scale was performed by Phillips et al. (2000). They investigated statistical errors involved in FIA estimates of state-wide volume, growth, and removal in the southern US. Of the three errors they considered (sampling, measurement, and regression), they found sampling error was by far the greatest contributor to total error (98.7%). Regression errors accounted for 1.2%, and measurement errors for the remaining 0.1%. However, they worked with only two equations, one each for hardwood and softwood and thus did not include

model uncertainty. They also assumed the measurement accuracy tolerances set by the southern FIA station were met and no measurement bias existed. If bias was present, it could have a large impact; Gertner (1990) found that calculated volumes could be dramatically affected by bias in dbh measurements.

Heath and Smith (Heath and Smith 2000; Smith and Heath 2000) employed Monte Carlo simulation to create an uncertainty analysis of current and future US forest C storage and fluxes. Their model, FORCARB, predicts C in trees, understory vegetation, forest floor, and soil by forest type based on FIA volume data that can be projected forward in time with the TAMM/ATLAS[1] models. Heath and Smith analyzed uncertainty by creating distributions around the expected values of these forest C components (by forest type), then running a Monte Carlo analysis to draw values from each distribution. At each run of the model, different values were selected and combined to produce a total C storage estimate. These total C estimates then formed a distribution of expected C storage values. They concluded that the distributional shape selected for a C component was not as influential on final uncertainty as the range of values or the covariance between model components (Smith and Heath 2000). The forest components with most influence on final C storage uncertainty were soil (approximately 33% of the overall uncertainty) and tree (approximately 30%) C pools; growth and removal uncertainties were most influential on total flux uncertainty (Heath and Smith 2000). They also noted that C predictions might be differentially affected by input uncertainties depending on site class, land use, and forest age.

3.2 Objectives

Our goal was to examine uncertainty from model error in live-tree C storage. Unlike previous analyses, this assessment of uncertainty did not assume that one model (meaning the assignment of one equation or conversion factor to a species and tree component) was correct. Objective 1 was to create live-tree C bounds by species and

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[1] TAMM is the Timber Assessment Market Model (Adams and Haynes, 1980) which predicts wood production and price; ATLAS stands for the Aggregate Timberland Assessment System and predicts timber volumes (Mills and Kincaid, 1992).

dbh class, then determine the tree components with the greatest contribution to model error.

Objective 2 was to bracket the estimated live-tree C store of six counties in northwest Oregon (NW OR) with uncertainty bounds created by assuming all equations and conversion factors developed for a species were equally valid under different patterns of tree component correlation. The effect of assumptions about tree density was also explored.

Further sources of uncertainty could be easily incorporated. Model uncertainty was assessed partly using regressions, which introduce regression error. Because height is a time-consuming variable to measure and not all tree records included a measured height, height had to be estimated even to estimate volume, thereby introducing additional error. Objective 3 was to test the effect on the uncertainty of incorporating two additional sources of error: regression error and variation from using estimated tree height.

It seems reasonable that the more information that is known about a population of trees, the more that the uncertainty in live-tree C storage can be reduced. Seemingly influential data available through the FIA inventory are the species of each sampled tree and an estimated dbh distribution by species for the study area. Objective 4 was to explore how the magnitude of model uncertainty varied with the availability of information on species and dbh distribution.

When making population estimates from a sample, using stratification to first divide the population into groups that are similar in some respect often results in lower variance of the population estimates. For example, FIA reduces variance of estimated volume by applying a stratification based on broad forest type, tree size and canopy density classes (Azuma et al. 2002). This approach to variance reduction inspired Objective 5: testing to what extent uncertainty introduced by model error could be reduced by a priori assignment of trees to specific equations.

The FIA program provides tree-level estimates of aboveground biomass that are created by using equations subjectively selected as most applicable for each tree

species and inventory area. Objective 6 was to compare the FIA estimate of aboveground biomass (converted to C) for the study area to the range of aboveground C produced in Objective 2.

3.3   Methods

3.3.1   Study Area

This study relied on FIA plot data from 6 counties in the northwest corner of Oregon (OR): Clatsop, Columbia, Polk, Tillamook, Washington, and Yamhill (Figure 3.2), referenced henceforth as NW OR. These counties cover 1.37 million ha, 64.7% of which is estimated by FIA to contain forest land (defined as having a current live-tree stocking or canopy cover of at least 10% or having had this in the past and having a high likelihood of having it in the future (Azuma et al. 2002)). The counties fall in the Coast Range and Willamette Valley provinces as defined by Franklin and Dyrness (1988). The Coast Range is characterized by steep ridges to about 750m, carved by numerous streams and blanketed by conifer-dominated forests. Within this province two major forest zones have been identified: the *Picea sitchensis* (see Table 3.1 for common names) and the *Tsuga heterophylla* zones. The former is a coastal strip with high rainfall and mild temperatures where the characteristic species is found growing with *Tsuga heterophylla*, *Thuja plicata*, *Pseudotsuga menziesii*, and *Alnus rubra*. The latter is essentially an extension of this zone with more seasonality in rainfall and temperature. Dominant trees are *Pseudotsuga menziesii*, *Tsuga heterophylla*, and *Thuja plicata,* with *Alnus rubra* and *Acer macrophyllum* occurring in disturbed or riparian areas. When undisturbed, trees in both zones attain large sizes and may live to be many hundreds of years old. Accumulated C in all forest components may exceed 1000 Mg ha^{-1} (Smithwick et al. 2002). The Willamette Valley lies inland of the Coast Range and encounters less precipitation and higher temperatures. While much of it is under cultivation, forests remain at the borders as scattered islands. Forests are generally dominated by *Pseudotsuga menziesii*, accompanied by *Acer macrophyllum* and *Quercus garryana*. Approximately 5% of the forest land area is
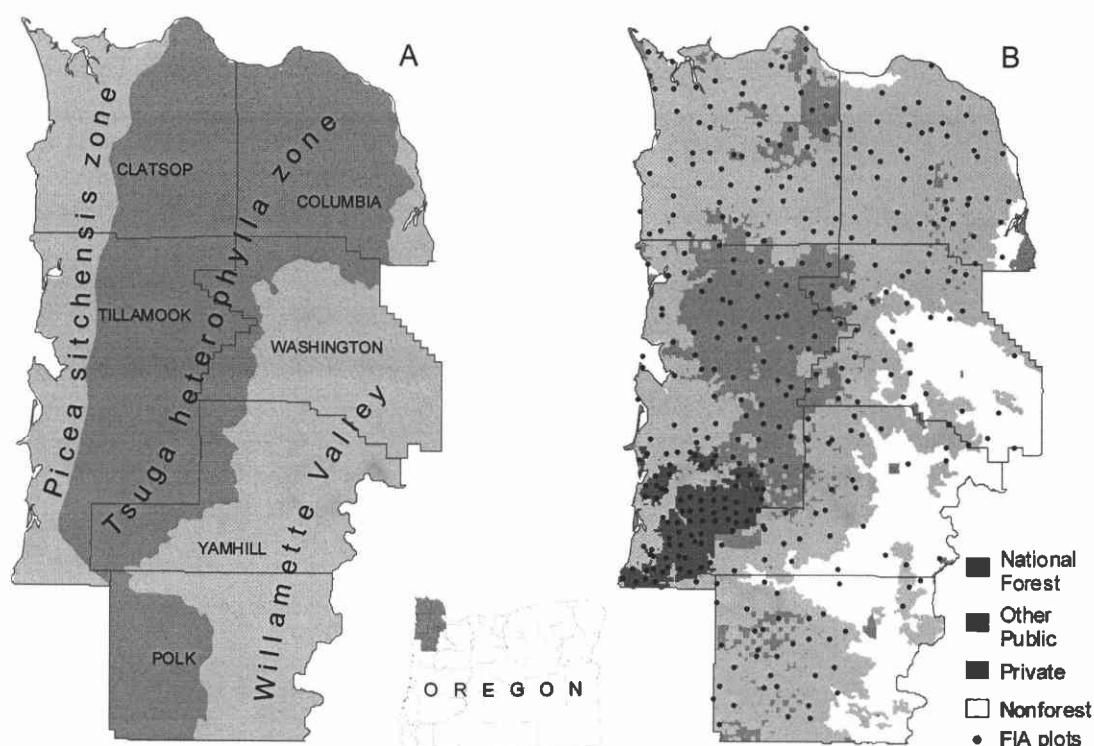
Figure 3.2. Six-county study area in NW OR. A: Vegetation zones defined by Franklin and Dyrness (1988). The *Picea sitchensis* zone boundary was is derived from Figure 27 in Franklin and Dyrness (1988); the Willamette Valley boundary was obtained from Woods et al. (2000). B: Forest ownership and FIA forest plots. Forest land data were obtained from the Gap Analysis Project Northwest Habitat Institute (2001) and do not correspond exactly to the locations of FIA plots (Hiserote and Waddell 2004), both because they were obtained by different methods, and because FIA plot locations have been altered to protect the privacy of landowner data. Plots are more concentrated in the NF because sampling intensity was greater there.

Table 3.1. Abundance and maximum dbh (in the NW OR study area, by species, as estimated by the 1997 WOR FIA inventory). The relative abundance of trees estimated in NW OR may be greater than the relative abundance in the inventory due to the use of different expansion factors for plots. Percents may not sum to 100 because of rounding. Inventoried tree seedlings of each species are included in the calculation of number of trees in NW OR. Nomenclature follows USDA NRCS (2004).

Scientific Name	Common Name	Trees Inventoried	Trees in NW OR		Maximum dbh
		(number)	(number)	(%)	(cm)
Pseudotsuga menziesii (Mirbel) Franco	Douglas-fir	6543	320,767,178	42.3	236
Alnus rubra Bong.	red alder	2597	138,621,987	18.3	108
Tsuga heterophylla (Raf.) Sarg.	western hemlock	2367	157,398,094	20.7	161
Picea sitchensis (Bong.) Carr.	Sitka spruce	729	27,609,701	3.64	224
Acer macrophyllum Pursh	bigleaf maple	301	38,314,456	5.05	117
Thuja plicata Donn ex D.Don	western redcedar	176	11,960,531	1.58	117
Quercus garryana Dougl. ex Hook.	Oregon white oak	144	13,813,925	1.82	89
Prunus spp.	cherry	53	13,990,958	1.84	35
Abies procera Rehd.	noble fir	49	2,691,641	0.35	69
Abies grandis (Dougl. ex D. Don) Lindl.	grand fir	41	3,419,697	0.45	71
Populus balsamifera L.	black cottonwood	36	4,102,776	0.54	126
Salix spp.	willow	33	8,269,417	1.09	72
Pinus contorta Dougl. ex Loud.	lodgepole pine	33	4,599,346	0.61	37
Cornus nuttallii Audubon ex Torr. & Gray	Pacific dogwood	17	2,893,701	0.38	18
Fraxinus latifolia Benth.	Oregon ash	16	3,833,832	0.51	79
Taxus brevifolia Nutt.	Pacific yew	10	2,307,362	0.30	32
Ilex spp.	holly	7	1,581,271	0.21	22
Malus spp. Mill	apple	7	613,849	0.08	46
Robinia pseudoacacia L.	black locust	4	1,075,451	0.14	3
Arbutus menzeisii Pursh	Pacific madrone	3	489,255	0.06	29
Alnus rhombifolia Nutt.	white alder	1	134,086	0.02	17
Abies amabilis Dougl. ex Forbes	Pacific silver fir	1	16,608	0.002	59
	unknown species	1	438,005	0.06	7

administered by the FS, 33% is administered by other public agencies (mainly the OR Department of Forestry), and the remaining 62% is privately owned (Figure 3.2).

3.3.2 Data

Tree data were drawn from FS inventories. FIA permanent plots were established in the 1950s and 1960s to monitor timber volume and forest conditions on US forest lands in all ownerships. The most recently completed PNW inventories were conducted on all unreserved lands (unreserved lands are those not dedicated to noncommodity use by statute, ordinance, or administrative order (Azuma et al. 2002)) outside of NF and were designed as a systematic sample with double sampling for stratification, where the primary sample consisted of a grid of points on aerial photos that were interpreted for basic characteristics such as ownership and forest type, and the secondary sample consisted of a $1/16^{th}$ subsample of the photo-points that were installed as field plots. Each plot represents several thousand acres of forest land. Inventories in NF were conducted by the Regional Office of the NF System, and are often referred to as the Current Vegetation Survey (CVS). CVS sampling intensity within wilderness areas is essentially the same as FIA's, but is four times more intense on unreserved NF land (Figure 3.2). Estimates of timber volume and forest land area by owner class, size class, site class, forest type, etc. for FIA inventories, and sometimes for CVS inventories, have been reported in periodic FIA reports (e.g., Azuma 2002; MacLean et al. 1992). These inventories provide reliable estimates for statewide and sub-state forest areas, with 68% confidence intervals for volume usually being no more than a few percent of most area and volume estimates.

The FIA's Integrated Database (IDB) version 1.4 (Hiserote and Waddell 2004) combines information from the most recently completed FIA and NF periodic inventories on the permanent plot system. It includes dbh, height, species, and geographic location of trees and the necessary 'expansion factors' for scaling up inventory plot data to county- and state-wide estimates. It also includes FIA-calculated tree bole volumes as well as aboveground total, stem wood, stem bark, and branch biomass estimates for each tree over 2.5 cm dbh. Metadata on the equations used is available for some species and components.

3.3.3 Equations

To avoid complicating the analysis (and increasing uncertainty) by substituting equations from one species for components of another species that had no equations, only the five most common species in NW OR were included. These species, referred to henceforth as target species, are all relatively well-represented in the volume and biomass equation literature. Target species were the conifers *Picea sitchensis, Pseudotsuga menziesii*, and *Tsuga heterophylla*, and the broadleaved trees *Acer macrophyllum* and *Alnus rubra*. Collectively they represent 89.9% of all trees inventoried in NW OR (Table 3.1). Therefore when total C estimates are given in this chapter, they do not refer to all live trees in NW OR - only to the five target species.

To find all possible models, the first step involved obtaining volume and biomass equations. Equations relevant to the five target species were extracted from BIOPAK (Means et al. 1994), the HJ Andrews dataset (Franklin 2002), and available literature (see Appendices B, C, and the final bibliography for equations and references). Equations were deemed relevant if data originated, at least in part, from BC, Alaska (AK), or from trees growing on the west side of the Cascades in OR and WA. The only consistent information available for an equation was its formula. Often there existed some measure of its fit to the dataset from which it was created (usually an R^2) and the dbh range of the original data. All equations and related metadata such as sample size, dbh range of sample trees, geographic location, and standard error of the equation were loaded into a database.

Equations were sorted by the tree component they predicted, and a generic structure for estimating biomass via various alternative calculation routes was established (Figures 3.3 and 3.4). These do not represent every calculation possibility; for example, there are other calculation pathways involving volume equations that predict from variable stump heights to different top diameters, and biomass equations that require input variables other than dbh and height. In the interests of simplicity these volume equations were excluded, and equations which required input parameters not in the IDB were rejected as well. Not all species had equations for all calculation

Figure 3.3. Calculation pathways considered. Most pathways to arrive at crown components are pictured in Figure 3.4. Each label is the name of a lookup table (see Section 3.3.4). Where multiple options for calculation of a component existed, lookup tables were numbered (with lookup table label numbering starting only with the 2nd option and beyond); "f" indicates the final lookup table for that component. A "v" following a component indicates a volume lookup table; "vb" denotes a volume table converted to biomass by multiplication with density. Calculations on the tables are indicated by: "+", tables were added; "*", multiplication was performed; and 'M', table values were compared. Each lookup table may be generated from many equations. Stump heights used in this analysis were 10, 15, or 30 cm, depending on equations available for a given species.
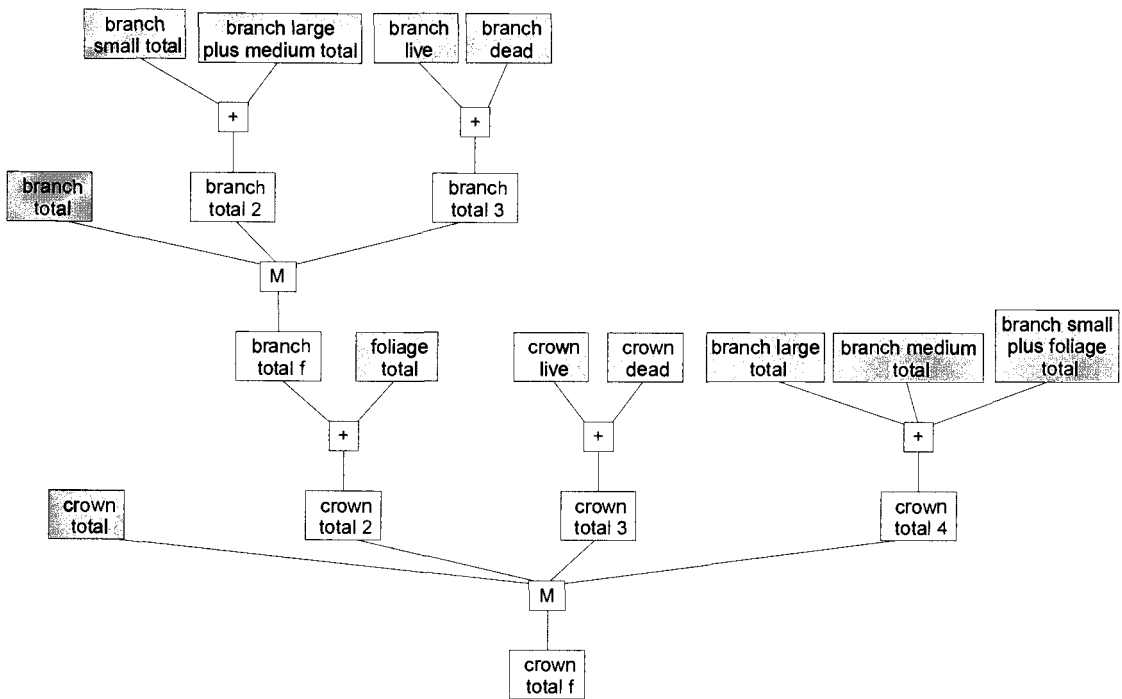
Figure 3.3.

Figure 3.4. Calculation pathways considered for most crown components. Calculations on the tables are indicated by: "+", tables were added; "*", multiplication was performed; and 'M', table values were compared. Each table may be developed from many equations.

pathways (see Figures A.1-A.10), and in some cases only one equation was available for predicting a given component.

For the five most common species in NW OR, 94 volume and 389 biomass equations were found for a variety of components. Eighteen possible volume and 26 biomass equations exist for stem wood of PNW *Pseudotsuga menziesii* alone.

To make every prediction represent the mean for the sample population, we attempted to apply a correction factor (Baskerville 1972; Yandle and Wiant 1981) whenever necessary. When information to make the correction was not provided, we approximated one using data from another study with a similar number of trees sampled from an approximately equal dbh range. If no indication was given as to whether an equation was corrected, we assumed it was not.

3.3.4 Basic Analysis

Our philosophy in conducting this study was to build and utilize lookup tables containing ranges for each species-diameter class combination instead of calculating a single estimate for each tree. We represented live-tree C variation within 1-cm dbh classes by storing maximum and minimum predicted values, as well as the midpoint for a measure of the central tendency. Using these three descriptors for each dbh class captured the pertinent information for transfer to the next step. Use of these descriptors also avoided the problem that arises when separate equations are chosen to represent the minimum, midpoint, and maximum. That would be a useful approach if equations were parallel, but they frequently cross (see figures in Appendices B and C); meaning there is often no consistent minimum or maximum equation. It would also be time-consuming to apply different equations to different subranges of dbh. Saving three values in a lookup table for each dbh class allowed the range information to be stored conveniently as a table for use in modeling. This modeling approach allowed flexibility in equation choice without undue calculation burden.

Biomass equations and accompanying data were stored in a spreadsheet accessed by a program that generated biomass lookup table containing predictions for every applicable equation at each 1-cm dbh class by component and species (Domingo

2004). Biomass in the 0-cm dbh class was calculated with a 0.25 cm dbh. All equation predictions were examined to determine whether estimates were acceptable, with equation slope as the main criterion for judging acceptability of each equation for each range of dbh (Figure 3.5). If one equation's dbh slope was much greater than the others, or if its slope remained extremely low even at large dbhs, the formula was first checked against the published information. If no errors were discovered, predictions from that equation were discarded for the range over which the slope appeared unreasonable relative to other equations. Unacceptable equations were removed or had their dbh ranges truncated.

A number of volume equations were complex and so volume lookup tables were generated using Matlab (The Mathworks 2001). Their predictions were assessed in a similar manner and used to create lookup tables of volume. Tree component density values from the literature with reported sample sizes and with reported or estimated standard errors were collected (Table D.1) and 95% confidence intervals based on Student's t-distribution were applied to each measurement. For each species and component, two density options were chosen for multiplication with volume equation predictions: the maximum density range using lowest minimum bound and the highest maximum density bound, and a midrange density range using the bounds for a single, middle value, density estimate (Table D.2). During multiplication with volume lookup tables to generate biomass tables by this calculation pathway, the low density value was multiplied by the minimum predicted volume for each dbh class and the maximum density was multiplied by the maximum volume.

To generate lines representing a prediction envelope (i.e., maxima and minima) over the full dbh range, all well-behaved equations were extrapolated to the full dbh range of the species. If, at the point of their termination, none of the truncated equations predicted values higher or lower than the extended equations, then maximum and minimum values at each dbh class were captured, midpoints were calculated, and all were input to the component lookup table. For components where some equations were truncated but one or more truncated equations (at their point of termination) predicted values above the volume or biomass range of the extended equations, a
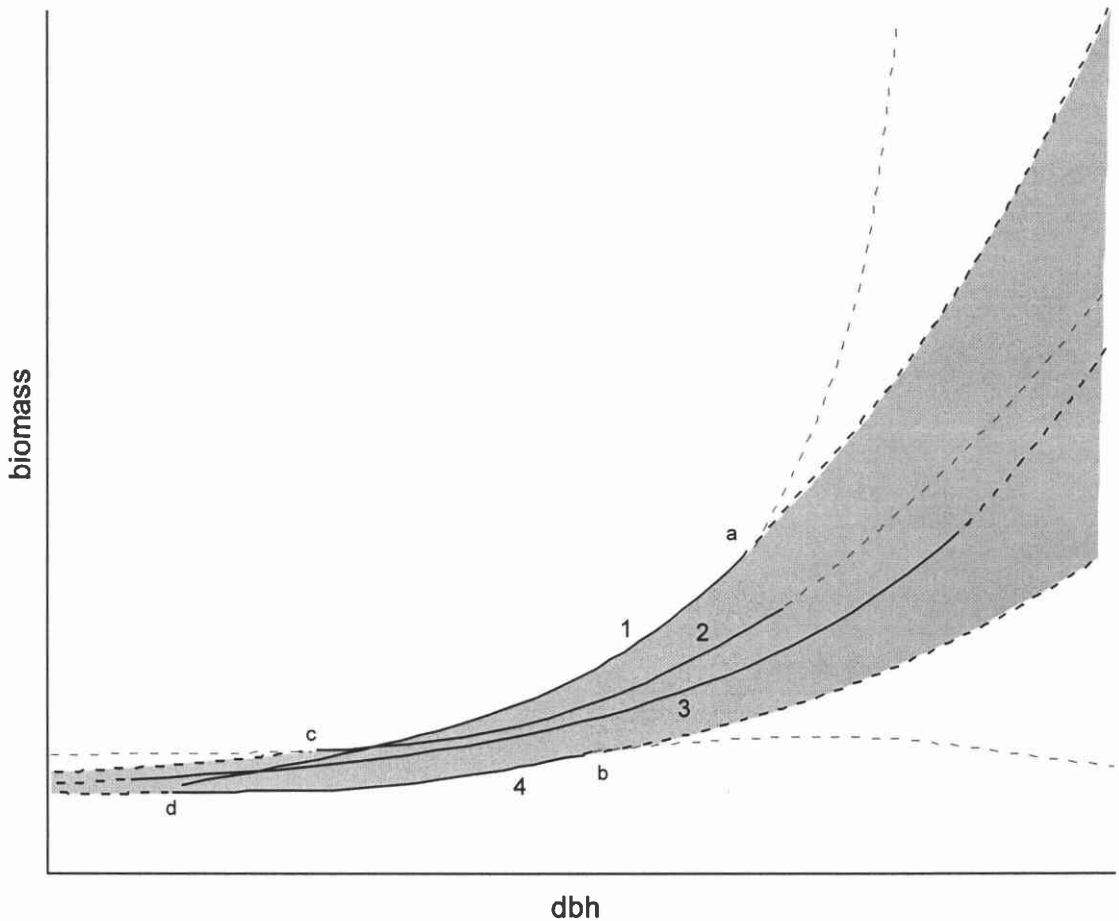
Figure 3.5. Example of equation extension to species dbh range. Grey shading indicates the final bounds input to the lookup table. In this example, equation 3 was chosen as the base equation because it had the longest experimental dbh range. Its predictions were therefore extended to the limits of the inventory data using the equation formula. Point a: equation 1's dbh range ended. Because the equation was considered to be too extreme after that point, it was truncated at the limit of its experimental data. It was extended by applying the percentage above the base equation at its point of termination to values of equation 3 for all higher dbhs. Point b: equation 4 was truncated after its slope began to diminish and was extended after that point by applying the percentage below the base equation to the base equation. Point c: equation 2 was considered to give unrealistic values at low dbhs so it was extended based on its percentage above equation 3. Point d: Equation 4 appeared reasonable at low dbhs and so was extended using its published formula to the minimum dbh in the NW OR inventory.

second method was employed (see Figure 3.5 for an example). An equation with a large experimental dbh range was selected as the 'base' equation. Truncated equations were extended to the full dbh range of a species by applying their percent above or below the base equation (at the truncated equation's point of termination) to the base equation. Values were extended down to the 0-cm dbh class in the same manner. Once maxima and minima were established for each dbh class, midpoints were calculated for each dbh class and all data was output as a lookup table. This method resulted in relatively smooth prediction lines, although they changed in slope as different equations formed the maximum and minimum or were truncated and extended as a percent of a base equation.

In some cases, no equations appeared acceptable when they were extended to smaller or larger dbhs. If only one equation existed, and it could not be made to behave reasonably, it was discarded and the species no longer had equations creating predictions for that component. If more than one non-extendible equation existed, the midpoint at each dbh class was calculated for each dbh class of their overlapping ranges and the midpoint was regressed on dbh using SAS (SAS Institute 2000). The prediction equation that resulted was then used to create the midpoint for that component over the full dbh range of the species.

All methods required equations to be extended beyond the range of the original data. However, very few equations have been developed using data that extend to the full range of dbhs collected by the FIA, so it was impossible to avoid extrapolation. For example, of stem wood volume equations used by the FIA, the original data exceed the NW OR data by 20 cm for *Picea sitchensis*, but fall short of the NW OR data range by 48 cm for *Tsuga heterophylla*, 27 cm for *Acer macrophyllum*, and 52 cm for *Alnus rubra*. Dbh range was not reported for the equation used for *Pseudotsuga menziesii* (Brackett 1977). Only 0.12% of *Tsuga heterophylla*, 2.3% of *Acer macrophyllum*, and 7.5 % of the *Alnus rubra* inventoried actually fall above the original equation dbh limits, however.

Whatever method was chosen, for each species, component, and dbh class there was either a maximum, minimum, and midpoint derived from multiple equations, or a

single prediction. Because no other information existed, single predictions were assumed to be midpoints. Percentages above and below the midpoint of a similar component (that had more prediction equations) were applied to them to create maxima and minima. An ad hoc penalty system was devised in an attempt to account for the effect of the substitution by widening the prediction range for each dbh class according to the perceived amount of difference between the component being predicted and the component from which percentages were derived. Percentages originating from a similar component of the same species received an extra 1% in addition to the applied percent. For example, if *Picea sitchensis* "stem wood no top" had percents substituted from the better-studied *Picea sitchensis* "stem wood", each percent was increased by 1% percent (of the midpoint) before being applied. If it was from a different component of the same species, an extra 3% uncertainty was added. A similar component of a different species was judged to require an extra 5%, and a different component of a different species received the maximum penalty, 7%.

No crown component equations (branches and foliage) were extended to the limits of the species dbh ranges. Instead, crown component equations were truncated at half of the species dbh range and their values at that point were applied to the rest of the dbh range. This resulted in increasing predictions for the first half of the dbh range and a level band thereafter. Crown components, especially foliage, are not expected to increase significantly after a tree reaches maturity, as suggested by the findings of Turner and Long (1975). They observed foliar biomass in *Pseudotsuga menziesii* peaked by 80 years of age for several stands with a range of tree densities.

Biomass lookup tables for all components were converted to C based upon average C:biomass ratios derived from the literature and reported in Birdsey (1992). Because no estimates of variability accompanied the ratios, the unweighted average of coefficients of variation from a study of several components of Australian-grown *Pinus radiata* (Gifford 2000) was applied to the average hardwood and softwood C:biomass ratios presented in Birdsey (1992) to produce standard deviations. The sample size of the Australian pine samples was applied to produce the standard error of the ratios, and generate 95% confidence intervals. This procedure resulted in an estimated

range for the mean C:biomass ratio of 48.6-50.6% for broad-leaved species and 50.1-52.3% for conifers.

The assessment of uncertainty in the live-tree C store proceeded from the uppermost components in Figures 3.3 and 3.4 to the lowest one. Where components were summed, the midpoints at each dbh class were added directly but the maxima and minima depended on the correlation between the components being aggregated and the relative magnitude of the ranges of the components. Two correlation options are possible: 1) larger trees have more of all components, and 2) biomass allocation between components differs between individuals or groups of individuals within a dbh class. Differential allocations would probably be a response to the biogeoclimatic environment faced by each tree or group of trees, and perhaps be influenced by genetics and a tree's position within a stand.

Because we were searching only to outline C storage bounds, we reasoned that the most extreme examples of correlations would occur when components displayed either perfect positive or negative correlation at each addition (Figure 3.6). These correlations were chosen deliberately to be extreme and is not expected to conform to any real-world examples. We made three simple assumptions about within-dbh class correlation between components. At every point where components were added, components: were perfectly positively correlated, had zero correlation, or were perfectly negatively correlated. To accomplish this, we borrowed from the mathematics of normal distributions. This was not strictly theoretically correct, because we possessed no information to indicate that the distribution of biomass in each species by dbh class was normally distributed, or that the maximum and minimum predicted biomass values in the lookup tables corresponded to certain percentiles in such a distribution. However, we used it for convenience. To calculate ranges of summed components, we employed the standard formula for addition of variance:

$$\text{var}(x+y) = \text{var}(x) + \text{var}(y) + 2\,\text{cov}(x,y),$$ Eqn 3.1
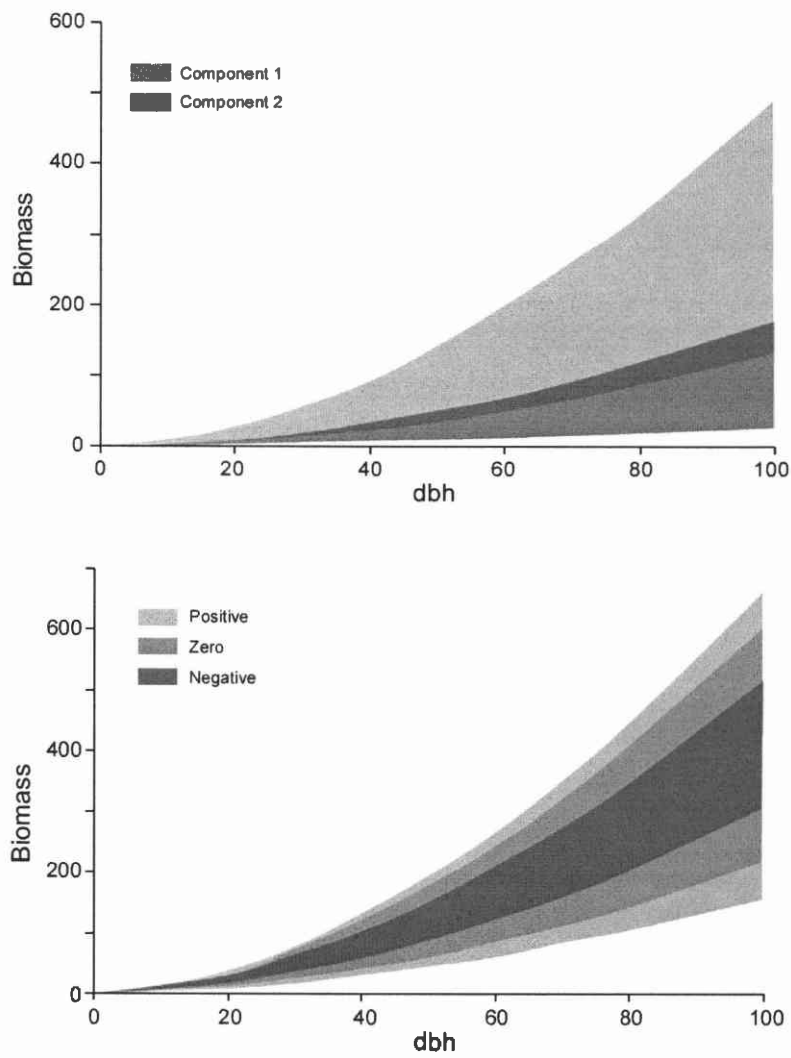
Figure 3.6. Example biomass component additions with correlation. The upper figure displays the ranges of two biomass components before addition. Ranges after addition are plotted in the lower figure. Positive correlation produces the largest output range; negative correlation the smallest.

where

var = the variance, and

cov = the covariance.

To determine covariance we used:

$$\rho = \frac{\text{cov}(x, y)}{\sqrt{\text{var}(x)}\sqrt{\text{var}(y)}},$$

Eqn. 3.2

where

ρ is the correlation between x and y.

For a positive correlation, ρ = 1; for a zero correlation, ρ = 0; for a negative correlation, ρ = -1. Variance in each dbh class for two components being added was estimated by assuming that the maximum and minimum values were two standard deviations from the midpoints. When these variances and the applicable correlation value were substituted into equation 3.2, an estimate of the covariance was obtained, which was then applied to equation 3.1. In cases where there were only two input components, the simplest way to obtain perfect positive correlation (with a result identical to using Equations 3.1 and 3.2) was to add the maximum of the first component to the maximum of the second to produce the new maximum for every dbh class. The minimums were treated similarly. This produced the widest possible range in the aggregated component. The simplest way to calculate the addition of two components that were perfectly negatively correlated was to add the maximum of one plus the minimum of the other and vice versa. In cases where more than two components were to be summed, the output range under positive correlation was simply the difference between the sum of all the maximums and the sum of all the minimums. However, it was more difficult to achieve perfect negative correlation when there were more than two components. Instead, we generated all possible additive combinations of maximums and minimums to determine which produced the smallest range. The resulting minimum range was used as the negative correlation. Zero correlation was calculated using Equation 3.1 with covariance set to zero.

Where multiple estimates for a single component arose from different pathways (as in Figure 3.3 where aboveground total biomass can be predicted directly or from several alternate routes), maximum and minimum values arising from different calculation pathways were compared for each dbh class. Values that produced the largest range within a dbh class were chosen for inclusion in the lookup table for the component in question. The overall midpoint was calculated from this range for each dbh class.

3.3.5 Contribution of Components to Uncertainty by Diameter Class

To fulfill Objective 1, the contribution of basic tree components to final uncertainty, we plotted the relative cumulative uncertainty of stem wood, stem bark, coarse roots, and branch total for each dbh class and species.

3.3.6 Northwest Oregon Live-Tree Carbon

Once total tree lookup tables were calculated for all species, they were applied to FIA inventory data. Each inventoried tree had a dbh and species recorded; minimum and maximum C values were obtained from the appropriate lookup table. All trees were multiplied by their expansion factors to obtain NW OR estimates. Maximum and minimum C for each tree were summed by species, and finally species totals were summed to produce an estimate of the minimum, midpoint, and maximum C storage in live trees (for target species only) in NW OR. This was performed for all three correlation patterns. Although it was unrealistic to expect that every tree would display the same within-dbh class correlation pattern, this assumption was used to produce the extremes of uncertainty. Uncertainty was calculated as half of the output range, and this number was also expressed as a percent of the midpoint. To determine the effect of density method, two sets of biomass tables arising from each volume lookup table were created, one using the maximum density range and the other the middle density range (Table D.2). The lookup table addition, application to inventory data, and summation to the NW OR level were performed using each density option.

3.3.7 Additional Uncertainty from Regressions

The first portion of Objective 3 explored the effect of uncertainty from the use of volume and biomass regressions. Each equation's predictions of a mean volume or biomass for every dbh class might have been different had different set of trees had been chosen. This variation can be expressed using the standard error of the regression.

For a regression equation formulated

$Y = b_0 + b_1 X_0$

where
Y = volume or biomass,
b_0 and b_1 = regression coefficients, and
X_0 = independent variable of interest (usually dbh),

the standard error can be written as

$$SE[\hat{\mu}\{Y \mid X_0\}] = \hat{\sigma}\sqrt{\frac{1}{n} + \frac{(X_0 - \overline{X})^2}{(n-1)s_x{}^2}}$$

where

$\hat{\mu}\{Y \mid X_0\}$ is the estimated biomass at a given dbh,

$\hat{\sigma}$ is the root mean squared error (RMSE) of the regression,

n is the number of observations,

X_0 is the dbh of interest,

$\overline{X}$ is the average dbh in the sample set, and

$s_x{}^2$ is the variance of the dbhs in the sample (after Ramsey and Schafer 1997).

To be reasonably sure of capturing the mean predicted value from an equation over its entire dbh range, we used the Workman-Hotelling procedure to create a 95% confidence band following the formula:

$$\hat{\mu}\{Y \mid X\} \pm \sqrt{2 \times F_{2,n-2}(0.95)} \times SE[\hat{\mu}\{Y \mid X\}]$$

where $F_{2,n-2}(0.95)$ indicates the 95th percentile of the F-distribution with 2 and n-2 degrees of freedom (Ramsey and Schafer 1997).

Unfortunately, most published biomass or volume regressions did not contain the statistics necessary to calculate standard error. Most contained n and the dbh range, many reported either the MSE or the RMSE, some contained average dbh, but none contained the variance of the sample dbhs. If sufficient data are provided, it is possible to obtain the variance of the dbhs through decomposition of standard errors for slope or intercept parameters (Ramsey and Schafer 1997). However, such standard errors were rarely reported.

We tested the effect of applying the regression standard error to the biomass equations of Grier and Logan (1977) for *Acer macrophyllum*. They report data for 18 trees, ranging from 7.6-35.3 cm and averaging 20.4 cm dbh. MSE was also reported for each regression equation. The variance of the dbh changes depending on the dbhs measured, so without a tabulation of the data it is impossible to determine exactly. We estimated it in the following manner: two of the 18 dbh measurements were assigned values from endpoints of the reported dbh range and one was assigned the mean value. Fifteen dbhs were then drawn from the intervening range at fixed intervals below and above the mean with the restriction that the mean of the dbhs must be close to that reported by Grier and Logan. This resulted in eight of the dbhs arranged between 7.6 and 20.4 cm with the remainder spaced evenly between 20.4 and 35.3 cm. The variance of these dbhs was determined, the standard error for each 1-cm dbh class was calculated, modified with the Workman-Hotelling procedure, and applied to the predicted biomass to generate a 95% confidence interval for the equation's range. This same procedure was repeated for each component biomass equation. Then individual equation predictions were summed to the aboveground total level using the positive correlation methodology.

We also used this method on the nationwide prediction equation for soft maple/birch species of Jenkins et al. (2003). Because they developed their equations by

generating pseudodata from previously published equations, there was not a sample size per se. We considered sample size to be 316, the number of pseudodata points they generated for their equation.

The second portion of Objective 3 dealt with the effect using estimating heights for volume and biomass calculations. Because our methodology to estimate volume and biomass required us to have a single height for each dbh class, and we predicted that height from dbh, we were essentially predicting volume and biomass from dbh alone. To make a preliminary estimate of how much variation due to height was likely to exist around the predicted C for each dbh class, we obtained NW OR *Pseudotsuga menziesii* mean, minimum, and maximum heights for each 1-cm dbh class from the IDB. Each set of heights was applied to the Shaw (1979) stem wood biomass equation (equation 157, Table C.2), and results were plotted versus dbh.

To test whether equation form influenced the amount of variation introduced when using measured heights, we selected equations #157 (Shaw 1979), #701 and 735 (Newnham in Evert 1985), and #1536 (St. Clair 1993) for *Pseudotsuga menziesii* stem wood and crown total biomass shown in Table C.2, as well as #20 (Penner et al. 1997) and #29 (Curtis in Brackett 1977) equations for *Pseudotsuga menziesii* stem wood volume detailed in Table B.1. As before, equations were run on mean, minimum, and maximum heights. Then each set of estimates using minimum and maximum heights were expressed as percent differences of the mean height for each dbh class to reveal the pattern of relative increase or decrease from the mean caused by height variation.

To apply these findings to all species at the level of NW OR, we calculated a conservative generic estimate of the variation from height in *Pseudotsuga menziesii* over a dbh range with many measured heights. This removed the artificial reduction in height variation due to small sample sizes at larger dbhs. After reviewing biomass and volume predictions made with minimum, mean, and maximum heights, we assumed variation in height would produce no more than a 40% increase above the biomass predicted with mean height and no more than a 50% decrease below it. To obtain a simple estimate of the effect at the NW OR scale for a single species, we

increased the maximum bound of every lookup table by 40% of the maximum value, and reduced the minimum by 50% of its value. Lookup tables were then summed as for the base analysis.

3.3.8 Effect of Altering the Amount of Available Information

Objective 4 consists of three sections: testing the effect of 1) using dbh and height as opposed to dbh alone to predict biomass, 2) removing information on species, and 3) removing information on dbh distribution.

Volume and biomass equations that incorporate height are sometimes referred to as standard equations. It is assumed that by accounting for the effect of height variation, standard equations are applicable to larger geographical areas than local equations that rely only on dbh (Grigal and Kernik 1984). To test whether incorporating height increased agreement among equation predictions, predicted biomass of several stem wood equations was plotted against the product of dbh^2 and height. If including height in a biomass equation enhanced applicability of equations, equation predictions should exhibit significant overlap along their ranges, or at least be much closer than when plotted against only dbh or height.

We tested whether knowing species of each tree affected the uncertainty of the regional live-tree C estimate by comparing total tree C lookup tables for all species and selecting the widest C range at each 1-cm dbh class for each correlation pattern. If the maximum or minimum occurred in a species with a limited natural dbh range, bounds were extrapolated to the maximum dbh present in the study (a 236-cm *Pseudotsuga menziesii*). The resulting generic bounds were then applied to the FIA data as for the base scenario to obtain C bounds for NW OR.

Because uncertainty in live-tree C varied over the dbh range of a species, the live-tree C uncertainty of a species at the NW OR level was a function of the shape of the species dbh distribution. To test how large an influence dbh distributions had on the live-tree C uncertainty of each species, we calculated quadratic mean diameter (QMD) for each target species using FIA expansion factors to estimate the number of trees of each species in NW OR. QMD was calculated as

$$QMD = \sqrt{\frac{\sum (d^2)}{n}} \, ,$$

where

QMD = quadratic mean diameter,

d = diameter outside bark at breast height, and

n = the number of trees.

QMDs for all individuals of the target species were 24.0 cm for *Picea sitchensis*, 24.3 cm for *Pseudotsuga menziesii*, 19.5 cm for *Tsuga heterophylla*, 16.0 cm for *Acer macrophyllum*, and 18.9 cm for *Alnus rubra* (with seedlings calculated at 0.25 cm dbh). We then determined the C bounds for the QMD dbh class. Each C bound was multiplied by the estimated number of trees in NW OR for the appropriate species, and summed to arrive at NW OR C bounds.

3.3.9 Equation Partitioning

If trees could be accurately assigned to equations, uncertainty of the live-tree C estimate should decrease. To test this, we created simple examples using several different scenarios, pictured in Figure 3.7.

In scenario 1, for each species and correlation pattern, the C range at each dbh class was divided up into 2, 3, 4, 6, or 10 equal segments. We divided the estimated number of trees in each species and dbh class in NW OR by 2, 3, 4, 6, or 10. Then we applied the appropriate number of trees to the new sets of C bounds for that species.

Scenario 2 divided the C range in each dbh class into two smaller ranges so that a) 90%, b) 70%, c) 30%, and d) 10% of the C range was in the upper portion of the original range. Half the number of trees in each dbh class was applied to each partition in each option.
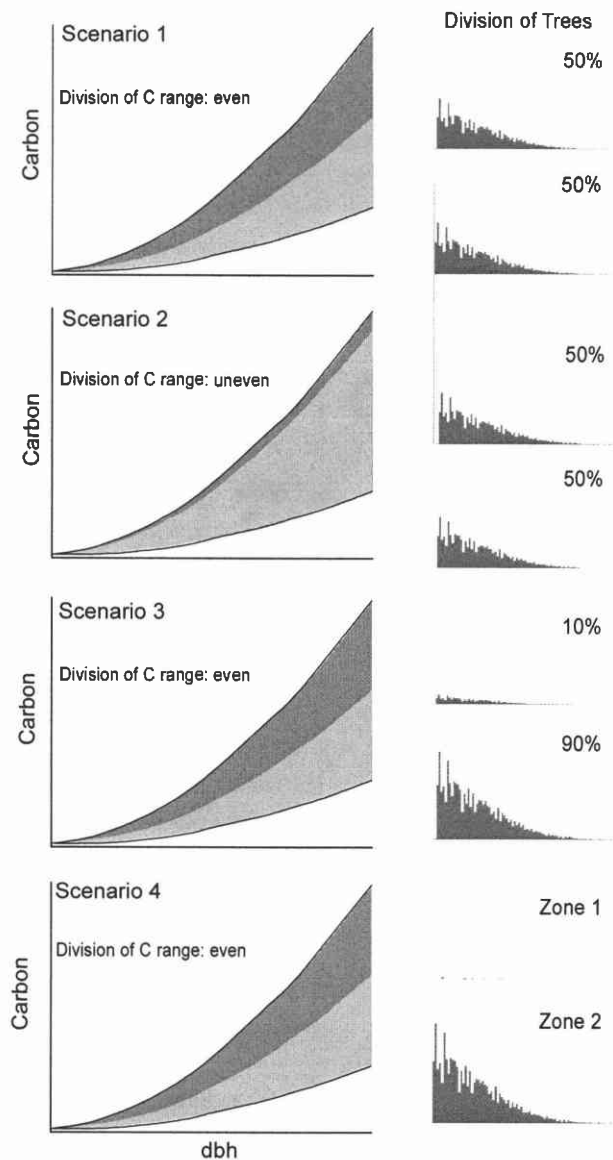
Figure 3.7. Four scenarios used to test the effect of partitioning C range. The distributions pictured to the right of each C-uncertainty plot demonstrate how the number of trees was partitioned in each scenario using *Pseudotsuga menziesii* as an example. Scenario 1: the C range in each dbh class was evenly partitioned and the number of trees within each C partition was equal. Scenario 2: C range was partitioned unevenly and the number of trees was equal. Scenario 3: C range was evenly partitioned but the number of trees was unequal. Scenario 4: the C range in each dbh class was partitioned evenly, and the trees were assigned to a class based on their approximate vegetation zone. In scenario 4, zone 1 contained very few *Pseudotsuga menziesii*.

This situation was reversed in Scenario 3 so that the C range was divided evenly in half, but a) 90%, b) 70%, c) 30%, and d) 10% of the trees were assigned to the uppermost partition.

Scenario 4 was introduced to make these partitioning scenarios a little more realistic. A forest type division of the NW OR area occurs between the coastal *Picea sitchensis* zone and the more inland *Tsuga heterophylla* zone. The FIA inventory database includes a forest type code for each inventory plot. All those with a primary forest type of *Picea sitchensis* were assigned to the coastal partition, all other plots were inland. Two tests were performed where the coastal trees were assigned to a) the lowest or b) the highest uncertainty (evenly partitioned) range.

3.3.10 Comparison with Forest Inventory and Analysis Estimates

The FIA database includes estimates of biomass for woody aboveground tree components. These estimates were calculated using biomass equations the FIA selected from the literature as being appropriate for the various states they inventory. FIA total aboveground biomass (which does not include foliage) was converted to C by multiplying with the generic C:biomass ratio of 0.5. To compare FIA estimates with values from this study, we used only the final aboveground total C lookup tables for each correlation pattern (with total foliage subtracted as appropriate for the correlation pattern) and applied them to tree dbhs from the FIA IDB.

3.4   Results

As expected, assuming perfect positive correlation at every lookup table addition produced the largest predicted C range in each dbh class, negative correlation the least, and zero correlation an intermediate value (Figure 3.8). The range of possible C values at large dbh classes was extremely wide, but the vast majority of trees were actually in the lowest half of the dbh ranges. Even though the absolute differences between maximum and minimum C were low for small trees, percent differences were often greater than at the high dbhs (Figure 3.8). Equations for *Acer macrophyllum* and *Pseudotsuga menziesii* produced the largest within-dbh-class uncertainties; *Picea sitchensis*'s equations the lowest.
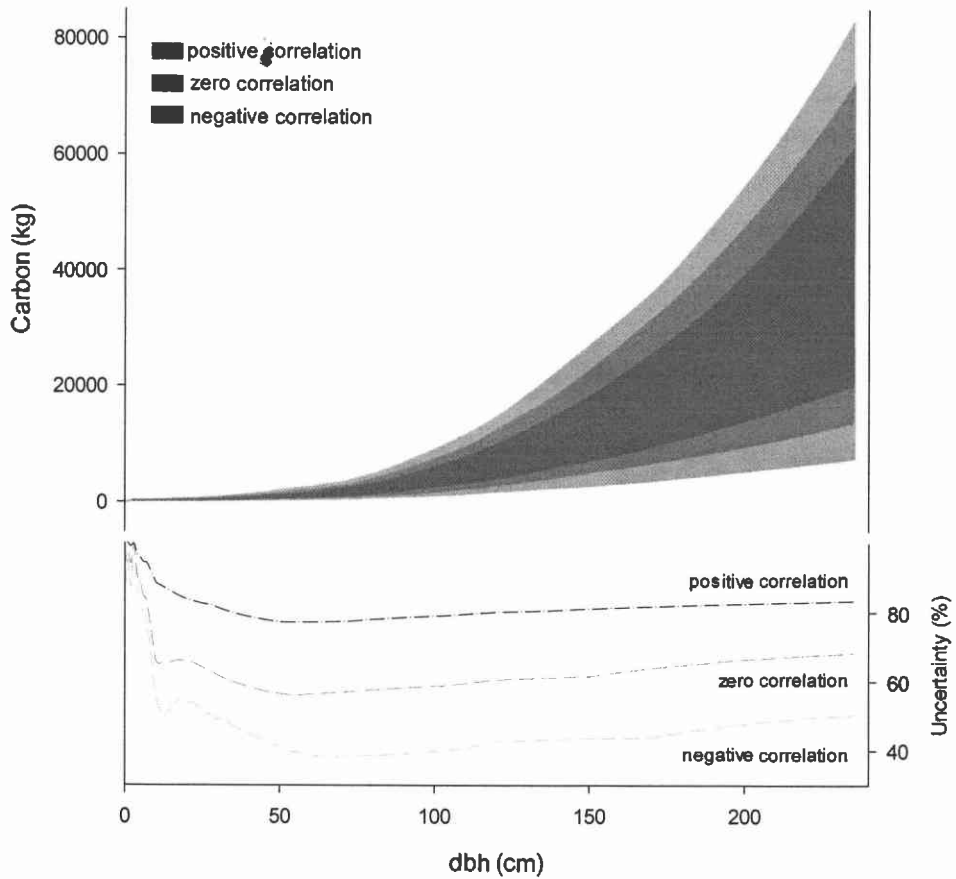
Figure 3.8. Live-tree C bounds for *Pseudotsuga menziesii* by dbh class and correlation pattern, with percent uncertainty by dbh class. As shown in the upper figure, positive correlation produced the largest range; negative correlation the smallest. The lower figure displays percent uncertainty (half the output range as a percent of the midpoint) at each dbh class for each correlation pattern.

3.4.1 Contribution of Components to Uncertainty by Diameter Class

Out of stem wood, stem bark, coarse roots, total branches and total foliage, the component with the greatest contribution to the total tree uncertainty was generally stem wood (Figure 3.9). Of all the components used in this comparison, total branches was the only aggregated component. Thus, its range varied slightly depending on the correlation pattern used.

The relationship of *Picea sitchensis* stem wood uncertainty to tree total uncertainty for all correlation patterns is shown in Figure 3.10. It is slightly wider than total uncertainty for the negative correlation assumption because the negative correlation procedure tended to reduce variation at every addition. Though not immediately apparent, the band of stem wood uncertainty is also slightly off-center with respect to the negative correlation total tree uncertainty bounds. This asymmetry is sometimes introduced during the merging of lookup tables.

3.4.2 Northwest Oregon Live-Tree Carbon

An extremely large output range of estimated C was produced when lookup table bounds were applied to all trees and expanded to the level of NW OR (Table 3.2). The total of all target species trees yielded a midpoint estimate of 119 Tg C with 76% uncertainty for positive correlation. Zero correlation produced a live-tree C midpoint estimate of 116 Tg C, with 57% uncertainty, and negative correlation assumptions resulted in 110 Tg C with 40% uncertainty. *Alnus rubra* showed the greatest percent uncertainty of all species for both positive and zero correlations, while *Pseudotsuga menziesii* had the greatest percent uncertainty of all species under negative correlation. *Acer macrophyllum* was the species most sensitive to changes in correlation assumptions, showing a 62% decrease in uncertainty between positive and negative correlation methods. *Picea sitchensis* was the least sensitive, with a 42% decrease.
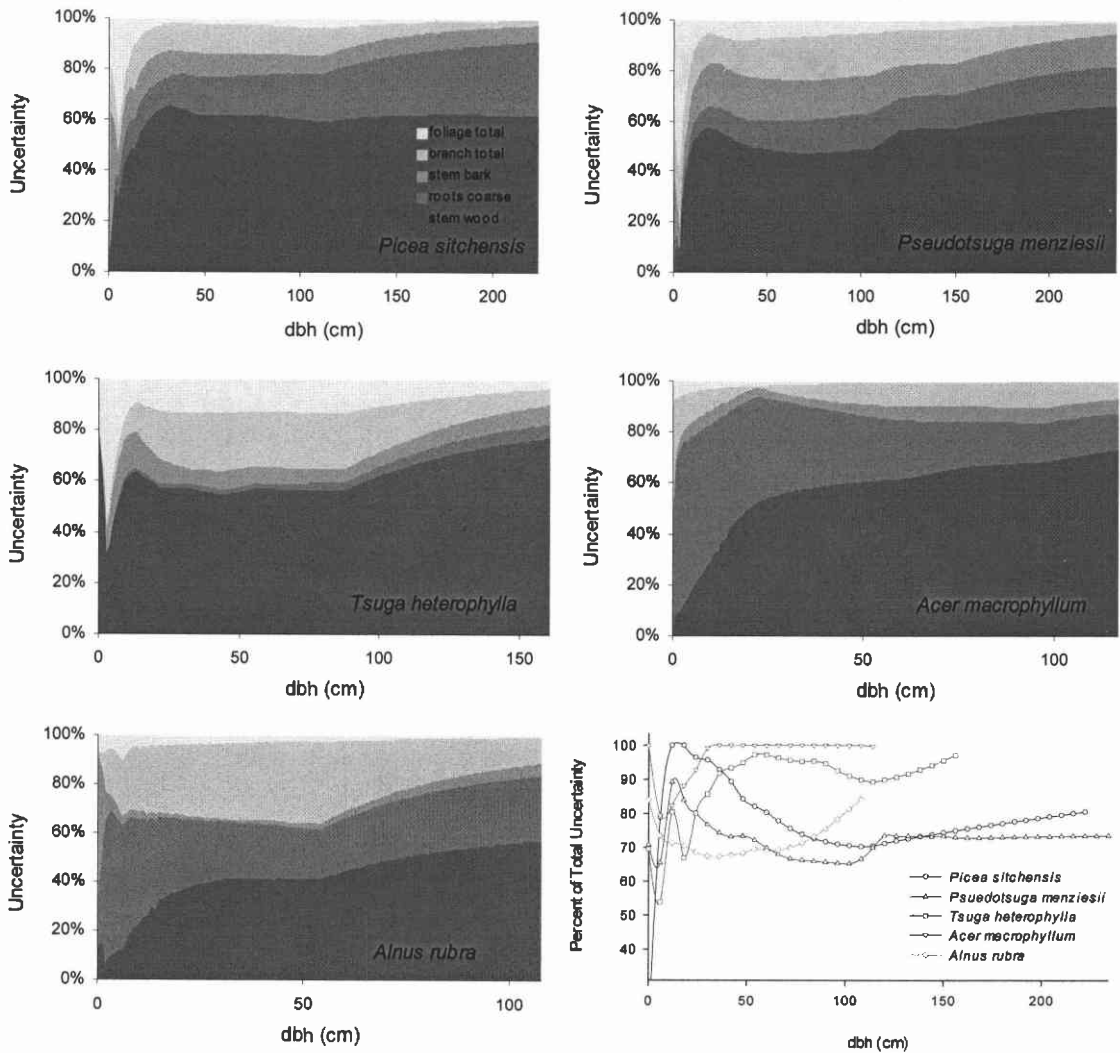
Figure 3.9. Contribution of stem wood, stem bark, coarse roots, total branch, and total foliage uncertainty to tree uncertainty under positive correlation assumptions, for all species. Figures for species show each component's uncertainty expressed relative to the tree uncertainty, which was the sum of all the abovementioned components. This tree uncertainty was not always equal to the total tree uncertainty because the input components were derived from only one of the possible pathways (Figures 3.3 and 3.4). The lower right figure depicts tree uncertainty as a percent of the total tree uncertainty. Lines are extended to the maximum dbh for each species in NW OR.
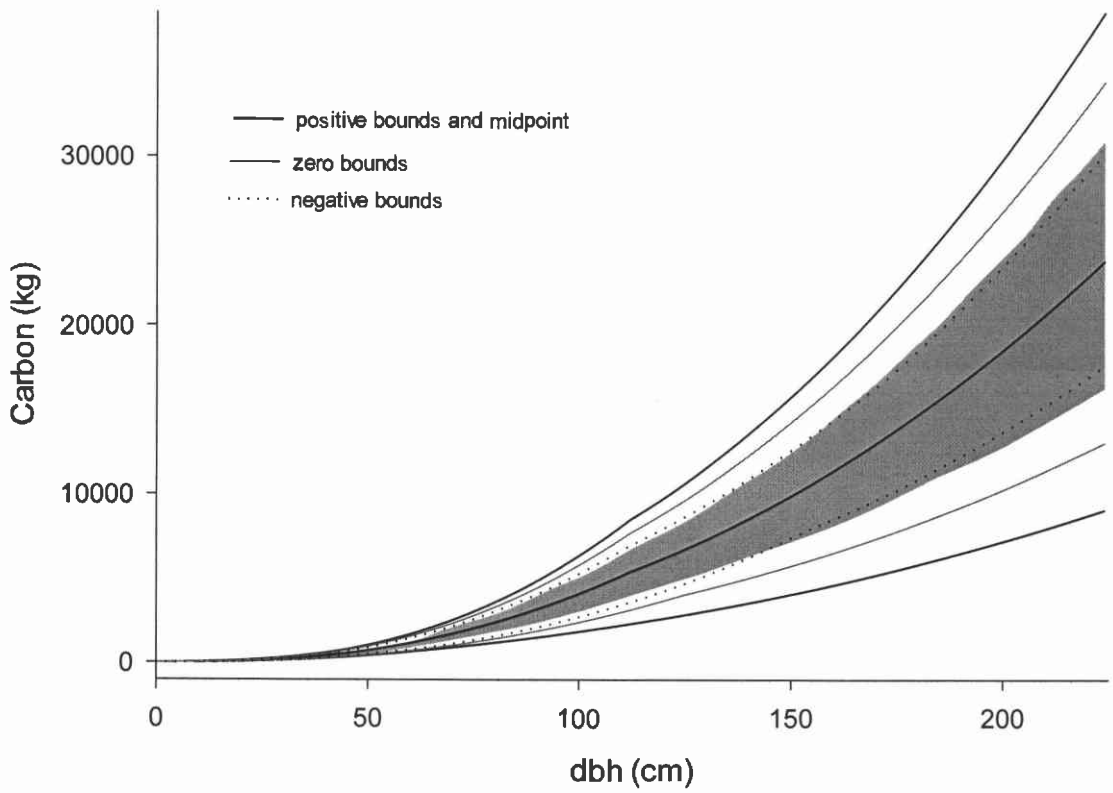
Figure 3.10. Stem wood uncertainty compared to tree total uncertainty from all correlation patterns, *Picea sitchensis*. Lines indicate the upper and lower predicted C values at each dbh. The shaded area encompasses the C bounds resulting from all *Picea sitchensis* stem wood equations.

Table 3.2. Estimated live tree C bounds within the NW OR study area, total and by species. All values are in Tg C and represent the base case.

Species	Positive Correlation			Zero Correlation			Negative Correlation		
	minimum	maximum	midpoint	minimum	maximum	midpoint	minimum	maximum	midpoint
Picea sitchensis	2.64	7.59	5.12	3.09	6.93	5.01	3.44	6.33	4.89
Pseudotsuga menziesii	12.67	112.44	62.55	24.38	97.07	60.73	32.24	85.11	58.68
Tsuga heterophylla	6.45	36.04	21.25	10.86	31.89	21.38	13.80	27.91	20.86
Acer macrophyllum	1.51	6.66	4.09	2.17	5.89	4.03	3.10	4.79	3.94
Alnus rubra	4.84	47.39	26.11	9.63	40.00	24.81	13.98	30.11	22.05
Total	28.12	210.11	119.12	50.13	181.78	115.96	66.57	154.26	110.41

Altering the range of density values applied to volume equations for each species produced C estimates that varied from the base case by only tenths of a Teragram. Therefore, these C estimates are not presented.

3.4.3 Additional Uncertainty from Regressions

Introducing regression standard errors for *Acer macrophyllum* produced the confidence intervals illustrated in Figure 3.11. Lower bounds were more similar over the dbh range than upper bounds. Bounds for equations from Grier and Logan (1977) are less wide than those for the Jenkins et al. (2003) equation at small dbhs, but they become much greater at large dbhs. One reason bounds for the aboveground biomass predicted from Grier and Logan equations are extreme at large dbhs is the narrow dbh range of their data, from 8 to 35 cm. As dbh values move away from the mean dbh, bounds produced by the regression standard error expand. This expansion was enhanced for Grier and Logan equations when stem wood, stem bark, total branches, and total foliage predictions (with confidence bounds) were summed using positive correlation; the Jenkins et al. equation already predicted aboveground biomass. Furthermore, a larger data dbh range (1 to 66 cm) and more observations limited the expansion of confidence bounds around the Jenkins et al. equation. Bounds would have been much greater for both sets of equations had coarse roots been incorporated. The Grier and Logan root biomass equation for trees above 50 cm dbh was taken from Santantonio et al. (1977), who derived it from three trees between 94-135 cm dbh. The estimated confidence bounds around that equation were so extreme as to be unusable.

Standard errors would be a legitimate way to introduce some of the error that naturally surrounds any regression from a sample of a population. But confidence intervals built from the addition of *Acer macrophyllum* components were so wide that they made bounds unusable at anything above the lowest half of the PNW dbh range. Furthermore, for some tested components, confidence intervals became so wide at the ends of the sampled dbh range that the line-smoothing procedure used for the equations themselves could not be performed. We conclude that before confidence
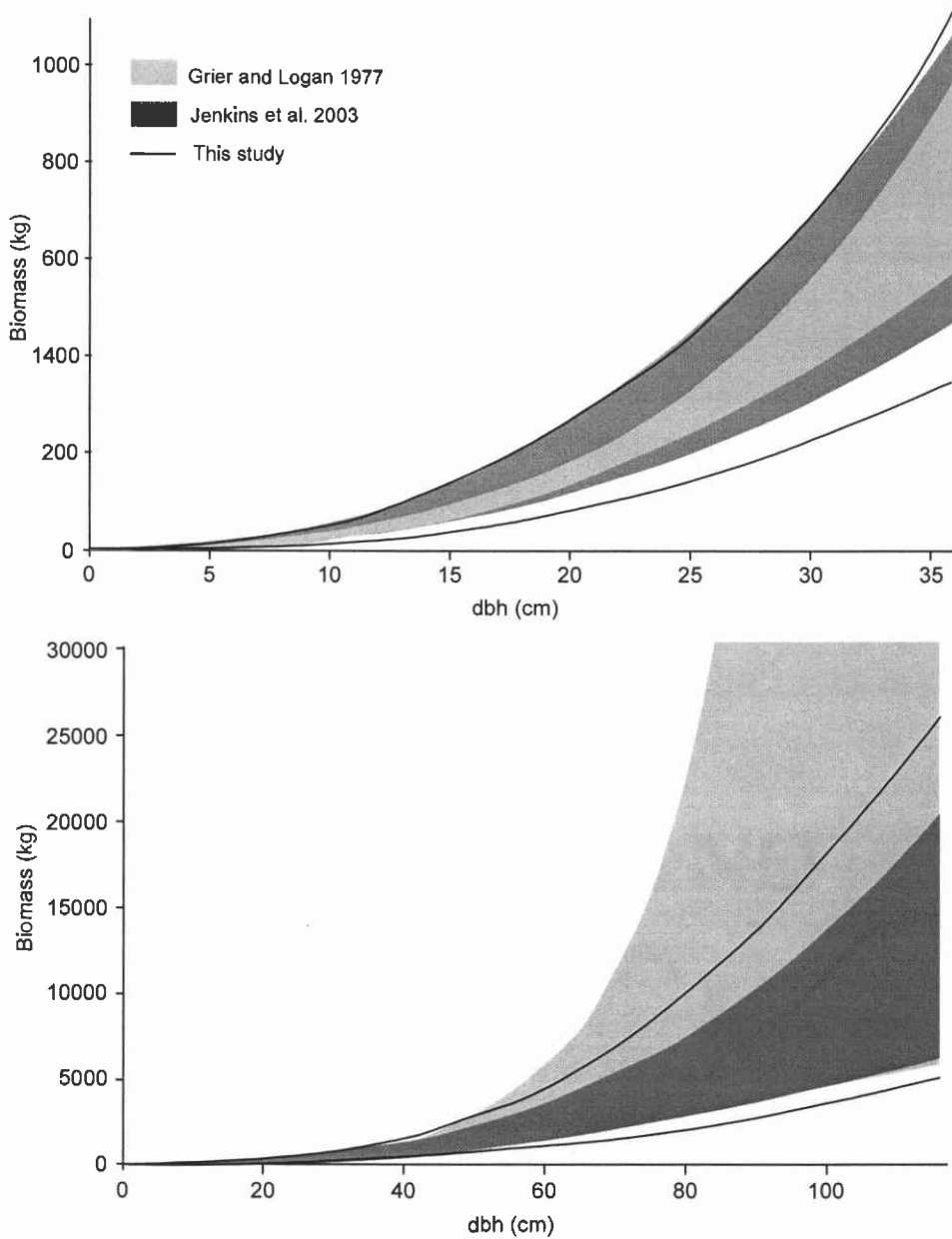
Figure 3.11. Ninety-five percent confidence bounds produced when standard errors were applied to prediction equations for aboveground biomass of *Acer macrophyllum* under positive correlation assumptions. The upper figure shows confidence bounds over the range of the Grier and Logan (1977) data; the lower pictures the bounds over the species dbh range in NW OR. Aboveground biomass uncertainty produced by this study is also depicted for comparison, however, these bounds were produced by different means than the confidence bounds.

intervals for the full range of PNW diameters can be incorporated into this study, each equation used must have a published variance of the independent variable, n must be large, and the dbh range of sampled data must be extended to the natural dbh range of the species. Uncertainty from regression error was therefore not attempted for other species or incorporated into any NW OR estimates.

For some volume and biomass equations, height is explicitly incorporated as a variable; in many others it is not included. Tree heights are quite variable within dbh classes (Figure 3.12). Examining equations which are dependent on both dbh and height indicated that tree height can have a dramatic effect on the predicted biomass for a given dbh (Figure 3.13). For the stem wood biomass equation depicted here, biomass estimated from minimum height created a 39% decrease in biomass within a dbh class, on average, for the first 50 cm, and use of maximum heights increased biomass predictions by about 56%. Within-dbh class variation introduced by height declined as dbh increased, because the small sample sizes at large dbhs (sometimes a sample of one measured height per dbh class) did not allow much variability to be expressed.

The way in which height appeared in an equation did affect the magnitude of the percent difference in predicted biomass, but percent differences followed the same basic pattern as the percent difference in height itself (Figure 3.14). When height appeared only as a divisor, as in the Newnham (in Evert 1985) crown total equation, maximum heights produced the lowest biomass values and minimum heights the highest.

When the generic estimate of error caused by height variation was applied to C bounds, NW OR uncertainty was estimated to rise to 91, 70, and 51% for the positive, zero, and negative correlation options. This represented increases of 20-30% over the percent uncertainty of the base case for all correlation assumptions.
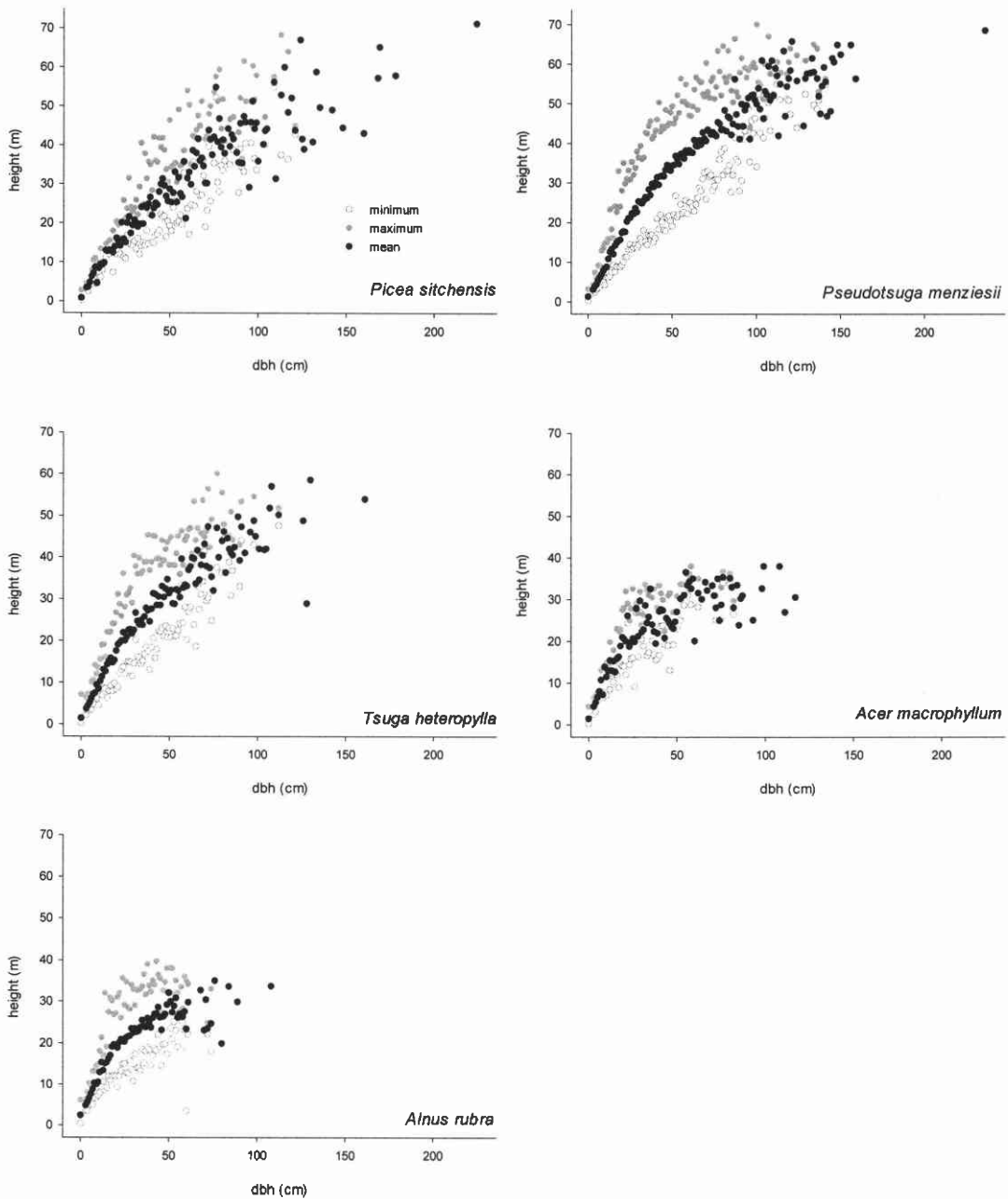
Figure 3.12. Minimum, mean, and maximum heights for target NW OR species with measured heights from the FIA IDB. Some species, such as *Picea sitchensis* and *Acer macrophyllum*, do not show as well-defined a separation between maximum and minimum heights and the mean height for each dbh class as does a species with many observations like *Pseudotsuga menziesii*. The most likely reason is the lack of observations in each dbh class.
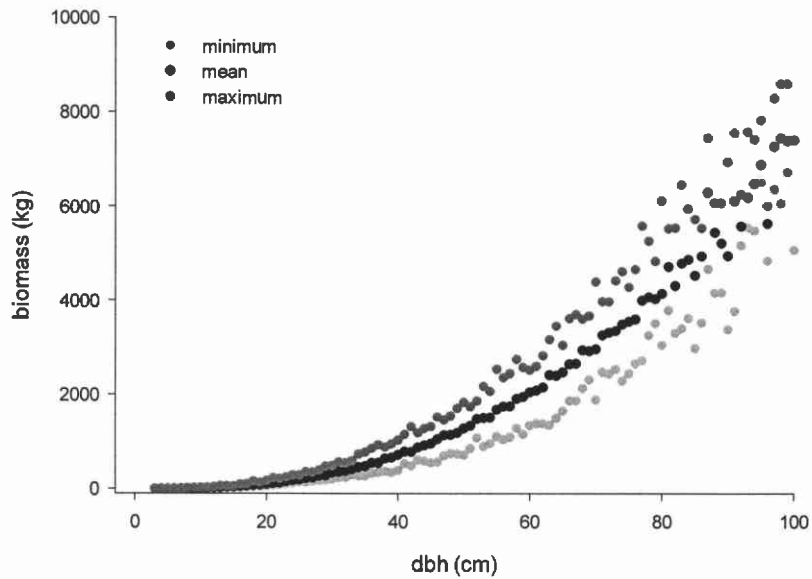
Figure 3.13. *Pseudotsuga menziesii* biomass predicted from the Shaw (1979) stem wood equation using minimum, mean, and maximum height for each 1-cm dbh class. Height data were drawn from the IDB v1.4 for the study counties in NW OR. Dbh classes are only shown to 100 cm for better visualization of biomass differences at small dbhs. Note that the Shaw equation was developed from trees with dbhs ranging from 1-221 cm.
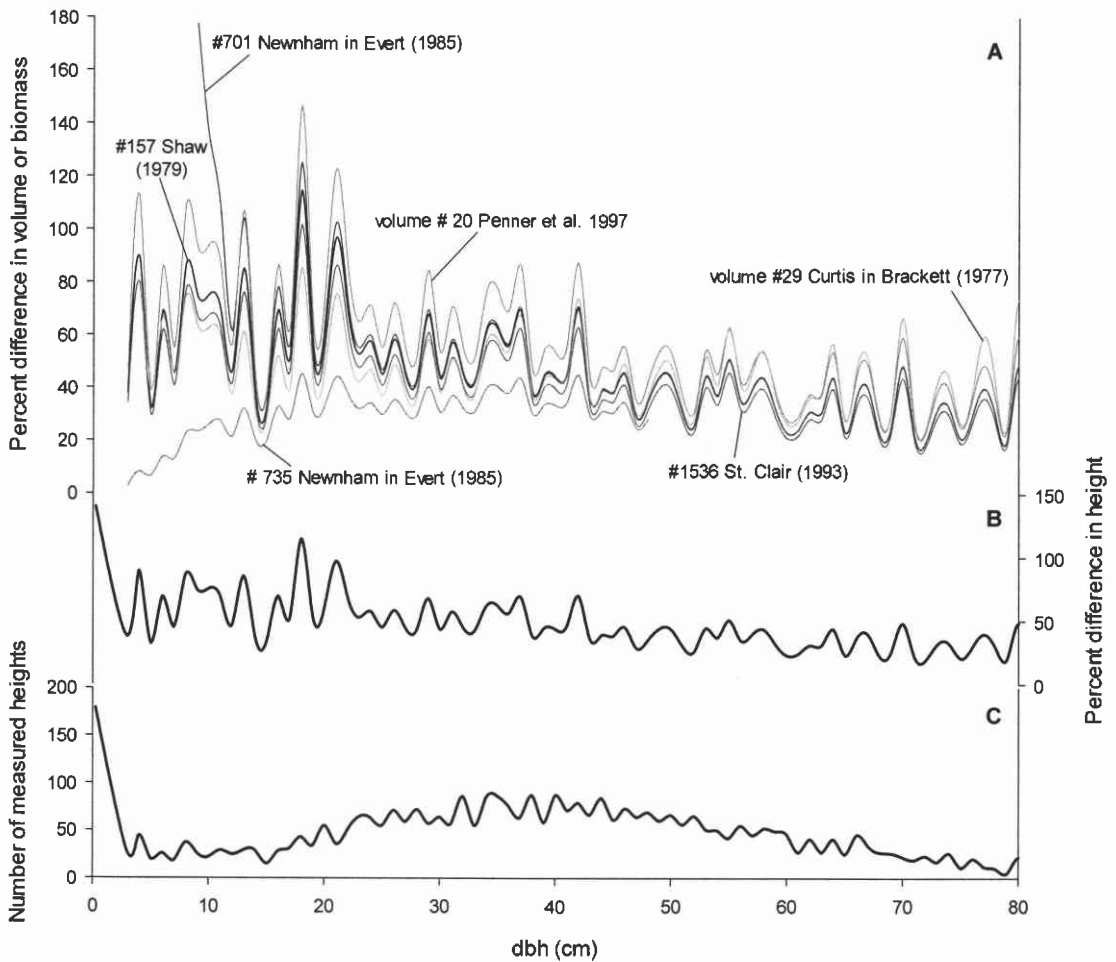
Figure 3.14. Percent difference in *Pseudotsuga menziesii* volume and biomass equations owing to variation in height. In plot A, the y-axis represents the difference between using mean or maximum measured heights for each dbh class, and is expressed as a percent of the volume or biomass obtained from mean heights. Measured heights were drawn from the IDB v1.4 for the study counties in NW OR. Plot B represents difference between maximum and mean height as a percent of mean height. Plot C indicates the number of *Pseudotsuga menziesii* with measured heights for each 1-cm dbh class in the IDB.

3.4.4   Effect of Altering the Amount of Available Information

An examination of Figure 3.15 did not suggest that incorporation of a height term produced greater agreement among equations. Several of the sample equations relied on d^2h terms, and when data were also plotted against d^2h, these equations produced straight lines with no scatter, as expected, but distance between equation predictions was not diminished. By this test, dbh-height equations appear no more universally-applicable than dbh-only forms.

Use of generic tree C bounds resulted in a 47 Tg increase in the live-tree C midpoint from the base case for positive correlation, and uncertainty rose from 76 to 87%. This represented an increase in uncertainty of 58% over the base case. For NW OR species totals, differences between the base and generic cases are most extreme where the generic range differs greatly from the individual species range (Figure 3.16), as for *Picea sitchensis* (a 218% increase in uncertainty over the base case for positive correlation) and *Tsuga heterophylla* (an 87% increase in uncertainty over the base case for positive correlation).

Figure 3.17 illustrates that using QMD for each species lowered the NW OR live-tree midpoint estimate to 90 Tg, or by about 25% from the base case, and uncertainty decreased by 22% from the base case, assuming positive correlation. Decreases of C midpoint estimates and uncertainty were only slightly lower for zero and negative correlation.

3.4.5   Equation Partitioning

As predicted, uncertainty at the regional level decreased as the number of classes rose, roughly in proportion to the number of classes, so the uncertainty with two even classes is about half the uncertainty with one class, and so on.

As shown in Figure 3.17, the amount of uncertainty was exactly the same when two partitions of the C range were used, no matter how they were divided, but the greater the upper partition was, the higher the regional C prediction. Scenario 3 indicated that the more trees assigned to the upper partition, the higher the NW OR live-tree C prediction. Partitioning the C range evenly between coastal and interior trees resulted
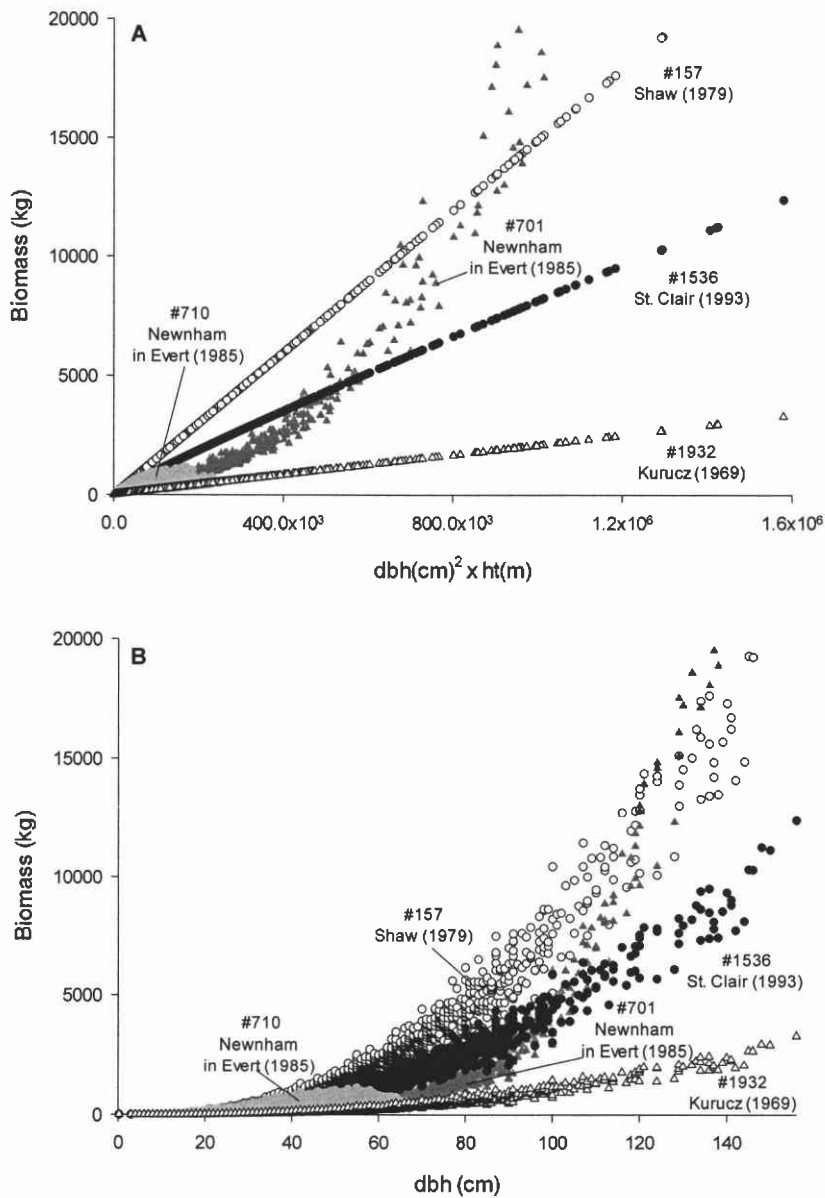
Figure 3.15. *Pseudotsuga menziesii* biomass predicted from several stem wood equations versus A) dbh^{2}h and B) dbh. Measured heights were drawn from the IDB v1.4 for the study counties in NW OR. X axes end at 156 cm dbh, or the equivalent, because data were sparse beyond that point.
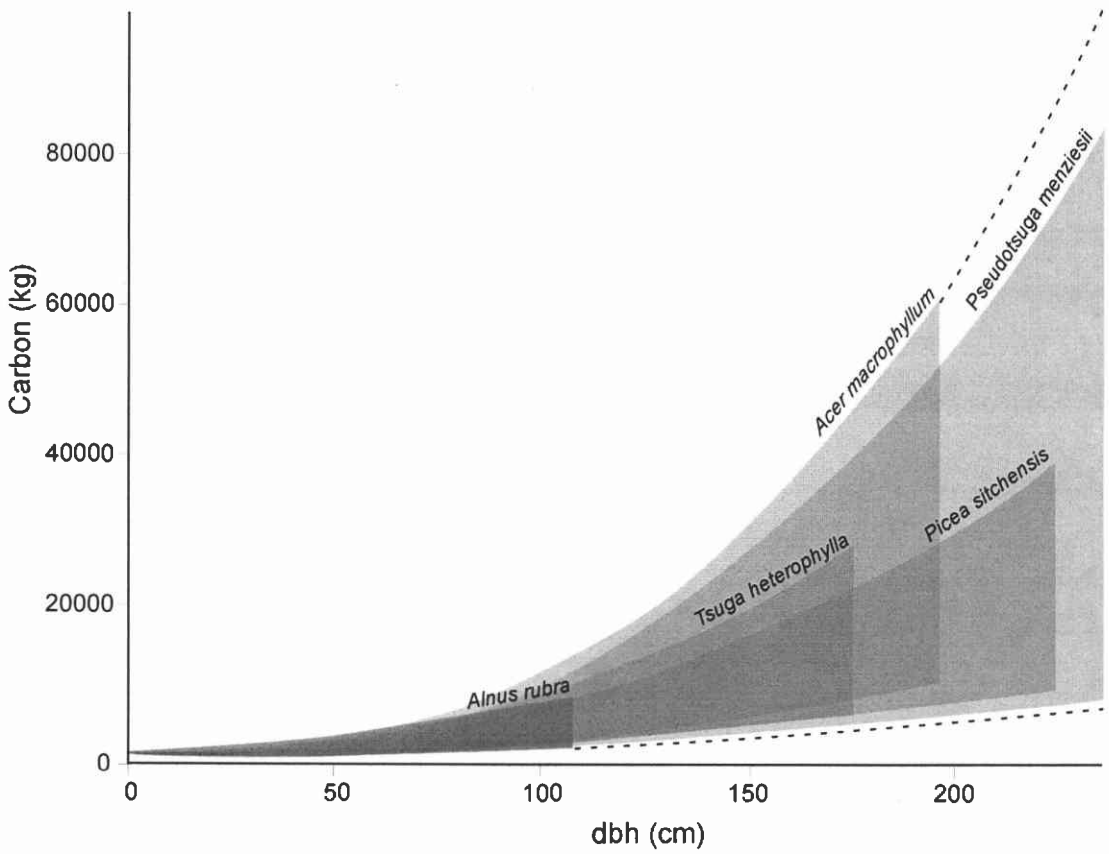
Figure 3.16. Generic total tree C bounds under positive correlation compared to species total tree C bounds. Individual species bounds are depicted in shades of gray. Dotted lines indicate where the *Acer macrophyllum* maximum and the *Alnus rubra* minimum were extended to the NW OR dbh range.
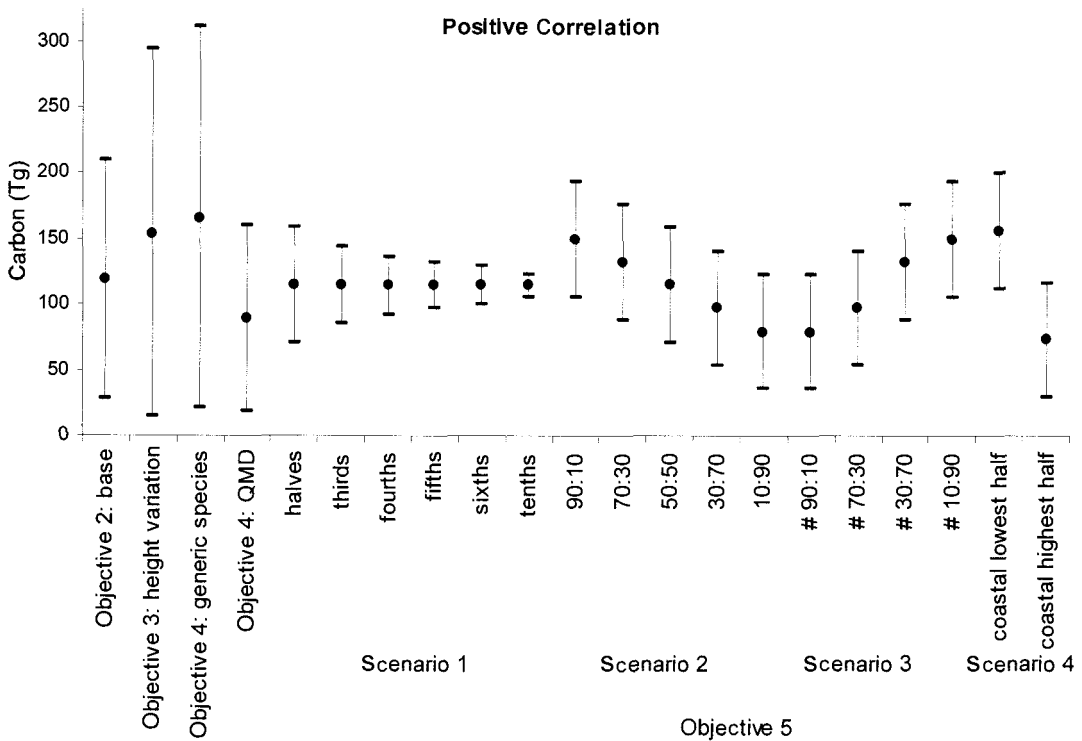
Figure 3.17. Range of C in NW OR under positive correlation for Objectives 2-5. In Objective 4, Scenario 1, 'halves' indicates the number of trees in each dbh class was divided in half before applying one of the halved C bounds, 'thirds' indicates the number of trees in each dbh class were divided by 3 before applying C bounds that were a third of the original prediction range. In Scenario 2, 90:10 means that the upper C partition encompassed upper 90% of the C range, and the lower C partition encompassed the lower 10%. For Scenario 3, 90:10 means that 90% of the trees were applied to the lower C partition, and 10% to the upper one. 'Coastal lowest half' in Scenario 4 indicates that trees in the coastal zone were assigned to the lower C partition.

in an uncertainty identical to all two-part partitions; predicted C stores were greatest when coastal types were assigned to the lowest C partition.

3.4.6 Comparison with Forest Inventory and Analysis Estimates

The FIA biomass calculations predicted an aboveground live-tree C store (excluding foliage) of 81 Tg C. The range of C predicted by this study under positive correlation assumptions for the identical tree components was 15-169 Tg, with a midpoint at 92 Tg. The FIA estimate was well within the uncertainty range from all correlation scenarios. This result was expected, because equations used by the FIA were incorporated into this study. It appears that the FIA selected biomass equations that sum to a value only 12% less than the midpoint of the NW OR C range. At the species level in NW OR, FIA estimates were within 5% of this study's estimates for all conifers, but were 20% and 40% less than this study's midpoint predictions of C for *Acer macrophyllum* and *Alnus rubra*.

3.5 Discussion

Live-tree C bounds by species and dbh were extremely wide (Figure 3.16), even under negative correlation assumptions (Figure 3.8). Because C uncertainty at each dbh for all species was large, the live-tree C uncertainty for target species at the NW OR level was also large. Uncertainty in the base case scenario was a function of the equations that have been developed for each species and does not provide information about the probability of any level of uncertainty. Midpoints of ranges were given to facilitate comparison between results and to allow calculation of percent uncertainty, but with the current data available and the methodology of this study there is no way to tell if midpoints are the most likely values.

Theoretically one might expect midpoints to remain the same for each correlation pattern, but our calculation procedure worked to prohibit that in the following manner: at each merge step, the lowest minimum and highest maximum were selected from all input tables so as not to artificially reduce the uncertainty. After an addition step (Figure 3.1), the output range under positive correlation was greater than that under zero correlation, which was greater than that under negative correlation. Usually addition was followed by a merge. If any of the merged tables had a maximum or a

minimum that was beyond the range of the summed table, that maximum or minimum would be input to the new lookup table. This asymmetrical lowering or raising of one extreme resulted in the shifting of midpoints. However, it also acted to keep bounds relatively similar by prohibiting perfect negative correlation predictions from collapsing to a very narrow range.

When variation from height prediction equations was included, uncertainty increased (Figure 3.17), and from the experiment with incorporating confidence bounds from regression standard error for aboveground biomass of Acer macrophyllum (Section 3.4.3) it appears that if standard errors were used to incorporate regression error around each equation, uncertainty would be much larger still.

Replacement of species-specific ranges with the generic range that encompassed all species ranges resulted in a widening of the uncertainty for the NW OR dataset similar in magnitude to that seen by incorporating variation from height prediction. The response to generic species data would vary based on the dataset and the species involved. In this case, use of generic species bounds increased uncertainty because uncertainty for the most numerous species was expanded for each dbh class. In contrast, had Acer macrophyllum been the species with the least uncertainty at each dbh and all other species had similar, larger ranges, increasing Acer macrophyllum's uncertainty would make little difference because it represented such a small proportion of the C stores.

Use of the QMD instead of the dbh range of each species did not alter the percent uncertainty over the base case, but it did lower the midpoint of the range and the absolute uncertainty. This is likely the result of aggregation error. Because C bounds were not linear, biomass of the average dbh, multiplied by the number of trees in NW OR, was less than biomass derived from the dbhs of all the trees. However, percent uncertainty at the QMD of each species was not much different from the percent uncertainty obtained from using the full dbh range, as can be seen for Pseudotsuga menziesii in Figure 3.8.

Correlation pattern among tree components contributed significantly to live-tree C storage uncertainty for the target species in NW OR. If we could determine how trees

were allocating their resources among components, uncertainty might be decreased. Positive correlation assumptions probably exaggerate C uncertainty. It is likely that within a tree there is a combination of positive and negative correlations among components. If there was zero correlation between tree components, uncertainty for the target species in NW OR could be reduced by 28% over the positive correlation assumption. Even when positive correlation exists, they are unlikely to be the perfect positive ($\rho = +1$) used in this study. It is equally unlikely that negative correlation would perfect ($\rho = -1$), as well. Therefore the bounds from negative correlation in this study probably represent a reduction in uncertainty that could never be realized by determining correlation among tree components alone.

The efficacy of uncertainty reduction through accurate representation of within-tree biomass correlation might depend on the scale over which correlations patterns occur. Perhaps correlation patterns differ among trees in a single stand, or by genetic family of trees. They may be solely a product of the biogeochemical environment, or they may depend on the position of the tree within the stand. Perhaps component correlation is a product of the interactions of several or all of these factors. Such interaction could be a complex and expensive undertaking requiring precise measurements of many tree components from numerous trees.

The scenarios tested in this study suggest that some form of partitioning of C ranges among trees of the same dbh class could reduce the large C uncertainty. In a sense, such partitioning is built in to the estimates produced FIA in that they choose equations thought most appropriate at a sub-state level. However, often the equations chosen for WOR and WWA are identical, but sometimes differen from those used in eastern OR and eastern WA. The main issue with partitioning is determining the influential factor or factors by which equations should be partitioned. A logical factor would be stand age, which would indicate the level of stand development. When used in combination with site index and stand density this might give a good indication of the amount of competition among trees and their likely form at various ages. Genetics might also be an influential factor, because different families of trees partition biomass preferentially to different tree components (St. Clair 1993).

Confidence bounds from regression standard errors are a legitimate measure of uncertainty and should not be ignored, however, when they were incorporated into equations, some of them created bounds so wide they could significantly reduce the benefit of partitioning. Bounds around each equation could also be expanded if error from predicting height from dbh is included as well, but variation from height prediction did not appear as extreme as bounds produced by some standard errors, at least over the majority of the species dbh ranges. If the effects of both standard errors and height prediction were to be included, the interaction of these errors would have to be determined.

If we desire equations that lower C uncertainty, either many new equations must be developed that are applicable to a variety of scales and represent all the different tree forms found in an area, or a way to accurately partition trees among existing equations must be created, or both. If new volume or biomass equations are intended for application at the regional or national level, they should sample large numbers of trees across the geographic range of the species. Possibly data from existing studies could be enhanced with new observations to defray expense. Most equations are created for trees of small dbh, which is practical for application to plantations, but is problematic when many trees fall above those dbh ranges. To avoid extrapolation and lower standard errors at the upper end of species dbh ranges, data should be gathered on large trees. Equations in Franklin (2002), Grier and Logan (1977), and Shaw (1979) and go some way towards this. However, they still fall short of some of the larger dbhs observed in the forest inventory data. It might not be practical, or even possible, to find trees of these sizes that can be sampled destructively, but perhaps dendrometer measurements at multiple points along tree boles could be attempted on just a few giant trees to provide volume data in an otherwise unmodeled region of the dbh range.

Stem wood made up a large percent of the uncertainty in dbh class. This is reasonable because stem wood is the largest component at most dbhs. But stem wood is also the component most often studied. It may be that the larger the number of equations that have been developed for a component, the wider the range of predictions as the form of more subpopulations are captured. An example is the

Franklin et al. (2002) *Tsuga heterophylla* biomass equation developed at Cascade Head. These trees contain little volume. Including the Cascade Head *Tsuga heterophylla* equation increased uncertainty for *Tsuga heterophylla* stem wood considerably (see Figure C.3). However, this is an equation that seems to accurately predict biomass of individuals from that subpopulation. In the partitioning approach, trees from that subpopulation could be assigned to that equation, and uncertainty for all other *Tsuga heterophylla* would be reduced.

Under a partitioning approach, concerns about the limited dbh range of some equations may be unfounded. If equations with limited dbh ranges, developed for plantations of specific ages, are applied only to other plantations of similar ages where the trees have the same form, then small dbh ranges would cause no problem. Furthermore, a large dbh range may not necessarily indicate an equation is suitable for application to a large geographic area, especially if the equation was developed using trees from a limited area.

Some researchers have attempted to obtain greater accuracy and wider applicability by adding terms to equations. Equations incorporating such variables as crown width were not examined in this study because these measurements were not routinely collected in forest inventories. Volume or biomass equations that incorporated both dbh and height, as opposed to dbh alone, were included. As demonstrated, a selection of these equations for *Pseudotsuga menziesii* stem wood did not appear to create similar predictions for trees of identical dbh and height. The statistical fit of most stem wood equations (both those based only on dbh and those based on dbh and height), as measured by R^2, is quite high already. *Pseudotsuga menziesii* stem wood biomass equations collected for this study, for example, have R^2 values ranging from 88-100%, with many in the upper 90s. Fit of equations for crown components is usually lower. In *Pseudotsuga menziesii*, total foliage R^2 values ranged from 40-96%. In mature coniferous trees, however, crown components contribute significantly less to total tree volume or biomass than does stem wood. This allocation of biomass means that even a poorly-fitting equation for a small component will not have much impact on total tree values. The problem is that a number of very good-fitting equations exist for many components, but equation predictions are still quite different.

The variety of mathematical equation forms chosen by different researchers is partly responsible for these differences. One approach to facilitate comparison would be to standardize equation forms whenever possible. This could be accomplished by obtaining original data and fitting to one chosen equation form, but in many cases original data are not available. Jenkins et al. (2003) recently employed an approach that generates pseudodata to create national biomass equations when individual tree data from studies were lacking. These data are created using the equation formula and statistical measures of fit presented in the literature. Once pseudodata have been generated, equations of any form may be fit to them.

Another source of differences arises from variations in tree form. Another productive approach to developing new equations would be to better understand how tree form varies over the region of interest. Many equations for the PNW come from research forests, such as the HJ Andrews or Cascade Head Experimental Forests in OR, and a few scattered sites on private lands where special projects have been conducted – far short of a full geographic coverage. A random or grid sampling procedure across the PNW would be the best way to remedy this. Generally, studies to create volume or biomass equations have required a great deal of labor and resulted in the destruction of the measured trees. A basic study to determine tree form need not be so onerous. One simple measure that might effectively determine a tree's form is the diameter of the tree midway between the ground and the tip. Height can be a difficult measurement to make in closed-canopy PNW forests, and measuring to half a tree's height, then ascertaining the diameter at that point, would add considerably to the time required to inventory trees. But with a Relaskop or laser such measurements should be possible. One way to determine which existing equations to apply to which tree form would be to establish the form of the trees used to create an equation from the old data. Another possibility is to undertake destructive sampling of trees with many forms and rigorously determine which equations are best matched to each form. In many cases it might be simpler to develop new equations.

As mentioned in the introduction, profile equations can be integrated to create tree volume estimates. Development of a profile equation may take 10 or more diameter measurements along the stem (Bruce and Max 1990), but once equations have been

developed for a tree form, accurate volume estimates can be created from three tree measurements (one height and two diameters along the stem). Compared to the time, effort, and expense of felling trees to determine volumes, taking even 20 measurements with a Relaskop or laser seems well within the range of feasibility.

A number of researchers have created regional volume or biomass equations, and recently biomass equations intended for use at the US level have been developed. The idea is that by incorporating data from a very large area to create the new equation, resulting predictions will be accurate at the regional (for regional equations), or national (for national equations) scale. For a large area these equations could be a beneficial simplification. When regression standard error was used to create 95% confidence bounds for the soft maple biomass equation of Jenkins et al. (2003), the bounds were not much different from those produced for this study's base case using all available *Acer macrophyllum* equations and assuming positive correlation. For this species, incorporating many equations into one produced almost the same limits as using all equations directly and assuming positive correlation.

One drawback of national equations is the necessity of assuming that equations or data collected to create the equation accurately represent the range of tree forms that exist in the nation. To insure that the equation is an accurate predictor of national volume or biomass, it might be necessary to weight equations or datasets according to the abundance of the tree form they describe in the region of interest. This is probably not known with much precision. The biggest danger probably lies in applying these regional or national equations to small areas. Given the variation seen in this study between equations developed from areas within close proximity to one another, however, estimates from regional or national equations may introduce no more bias than using an equation developed at a nearby site.

As has been discussed in the biomass literature (Cunia 1987b; Parresol 2001), additivity is an important quality to consider. When predictions from equations for small components can be added together to produce the same value obtained directly from an equation for the larger component, additivity is present. For example, if a researcher provided equations for total branches, total foliage, and total crown,

these equations would be additive if, at a given dbh, the value predicted by the total branches equation plus the total foliage equation were equal to the value predicted by the total crown equation. Special procedures must be followed during equation development to ensure additivity, as described by Cunia (1987b) and Parresol (2001). Many of the equations used in this study were not additive. The methods used in this study required that equations to predict aggregated components be compared with those that were summed from smaller components. In most cases the summed components provided the larger C ranges for each dbh and so were chosen to enter the summation at the next level. Consequently, the reader should be aware that some of the uncertainty could come from incorporating non-additive equations.

Use of future volume and biomass equations would be enhanced if researchers were to publish data sufficient for creating the standard error of regression. Log-log transformations, though convenient, are too problematic and create too many complications. Use of correction factors with logarithmic equations is of debatable value. Some researchers prefer not to employ a correction factor. Krumland and Wensel (1975) used log-log transformation but attempted no correction since their experience suggested the bias introduced was limited. Jenkins et al. (2003) rejected the Baskerville (1972) correction factor because MSE varies with sample size, and thus may impose a bias of its own. Flewelling and Peinaar (1981) examined several correction factors, including Baskerville's, and concluded that for cases where there were more than 30 degrees of freedom, correction factor values were almost always within $e^{3/2 s^2}$ (where s^2 = the sample biomass variance) of one another, except when extrapolation was employed. If researchers felt this amount of variability was acceptable, then several estimators were roughly equivalent, including a correction factor of 1 (no correction) and Baskerville's correction. For small sample sizes, correction factors may make a difference. On the other hand, their use may introduce bias. At the level of uncertainty seen in this study, it does not seem that a little bias would have a great impact, but even a small bias at a tree level may blossom into a large discrepancy when aggregated over a large region. Weighted regression may be an attractive option as it also reduced heteroscedasticity but no log transformations are involved. Adoption of standard equation formats, or reporting equations in a

common format along with a researcher's favorite equation form, would greatly aid statistical comparison of equations.

Much refinement of methods must occur to determine a most probable uncertainty value. This study assumed each equation was equally applicable to every tree, but this is unlikely to be correct. One modification would be alteration of the study methods to create a Monte Carlo simulation where trees were assigned to equations with varying probabilities based on their geographic proximity to the area in which the equation was developed, or through similarity of site characteristics, or similarities in (estimated) tree form. The partitioning method used in this study might also be made more realistic by adapting this analysis to a larger area such as OR and WA. This would increase the biogeoclimatic diversity and allow the incorporation of many more equations that could be more region-specific, such as those from the eastern sides of the states or from southern OR and CA.

A further improvement would be development of more root biomass equations. Root equations in general were problematic. First, they were not numerous - we borrowed extensively from more or less related species growing in other areas of the world. Second, some root equations were developed by excavating as much of the root system as possible, but others removed only roots directly around the tree base. Third, no fine root C was estimated in this study. Most fine root biomass estimates are made on a per-area basis, so estimates cannot be linked to tree size. Although fine roots are not large, they are numerous, so it is expected that C estimates would rise slightly (by only a few percent of the tree total estimate) if fine roots were included.

This study concluded that the uncertainty for the live-tree C store of the target species in NW OR ranged from 76% for positive correlation to 40% for negative correlation. When the effect of height variation was incorporated, C storage uncertainty rose to 91% for positive, and 51% for negative correlation. If regression standard errors had been included, uncertainties would have been enormous. Given the already substantial uncertainty in the base case, it appears extremely difficult to make comparisons among regional C stores, or simply to determine the amount of C in a given forest area, when model error is incorporated in the manner used here.

Large uncertainties in live-tree C storage do not necessarily mean that meaningful comparisons of live-tree C flux would be impossible. If uncertainties attendant on each live-tree C estimate made at different time periods were of identical or similar magnitude, then the estimate of live-tree C change might not have much associated uncertainty.

These percents should not be interpreted as the "real" uncertainty of NW OR live-tree C storage. This study did not measure live-tree C by the "best" method and compare it with predicted values. Instead, it captured C uncertainty from model error under a variety of assumptions. It is important not to place too much emphasis on the exact numbers for midpoints and ranges presented herein, because they are a function of the equations that happen to have been developed to date. This study demonstrated that model error can be extremely large. Now that the magnitude of model error has been illustrated, work can begin on refining the procedures and integrating model and other errors into the estimate of C store uncertainty.

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4 CONCLUSIONS

4.1 Pacific Northwest Historic Live-Tree Carbon Storage

Between 1963-91, C on all timberland in the Pacific Northwest (PNW) was estimated to decrease from 1636 to 1392 Tg, or by 15% of the 1963 total. National forest, other public (other federal, state, and local government), forest industry, and miscellaneous private land lost 15, 5 (non-significant), 24, and 18% of their 1963 total timberland live-tree C by 1991, respectively. All landowners except forest industry experienced significant declines in total timberland area. C density (live-tree C per area) on total timberland dropped by 13% on national forests and by 30% on forest industry, but rose by 1% (non-significant) on other public and 26% on miscellaneous private land. For the PNW as a whole, C density on total timberland decreased by 8% over the 28-year study period. C density declined most dramatically between 1963 and 1974. Since 1974, increasing C density on other public and, for a time, miscellaneous private lands balanced declining C density on national forest and forest industry, resulting a C density ranging between 135-136 Mg C ha^{-1} on all timberland.

Forest inventory data from 1933 indicated that C storage may have risen between 1933-63. Even though some of the timberland was recovering from large fires earlier in the century, and before the turn of the century, such an increase seems counterintuitive. A change in forest inventory methods between the two dates could have contributed to the difference in inventory totals. Our estimation of likely bounds on the 1933 figures suggested C could have been anywhere from 1398 to 2779 Tg, and C density could have ranged from 127 to 257 Mg C ha^{-1}.

Land-use history influenced the current level of C on PNW timberland. This history is dictated by natural events as well as the action of human land managers responding to political and economic situations. If future harvest intensity on public lands remains at the level of the early 1990s, and all private lands are managed on 45-year rotations, then PNW live-tree C density should drop from 135 to 113 Mg C ha^{-1}.

4.2   Uncertainty of Northwest Oregon Live-Tree Carbon Storage

Our estimate of live-tree C uncertainty from model error in Northwest Oregon (NW OR) was very large. For the base case scenario under perfect positive correlation among tree components (i.e., tree parts), NW OR live-tree C storage ranged from 28-210 Tg C, or 119 Tg with ±70% uncertainty. Assuming zero correlation among tree components produced an estimate of 50-182 Tg C, or 116 Tg with ±57% uncertainty. Perfect negative correlation among tree parts resulted in the narrowest bounds of 67-154 Tg, or 110 Tg with ±40% uncertainty. The midpoints of ranges facilitate comparison among results as they allow calculation of percent uncertainty, but with the current data available there is no way to determine if these midpoints are the most likely values.

Altering the range of wood and bark densities applied to volume equations changed the final C uncertainty by only fractions of a Teragram at the NW OR level and thus improvements in density estimates would be overshadowed by variation introduced through volume and biomass equations.

Replacement of species-specific equations with a generic equations encompassing all species increased uncertainty for NW OR. In the PNW case, use of generic species bounds increased uncertainty because uncertainty for the most numerous species was expanded for each diameter at breast height (dbh) class.

Removing information about dbh distribution by using the quadratic mean diameter reduced the absolute uncertainty, but not the percent uncertainty. The lower midpoint resulting form this method was likely the result of aggregation error owing to the non-linear relationship between dbh and live-tree C. However, percent uncertainty at the quadratic mean diameter of each species was not much different from the percent uncertainty obtained from using the full dbh range, so this was little affected by aggregation error.

We attempted to incorporate the variation around each equation introduced by regression error. In addition to having to estimate one of the terms, standard errors of regression produced were so great for some equations that we decided this

procedure was not currently useful. Regression errors nevertheless contribute to total uncertainty and eventually they should be incorporated into future uncertainty estimates.

Incorporating estimated variation introduced by the height estimation equations used in this study increased uncertainty to ±92, 73, and 53% under positive, zero, and negative correlation among components. Therefore uncertainty could be reduced 20-25% if better height predictions could be made.

If we could determine how trees were allocating their resources among components, uncertainty might be decreased. Three correlation patterns among tree components were employed, but it is not clear which one most accurately reflects biomass allocation by real trees. Positive correlation assumptions probably exaggerate actual C uncertainty. It is likely that within a tree there is a combination of positive and negative correlations among components. If there were zero correlation between tree components, uncertainty for the target species in NW OR is 28% lower than the positive correlation assumption we used. Even when correlations exist, they are unlikely to be the perfect positive ($\rho = +1$) or perfect negative ($\rho = -1$) used in this study. Our estimates therefore bracket the actual range of uncertainties.

Some researchers have created regional or national volume and biomass equations. By essentially creating only one model, such equations bypass the problem of model error. Although these equations simplify calculation, our experimentation with incorporating standard errors indicated they may not significantly reduce uncertainty (over uncertainty from model error) when confidence bounds from regression error are considered. Furthermore, use of these equations may introduce bias if trees used to create the regional or national equation did not represent the full range of variation in tree form. Incorporation of additional independent variables into regression equations to improve precision has also been attempted. Our results suggest that using an equation containing both dbh and height (instead of dbh alone) does not reduce uncertainty because tree form varies greatly and this is typically not included in these equations.

Our investigations suggested that the most effective way to reduce uncertainty from model error would be to partition the C range among groups of trees. This is equivalent to accurately assigning equations to individual trees. Previous researchers have attempted to assign equations, often based on geographic region or similar site characteristics. The problem with these assignments is there is often no way to determine whether they were appropriate.

If we desire equations that provide more accurate and precise descriptors of volume or biomass, either new equations must be developed, or a way to accurately assign existing equations to individual trees must be created, or both. Possibly data from existing studies could be enhanced with new observations to defray expense. Most equations are created for trees of small dbh, which is practical for application to plantations, but is unhelpful when many fall outside these limited dbh ranges. To avoid extrapolation and to narrow bounds calculated from regression standard errors at the ends of species natural dbh ranges, data should be collected for very small and very large trees.

Under a partitioning approach, concerns about the limited dbh range of some equations may be unfounded. If equations with limited dbh ranges, developed for plantations of specific ages, are applied only to other plantations of similar ages where the trees have the same form, then limited dbh ranges would cause no problem. Furthermore, a large dbh range may not indicate an equation is suitable for application to a large geographic area, especially if the equation was developed using trees from a small area.

Much refinement of this study's methods must occur to determine a most probable uncertainty value. One modification would be to create a Monte Carlo system where trees were assigned to equations with varying probabilities based on their geographic proximity to the area in which the equation was developed, or through similarity of sites, or similarities of tree form. The partitioning method used in this study might also be made more realistic by adapting this analysis to a larger area such as all of western Oregon and Washington, or perhaps all of both states. This would increase the biogeoclimatic diversity and allow the incorporation of more equations that could

be more region-specific, such as those from the eastern sides of the Oregon and Washington or from California.

As this study demonstrated, there are many ways to calculate live-tree C from inventory data and each choice of calculation route (i.e., a model) produces a different estimate. One model cannot be deemed better than the others because no 'best' method to calculate live-tree C currently exists. It is important not to place too much emphasis on the exact numbers for midpoints and ranges presented in Chapter 3, because they can be considerably altered based by the choice of input equations. Although model error can be extremely large, this study suggests it can be most effectively reduced by accurately assigning trees to suitable equations.

4.3   Policy Implications

This study indicates live-tree C storage declined on all land ownerships between 1963-91 and will continue to decline if more timberland is converted to short rotation ages. However, PNW live-tree C storage might be increased by state and national policies that promote retention of older age classes in the PNW region. One policy that may lead to increased C density on public lands is the Northwest Forest Plan, particularly if the original provisions are not much altered by future administrations. Plans by state forest managers to implement structure-based management and decrease clear cutting in favor of partial harvesting may contribute to increased C density in the future on other public lands. State Forest Practices Acts that mandate green tree and riparian area retention may also contribute to higher C densities on all lands. Forests dedicated primarily to C storage may appear in the region should financially attractive options (such as C sequestration incentive payments) for forest C storage materialize. However, risks associated with the added accumulation of biomass (e.g.,, fire), and the extent of climate change will also be factors in future live-tree C storage levels in the PNW. It is evident that if the PNW is to be a large contributor to future live-tree C sequestration in the US, then land will have to be allocated to older age classes, harvest strategies must change, or both.

Uncertainty (introduced from model error) of the live-tree C store obtained from our methods is too great to allow informed decision-making. If bounds from Chapter 3

were applied to the live-tree C storage estimates from Chapter 2, it would be impossible to determine if C densities were really different among most landowners. If we accepted these as the "real" uncertainty, all estimates would be so uncertain that there would be little to direct policy. If live-tree C does come to have a high monetary value attached to it, uncertainties surrounding live-tree C storage must be reduced. Partitioning the possible C range dramatically reduces uncertainty. The same effect can be accomplished by accurately assigning trees to regression equations. This would diminish uncertainty from model error to a reasonable level for comparing C stores. Although uncertainty of C stores from model error might not be currently acceptable, assessing whether change in C stores occurred might not be so problematic. If contributing errors are identical or very similar for all time periods being compared, uncertainty in C flux can be virtually nonexistent.

Uncertainty in the live-tree C store estimate will never be eliminated. Even if model error were dramatically decreased by development of accurate equations and effective means of assigning equations to trees, uncertainty would still be introduced through inventory sampling error, regression standard error, and measurement error. The important thing for policy makers is to acknowledge the presence of uncertainty and learn to make judgments after taking uncertainty of the estimates into consideration.

4.4   Future Research

Research to continue efforts in begun in Chapter 2 will soon be able to make use of new Forest Inventory and Analysis Program annual inventory data. There are a limited number of things that can be done to improve the accuracy of past data, however. One improvement would be the preservation, and the presentation, of the data themselves. This is impossible for the PNW 1933 inventory data, as they are reported to have been lost. However, some old forest-type maps made to aid this original forest inventory survive. PNW data from 1963 are not available either; in 2004 the PNW Forest Inventory and Analysis Program began to create computer files of these data, but most of the original (and only) data exist on 1950s and 60s field forms, which are sent to the field every year the plots are re-visited. The preservation of these data in electronic format could be very useful to researchers performing

retrospective studies. If they were to be placed in a database with appropriate expansion factors re-created, they could be used as the modern inventory data are used today. Such a project will be time intensive, but a great deal of effort and money went into collecting this data, and every effort should be made to preserve it.

Many refinements could be made to extend the findings presented in Chapter 3. Study results suggest the most useful would be working with regression equations to accurately partition the possible C range. Often researchers assume that equations generated from the same general geographic area are appropriate for their study, but examination of equation predictions suggests this is not always the case. Therefore better ways of assigning equations to individual trees or to populations of trees should be developed. Possibly new equations should be developed, as well. This would entail a great effort to collect data on tree form, geographic location, and associated data such as stand development stage, age, and site index, but it would result in a substantial reduction of model error.

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APPENDICES

Appendix A Species Calculation Pathways
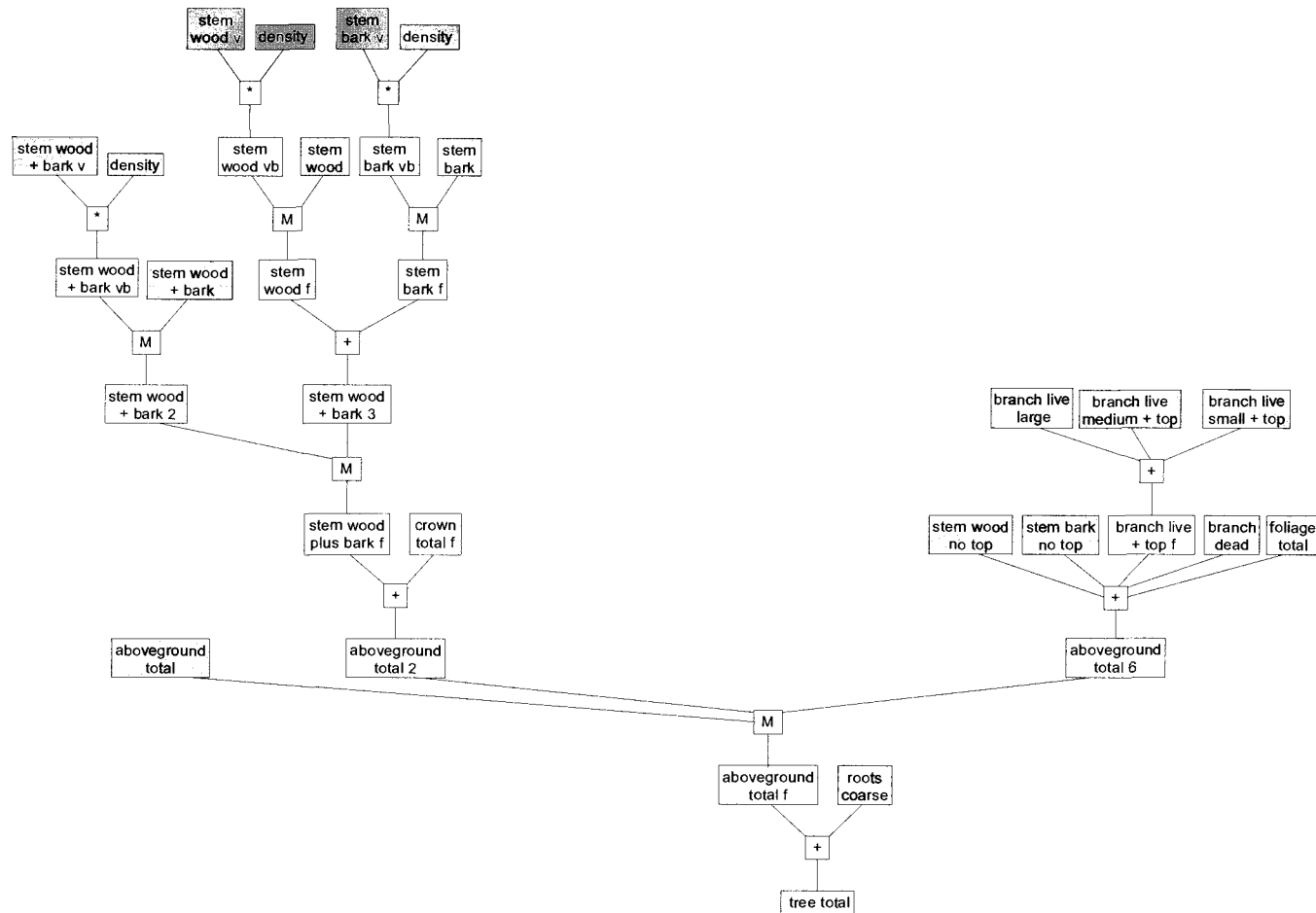
Figure A.1. Partial calculation pathway for *Picea sitchensis*. Shaded boxes indicate components where one or more equations or values exist. Components arising from another path, such as crown total f, are not shaded. Symbols are:"*"- volume table was multiplied by density range;"+"- tables were added together as described in the text;"M"– tables were merged as described in the text.
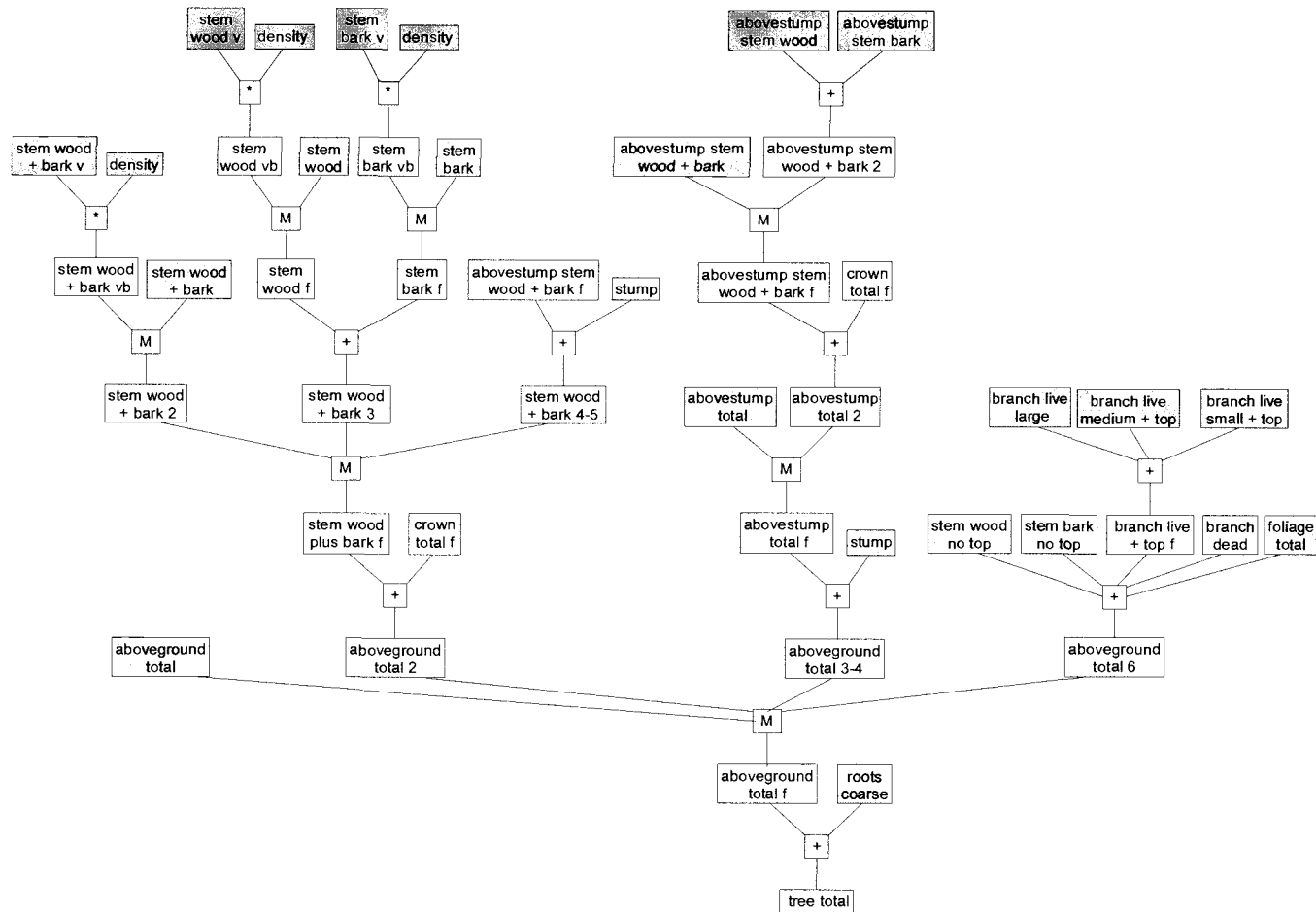
Figure A.2. Partial calculation pathway for *Pseudotsuga menziesii*. Shaded boxes indicate components where one or more equations or values exist. Components arising from another path, such as crown total f, are not shaded. Symbols are:"*"- volume table was multiplied by density range;"+"- tables were added together as described in the text;"M"– tables were merged as described in the text.
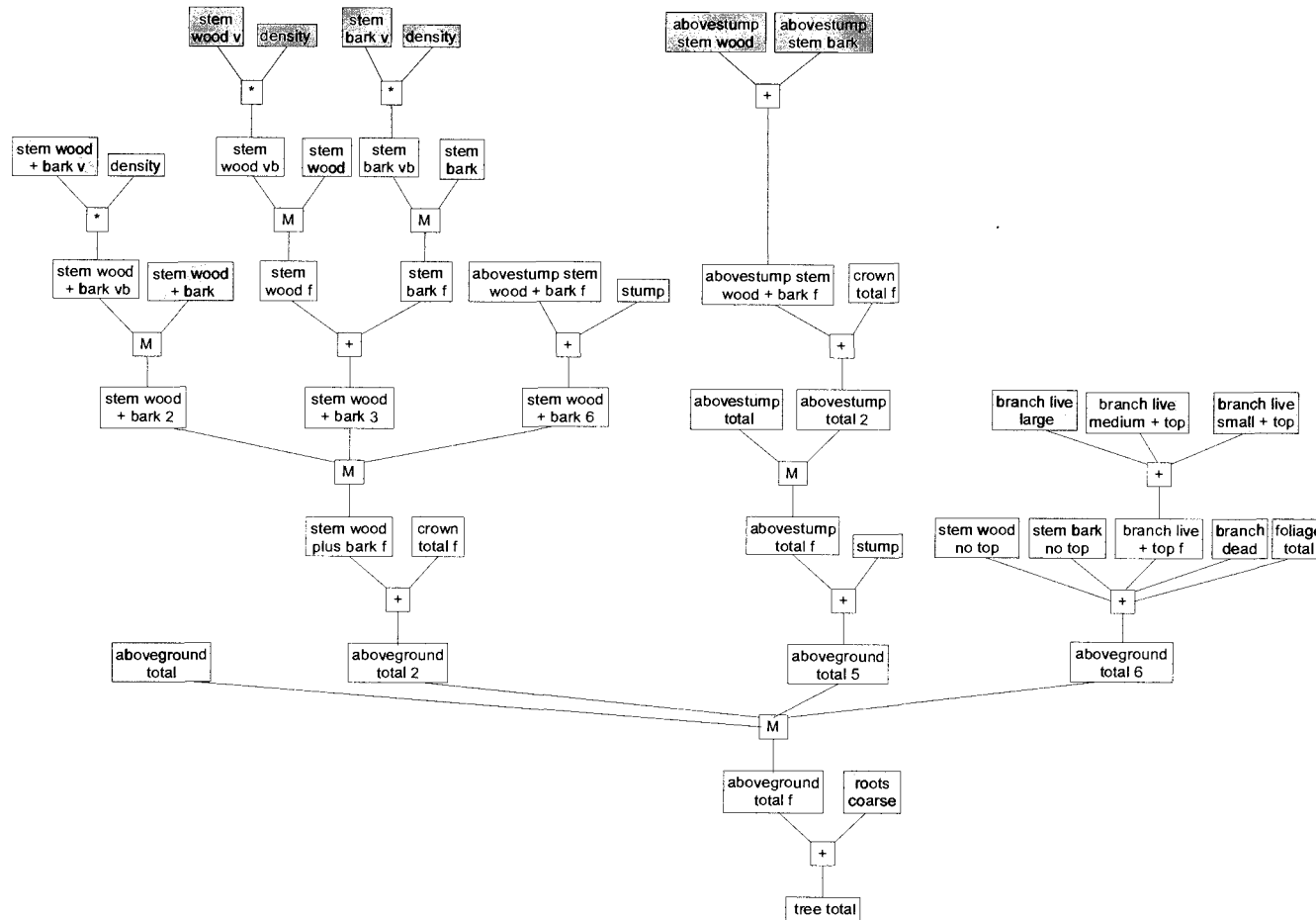
Figure A.3. Partial calculation pathway for *Tsuga heterophylla*. Shaded boxes indicate components where one or more equations or values exist. Components arising from another path, such as crown total f, are not shaded. Symbols are:"*"- volume table was multiplied by density range;"+"- tables were added together as described in the text;"M"– tables were merged as described in the text.
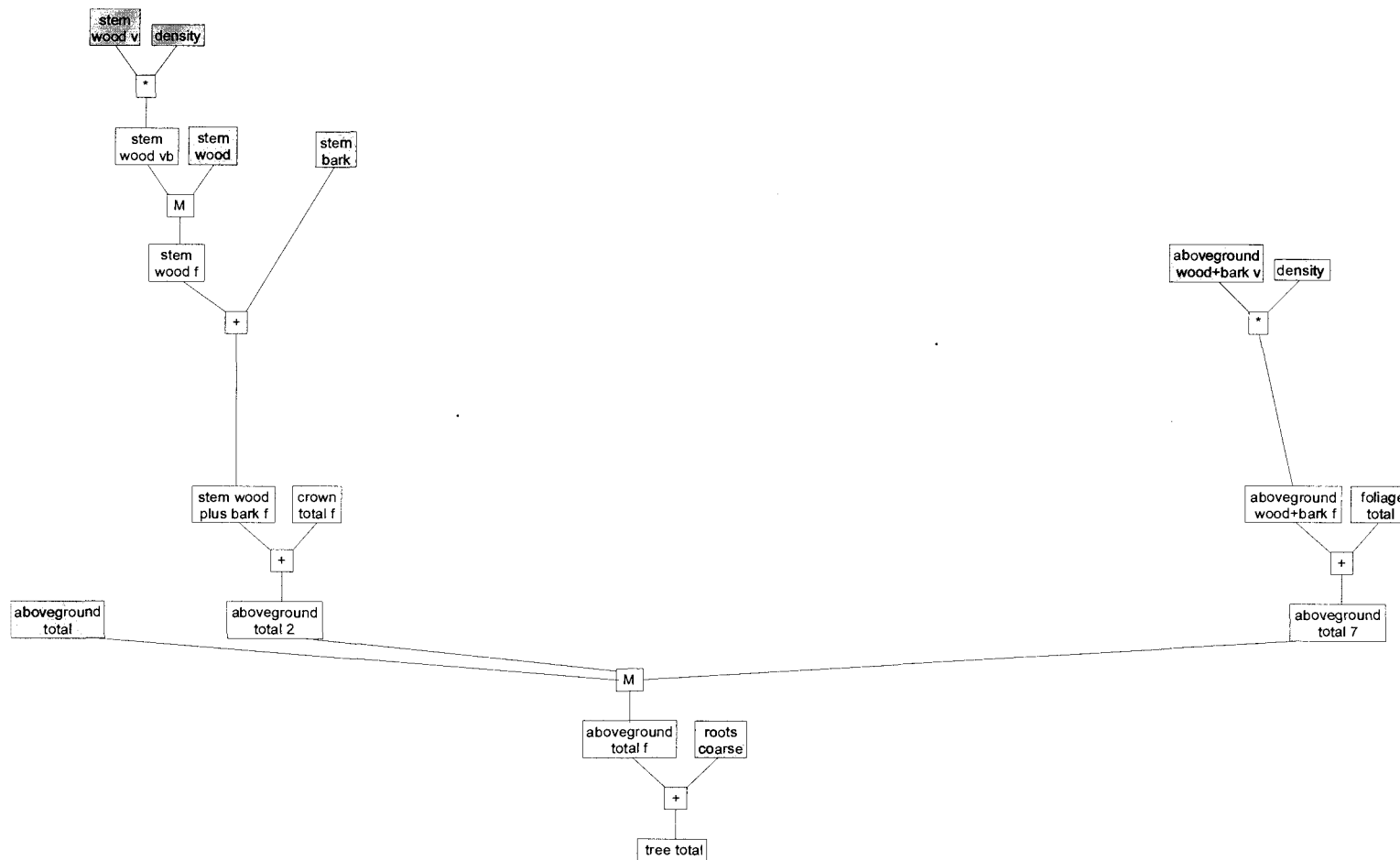
Figure A.4. Partial calculation pathway for *Acer macrophyllum*. Shaded boxes indicate components where one or more equations or values exist. Components arising from another path, such as crown total f, are not shaded. Symbols are:"*"- volume table was multiplied by density range;"+"- tables were added together as described in the text;"M"– tables were merged as described in the text.

Figure A.5. Partial calculation pathway for *Alnus rubra*. Shaded boxes indicate components where one or more equations or values exist. Components arising from another path, such as crown total f, are not shaded. Symbols are:"*"- volume table was multiplied by density range;"+"- tables were added together as described in the text;"M"- tables were merged as described in the text.
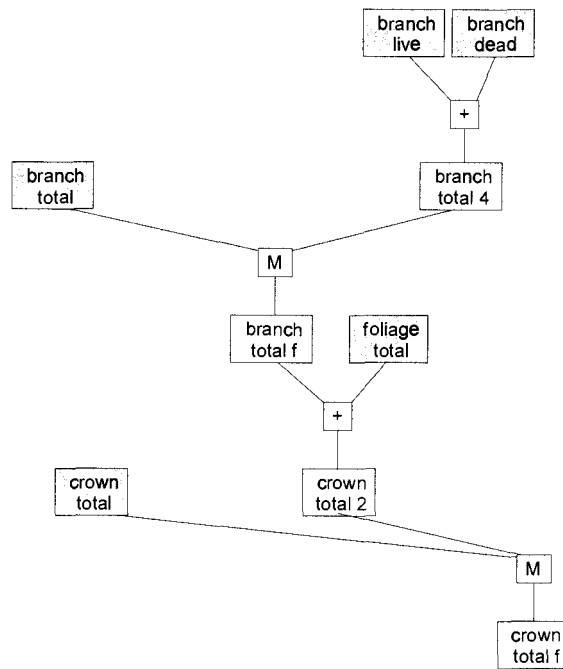
Figure A.6. Crown component pathway for *Picea sitchensis*. Shaded boxes indicate components where one or more equations or values exist. Symbols are:"+"- tables were added together as described in the text;"M"– tables were merged as described in the text.
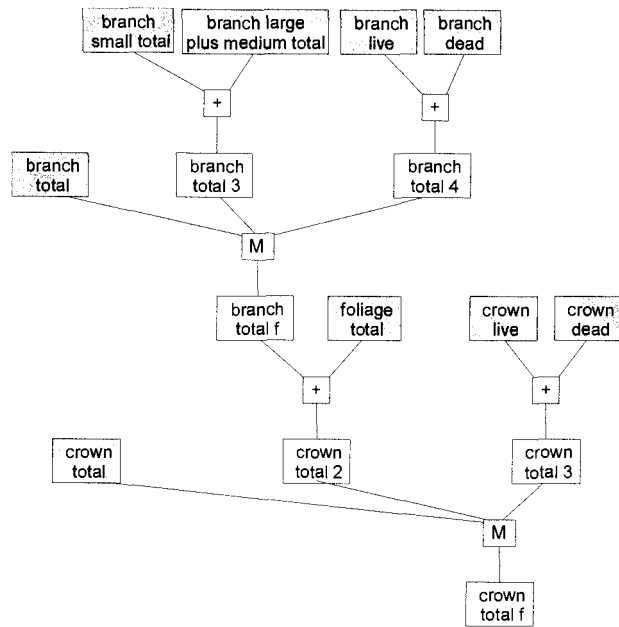
Figure A.7. Crown component pathway for *Pseudotsuga menziesii*. Shaded boxes indicate components where one or more equations or values exist. Symbols are:"+"- tables were added together as described in the text;"M"– tables were merged as described in the text.
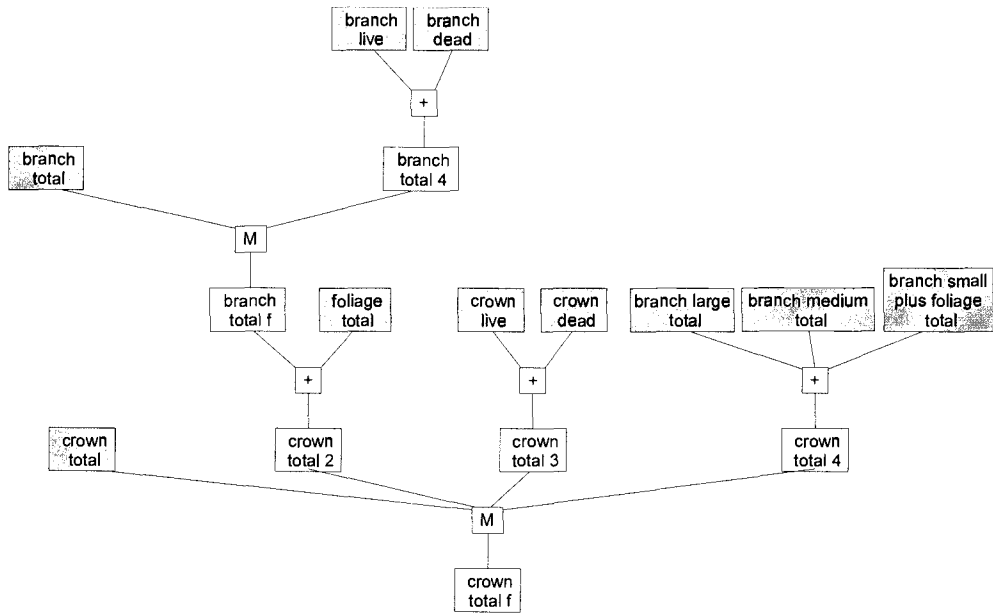
Figure A.8. Crown component pathway for *Tsuga heterophylla*. Shaded boxes indicate components where one or more equations or values exist. Symbols are:"+"- tables were added together as described in the text;"M"– tables were merged as described in the text.
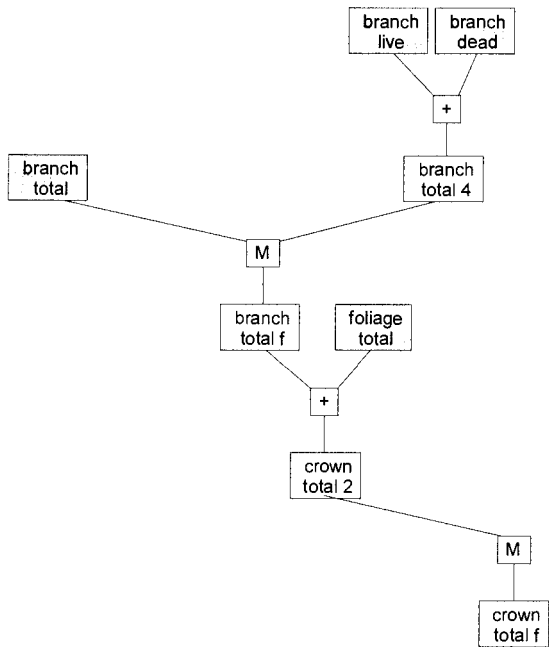
Figure A.9. Crown component pathway for *Acer macrophyllum*. Shaded boxes indicate components where one or more equations or values exist. Symbols are:"+"- tables were added together as described in the text;"M"– tables were merged as described in the text.
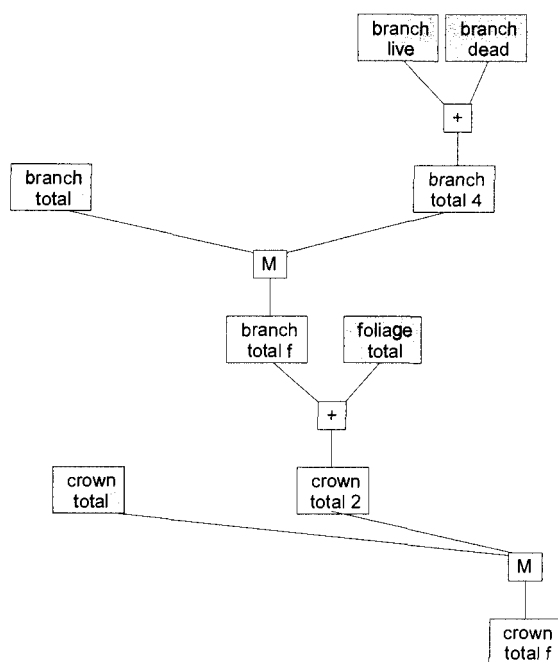
Figure A.10. Crown component pathway for *Alnus rubra*. Shaded boxes indicate components where one or more equations or values exist. Symbols are:"+"- tables were added together as described in the text;"M"– tables were merged as described in the text.

Appendix B Volume Equations

Table B.1. Volume equations for NW OR by species and component. Equations used by FIA appear with a gray background. All equations from Franklin (2002) listed here were developed for areas west of the Cascades. Spc is the species code (the first two letters of the code are the first two letters of the genus name, the second two are the first two letters of the species name, i.e. *Picea sitchensis* is PISI) n is the number of observations, CF indicates whether a correction factor was applied to the equations by the authors or not, and MSE is the mean squared error from regression. Unk stands for unknown. References appear in the general bibliography.

Spc	#	y	x	z	Equation	dbh low (cm)	dbh high (cm)	Author	Location or Study	n	CF	R^2	MSE
PISI	54	stem bark (m^3)	dbh (cm)		$y = 0.0002 * 1.0541 * (x^{1.7059})$	20.7	176.0	Franklin 2002	hemlock growth study	41	yes	0.95	0.1054
PISI	55	stem bark (m^3)	dbh (cm)		$y = 0.0000424 * 1.0764 * (x^{2.0887})$	20.7	176.0	Franklin 2002	hemlock growth study	27	yes	0.93	0.1472
PISI	56	stem bark (m^3)	dbh (cm)		$y = 0.0000272 * 1.0295 * (x^{2.1245})$			Franklin 2002	thinning study	14	yes	0.88	0.0581
PISI	57	stem bark (m^3)	dbh (cm)	ht (m)	$y = 0.006 * (x/100)^2 * z$			Franklin 2002	all coast	83		0.96	unk
PISI	2	stem wood (ft^3)	dbh (in)	ht (ft)	$y = (10^{-2.550299} * x^{1.835678} * z^{1.042599})$	2.0	44.0	Browne 1962	BC coastal immature <140 years	492	unk	unk	9.50%
PISI	3	stem wood (ft^3)	dbh (in)	ht (ft)	$y = (10^{-2.700574} * x^{1.754171} * z^{1.164531})$	4.0	96.0	Browne 1962	BC coastal mature >140	736	unk	unk	12.50%
PISI	4	stem wood (ft^3)	dbh (in)	ht (ft)	$y = (10^{-2.539944} * x^{1.841226} * z^{1.034051})$	2.0	46.0	Browne 1962	BC interior	5094	unk	unk	9.90%
PISI	5	stem wood (m^3)	dbh (cm)	ht (m)	$y = 4.893098969 * 10^{-5} * x^{1.822840} * z^{1.057290}$	unk		Penner et al. 1997	BC < 120 years	unk		unk	unk
PISI	6	stem wood (m^3)	dbh (cm)	ht (m)	$y = 4.280110684 * 10^{-5} * x^{1.646990} * z^{1.282450}$	unk		Penner et al. 1997	BC > 120 years	unk		unk	unk
PISI	7	stem wood (m^3)	dbh (cm)		$y = 0.000288 * 1.0237 * (x^{2.3633})$	20.7	176.0	Franklin 2002	hemlock growth study	41	yes	0.82	0.0468
PISI	8	stem wood (m^3)	dbh (cm)		$y = 0.0001281 * 1.0768 * (x^{2.4995})$	20.7	176.0	Franklin 2002	hemlock growth study	27	yes	0.91	0.1480
PISI	9	stem wood (m^3)	dbh (cm)		$y = 0.0006315 * 1.0071 * (x^{2.0004})$			Franklin 2002	thinning study	14	yes	0.66	0.0141
PISI	10	stem wood (m^3)	dbh (cm)	ht (m)	$y = 0.2286 * (x/100)^2 * z$			Franklin 2002	all coast	83		0.87	unk
PISI	73	stem wood + bark (m^3)	dbh (cm)		$y = 0.000346 * 1.0222 * (x^{2.332})$	20.7	176.0	Franklin 2002	hemlock growth study	41	yes	0.95	0.0439
PISI	74	stem wood + bark (m^3)	dbh (cm)		$y = 0.0001499 * 1.0748 * (x^{2.4765})$	20.7	176.0	Franklin 2002	hemlock growth study	27	yes	0.93	0.1443
PISI	75	stem wood + bark (m^3)	dbh (cm)		$y = 0.0006475 * 1.0074 * (x^{2.012})$			Franklin 2002	thinning study	14	yes	0.87	0.0147
PISI	76	stem wood + bark (m^3)	dbh (cm)	ht (m)	$y = 0.2346 * x^2 * z$			Franklin 2002	all coast	83	yes	0.96	unk
PSME	58	stem bark (m^3)	dbh (cm)		$y = 0.0001469 * 1.1173 * (x^{2.2136})$			Franklin 2002	Mt Rainier	45	yes	0.84	0.2218
PSME	59	stem bark (m^3)	dbh (cm)		$y = 0.0000384 * 1.0834 * (x^{2.4818})$	17.2	177.4	Franklin 2002	HJ Andrews	116	yes	0.93	0.1602

Table B.1. (Continued)

Spc	#	y	x	z	Equation	dbh low (cm)	high (cm)	Author	Location or Study	n	CF	R^2	MSE
PSME	60	stem bark (m^3)	dbh (cm)		y = 0.0000103 * 1.0866 * (x^2.7023)	24.6	206.5	Franklin 2002	noble fir growth study	34	yes	0.96	0.1077
PSME	61	stem bark (m^3)	dbh (cm)		y = 0.0000369 * 1.11 * (x^2.4785)			Franklin 2002	all cascades	215	yes	0.92	0.1661
PSME	62	stem bark (m^3)	dbh (cm)	ht (m)	y = 0.0519 * (x / 100)^2 * z			Franklin 2002	all cascades	215		0.89	0.2087
PSME	11	stem wood (ft^3)	dbh (in)	ht (ft)	y = (10^-2.658025 * x^1.739925 * z^1.133187)	2.0	48.0	Browne 1962	BC coastal immature <140 years	665	unk	unk	10.10%
PSME	12	stem wood (ft^3)	dbh (in)	ht (ft)	y = (10^-2.712153 * x^1.659012 * z^1.195715)	4.0	94.0	Browne 1962	BC coastal mature 80+ years	978	unk	unk	12.10%
PSME	13	stem wood (ft^3)	dbh (in)	ht (ft)	y = (10^-2.734532 * x^1.739418 * z^1.166033)	2.0	52.0	Browne 1962	BC interior	3131	unk	unk	11.30%
PSME	14	stem wood (ft^3)	dbh (in)	ht (ft)	y = 10^(- 3.215809 + 0.04948 * log10(z) * log10(x) - 0.15664 * (log10(x))^2 + 2.02132 * log10(x) + 1.63408 * log10(z) - 0.16185 * (log10(z))^2)			Weyerhauser in Brackett 1977	unk	unk	unk	unk	unk
PSME	15	stem wood (m^3)	dbh (cm)	ht (m)	y = exp(- 7.88448531 + 1.34686970 * log(x) + 0.12033677 * log(z))	0.5	5.0	Omule et al. 1987	BC coastal very small dbh < 5cm or ht <4m	108	yes	0.99	0.0951
PSME	16	stem wood (m^3)			y = exp(- 9.896325907 + 1.83478844 * log(x) + 1.00511916 * log(z))	5.0	44.8	Omule et al. 1987	BC coastal, larger	2450	yes	0.99	0.0951
PSME	17	stem wood (m^3)	dbh (cm)	ht (m)	y = 10^(- 4.319071 + 1.813820 * log10(x) + 1.042420 * log10(z))			BCFS 1976 in Omule, Penner et al. 1997	BC	393	unk	unk	10.30%
PSME	18	stem wood (cm^3)	dbh (cm)	ht(cm)	y = exp(- 3.33875 + 1.70435 * log(x) + 1.38551 * log(z) + 2.30499 * (137 / (z)))			Kovats 1977	BC coastal	100	unk	1.00	10.29%
PSME	19	stem wood (m^3)	dbh (cm)	ht (m)	y = exp(- 9.872837 + 1.869321 * log(x) + 0.967596 * log(z))			Godfrey in Omule et al. 1987	BC	630	unk	unk	0.0877
PSME	20	stem wood (m^3)	dbh (cm)	ht (m)	y = 4.48580793 * 10^-5 * x^1.692440 * z^1.181970	unk		Penner et al. 1997	BC > 120 years	unk		unk	unk
PSME	21	stem wood (m^3)	dbh (cm)	ht (m)	y = 4.139024528 * 10^-5 * x^1.742940 * z^1.156410	unk		Penner et al. 1997	BC interior	unk		unk	unk
PSME	22	stem wood (m^3)	dbh (cm)		y = 0.0001205 * 1.0352 * x^2.493			Franklin 2002	Mt Rainier	45	yes	0.95	0.0692
PSME	23	stem wood (m^3)	dbh (cm)		y = 0.0002719 * 1.0311 * x^2.3323	17.2	177.4	Franklin 2002	HJ Andrews	116	yes	0.97	0.0613
PSME	24	stem wood (m^3)	dbh (cm)		y = 0.0001163 * 1.0211 * x^2.503	24.6	206.5	Franklin 2002	noble fir growth study	34	yes	0.99	0.0400
PSME	25	stem wood (m^3)	dbh (cm)		y = 0.0001857 * 1.0333 * x^2.4153			Franklin 2002	all cascades	215	yes	0.97	0.0418

Table B.1. (Continued)

Spc	#	y	x	z	Equation	dbh low (cm)	dbh high (cm)	Author	Location or Study	n	CF	R^2	MSE
PSME	26	stem wood (m^3)	dbh (cm)	ht (m)	y = 0.2346 * (x / 100)^2 * z			Franklin 2002	all cascades	215		0.97	0.0655
PSME	27	stem wood (ft^3)	dbh (in)	ht (ft)	if ht <= 18 ft, form factor = 0.406098 * (z - 0.9)^2 / (z - 4.5)^2 - 0.0762998 * x * (z - 0.9)^3 / (z - 4.5)^3 + 0.00262615 * x * z * (z - 0.9)^3 / (z - 4.5)^3 ; if height > 18ft, form factor= 0.480961 + 42.46542 / z^2 - 10.99643 * (x / z^2) - 0.107809 * (x / z) - 0.00409083 * x vol = (0.005454154 * form factor * (x^2 * z))	0.4	32.0	Bruce & DeMars 1974	OR, WA, BC	1127		unk	varies
PSME	29	stem wood (ft^3)	dbh (in)	ht (ft)	y = 10^(- 2.1029 + 3.94426 * log10(x) + 0.16352 * (z / 100) - 0.80532 * (log10(x))^2 - 0.04705 * (100 / z) - 0.10849 * log10(x) * (100 / z) + 0.27677 * (1 / log10(x)) + 0.02815 * ((z / 100)^2) + 0.00140 * ((x / 10)^2 * (z / 100)))			Curtis in Brackett 1977	unk	unk	unk	unk	unk
PSME	77	stem wood + bark (m^3)	dbh (cm)		y = 0.0002146 * 1.0309 * (x^2.4367)			Franklin 2002	Mt Rainier	45	yes	0.96	0.0609
PSME	78	stem wood + bark (m^3)	dbh (cm)		y = 0.0003091 * 1.03 * (x^2.3602)	17.2	177.4	Franklin 2002	HJ Andrews	116	yes	0.97	0.0591
PSME	79	stem wood + bark (m^3)	dbh (cm)		y = 0.0001288 * 1.016 * (x^2.5277)	24.6	206.5	Franklin 2002	noble fir growth study	34	yes	0.99	0.0327
PSME	80	stem wood + bark (m^3)	dbh (cm)		y = 0.0002286 * 1.0296 * (x^2.4247)			Franklin 2002	all cascades	215	yes	0.97	0.0317
PSME	81	stem wood + bark (m^3)	dbh (cm)	ht (m)	y = 0.2865 * x^2 * z			Franklin 2002	all cascades	215	yes	0.97	0.0583
TSHE	63	stem bark (m^3)	dbh (cm)		y = 0.00008 * 1.0591 * (x^2.0166)	19.3	121.6	Franklin 2002	hemlock growth study	47	yes	0.90	0.1148
TSHE	64	stem bark (m^3)	dbh (cm)		y = 0.0000276 * 1.1325 * (x^2.3623)			Franklin 2002	Mt Rainier	80	yes	0.87	0.2489
TSHE	65	stem bark (m^3)	dbh (cm)		y = 0.0000308 * 1.2438 * (x^2.3474)	14.4	114.8	Franklin 2002	HJ Andrews	91	yes	0.78	0.4363
TSHE	66	stem bark (m^3)	dbh (cm)		y = 0.000005 * 1.059 * (x^2.7876)	15.3	134.7	Franklin 2002	noble fir growth study	21	yes	0.96	0.0597
TSHE	67	stem bark (m^3)	dbh (cm)		y = 0.0000687 * 1.0343 * (x^2.0831)	19.3	121.6	Franklin 2002	hemlock growth study	41	yes	0.94	0.1147
TSHE	68	stem bark (m^3)	dbh (cm)		y = 0.0005135 * 1.0584 * (x^1.5855)			Franklin 2002	cascade head	31	yes	0.59	0.0674
TSHE	69	stem bark (m^3)	dbh (cm)		y = 0.0000239 * 1.1689 * (x^2.4109)			Franklin 2002	all cascades	207	yes	0.84	0.1135
TSHE	70	stem bark (m^3)	dbh (cm)		y = 0.0006274 * 1.0556 * (x^1.3129)			Franklin 2002	thinning study	25	yes	0.29	0.3121
TSHE	71	stem bark (m^3)	dbh (cm)	ht (m)	y = 0.0317 * (x / 100)^2 * z			Franklin 2002	all cascades	207		0.89	0.1082

Table B.1. (Continued)

Spc	#	y	x	z	Equation	dbh low (cm)	dbh high (cm)	Author	Location or Study	n	CF	R^2	MSE
TSHE	72	stem bark (m^3)	dbh (cm)	ht (m)	y = 0.018 * (x / 100)^2 * z			Franklin 2002	all coast	144		0.89	unk
TSHE	30	stem wood (ft^3)	dbh (in)	ht (ft)	y = 10^(- 2.72170 + 2.00857 * log10(x) + 1.08620 * log10(z) - 0.00568 * (x))	2.0	50.0	Chambers & Foltz 1979	NW OR, WWA	638	unk	1.0	0.0430
TSHE	31	stem wood (ft^3)	dbh (in)	ht (ft)	y = (10^-2.702922 * x^1.842680 * z^1.123661)	2.0	34.0	Browne 1962	BC coastal immature <140 years	957	unk	unk	10.30%
TSHE	32	stem wood (ft^3)	dbh (in)	ht (ft)	y = (10^-2.663834 * x^1.790230 * z^1.124873)	2.0	74.0	Browne 1962	BC coastal mature 80+ years	1494	unk	unk	11.70%
TSHE	33	stem wood (ft^3)	dbh (in)	ht (ft)	y = (10^-2.571619 * x^1.969710 * z^0.977003)	2.0	11.4	Browne 1962	BC interior	1653	unk	unk	11.40%
TSHE	34	stem wood (ft^3)	dbh (in)	ht (ft)	y = (10^(- 3.72948 + 0.06619 / (log10(x)^2)) * x^(2.75543 - 0.44279 * log10(z)) * z^1.5971)			WA DNR in Brackett 1977	WWA	unk	unk	unk	unk
TSHE	35	stem wood (m^3)	dbh (cm)	ht (m)	y = 3.812237947 * 10^-5 * x^1.867780 * z^1.099890	unk		Penner et al. 1997	BC < 120 years	unk		unk	unk
TSHE	36	stem wood (m^3)	dbh (cm)	ht (m)	y = 4.597788609 * 10^-5 * x^1.783500 * z^1.120230	unk		Penner et al. 1997	BC > 120 years	unk		unk	unk
TSHE	37	stem wood (m^3)	dbh (cm)	ht (m)	y = 4.030574937 * 10^-5 * x^1.94290 * z^0.990275	unk		Penner et al. 1997	BC	unk		unk	unk
TSHE	38	stem wood (m^3)	dbh (cm)		y = 0.000212 * 1.0321 * (x^2.4222)	19.3	121.6	Franklin 2002	hemlock growth study	47	yes	0.96	0.0632
TSHE	39	stem wood (m^3)	dbh (cm)		y = 0.0000585 * 1.0294 * (x^2.7429)			Franklin 2002	Mt Rainier	80	yes	0.86	0.0580
TSHE	40	stem wood (m^3)	dbh (cm)		y = 0.0001431 * 1.081 * (x^2.5353)	14.4	114.8	Franklin 2002	HJ Andrews	91	yes	0.92	0.1558
TSHE	41	stem wood (m^3)	dbh (cm)		y = 0.0000697 * 1.0345 * (x^2.6648)	15.3	134.7	Franklin 2002	noble fir growth study	21	yes	0.98	0.0425
TSHE	42	stem wood (m^3)	dbh (cm)		y = 0.0001983 * 1.0137 * (x^2.4215)	19.3	121.6	Franklin 2002	hemlock growth study	41	yes	0.98	0.0678
TSHE	43	stem wood (m^3)	dbh (cm)		y = 0.0000807 * 1.019 * (x^2.113)			Franklin 2002	cascade head	31	yes	0.88	0.0272
TSHE	44	stem wood (m^3)	dbh (cm)		y = 0.0000962 * 1.0564 * (x^2.6253)			Franklin 2002	all cascades	207	yes	0.95	0.0376
TSHE	45	stem wood (m^3)	dbh (cm)		y = 0.0010121 * 1.0086 * (x^1.9237)			Franklin 2002	thinning study	25	yes	0.85	0.1097
TSHE	46	stem wood (m^3)	dbh (cm)	ht (m)	y = 0.2961 * (x / 100)^2 * z			Franklin 2002	all cascades	207		0.98	0.0171
TSHE	47	stem wood (m^3)	dbh (cm)	ht (m)	y = 0.2542 * (x / 100)^2 * z			Franklin 2002	all coast	144		0.96	unk
TSHE	48	stem wood (ft^3)	dbh (in)	ht (ft)	y = 10^(-2.71907159 + 2.02477817 * log10(x) - 0.00590929 * x + 1.07716464 * log10(z))	2.0	50.0	Hoyer 1985	NW OR, WWA	638	unk	1.00	0.0427
TSHE	82	stem wood + bark (m^3)	dbh (cm)		y = 0.000265 * 1.0283 * (x^2.3863)	19.3	121.6	Franklin 2002	hemlock growth study	47	yes	0.96	0.0558
TSHE	83	stem wood + bark (m^3)	dbh (cm)		y = 0.0000786 * 1.0297 * (x^2.7017)			Franklin 2002	Mt Rainier	80	yes	0.98	0.0585

Table B.1. (Continued)

Spc	#	y	x	z	Equation	dbh low (cm)	dbh high (cm)	Author	Location or Study	n	CF	R^2	MSE
TSHE	84	stem wood + bark (m^3)	dbh (cm)		$y = 0.0001756 * 1.09 * (x^{2.5095})$	14.4	114.8	Franklin 2002	HJ Andrews	91	yes	0.91	0.1724
TSHE	85	stem wood + bark (m^3)	dbh (cm)		$y = 0.0000751 * 1.0322 * (x^{2.6741})$	15.3	134.7	Franklin 2002	noble fir growth study	21	yes	0.98	0.0374
TSHE	86	stem wood + bark (m^3)	dbh (cm)		$y = 0.0002421 * 1.0134 * (x^{2.3938})$	19.3	121.6	Franklin 2002	hemlock growth study	41	yes	0.98	0.0634
TSHE	87	stem wood + bark (m^3)	dbh (cm)		$y = 0.0010379 * 1.0194 * (x^{2.0696})$			Franklin 2002	cascade head	31	yes	0.88	0.0266
TSHE	88	stem wood + bark (m^3)	dbh (cm)		$y = 0.0001189 * 1.0596 * (x^{2.5989})$			Franklin 2002	all cascades	207	yes	0.94	0.0384
TSHE	89	stem wood + bark (m^3)	dbh (cm)		$y = 0.001296 * 1.0085 * (x^{1.8743})$			Franklin 2002	thinning study	25	yes	0.84	0.1158
TSHE	90	stem wood + bark (m^3)	dbh (cm)	ht (m)	$y = 0.3278 * x^2 * z$			Franklin 2002	all cascades	207	yes	0.98	0.0169
TSHE	91	stem wood + bark (m^3)	dbh (cm)	ht (m)	$y = 0.2723 * x^2 * z$			Franklin 2002	all coast	144	yes	0.95	unk
ACMA	1	aboveground wood + bark (m^3)	dbh (cm)	ht (m)	$y = 0.0000718042 * (x^{2.22462}) * (z^{0.57561})$	10.0	90.0	Pillsbury & Kirkley 1984	CA	61		0.94	1.2900
ACMA	49	stem wood (m^3)	dbh (cm)		$y = exp(- 8.4397 + 2.305 * log(x))$	5.1	45.7	Snell and Little 1983	WWA	16	unk	0.97	0.5530
ACMA	50	stem wood (ft^3)	dbh (in)	ht (ft)	$y = (10^{-2.770324} * x^{1.885813} * z^{1.119043})$	2.0	26.0	Browne 1962	BC coastal	197	unk	unk	10.60%
ALRU	52	stem wood (ft^3)	dbh (in)	ht (ft)	$y = (10^{-2.672775} * x^{1.920617} * z^{1.074024})$	2.0	22.0	Browne 1962	BC coastal	599	unk	unk	8.30%
ALRU	53	stem wood (m^3)	dbh (cm)		$y = exp(- 8.8272 + 2.4999 * log(x))$	1.0	25.0	Snell and Little 1983	WOR, WWA	53	unk	0.98	0.0708
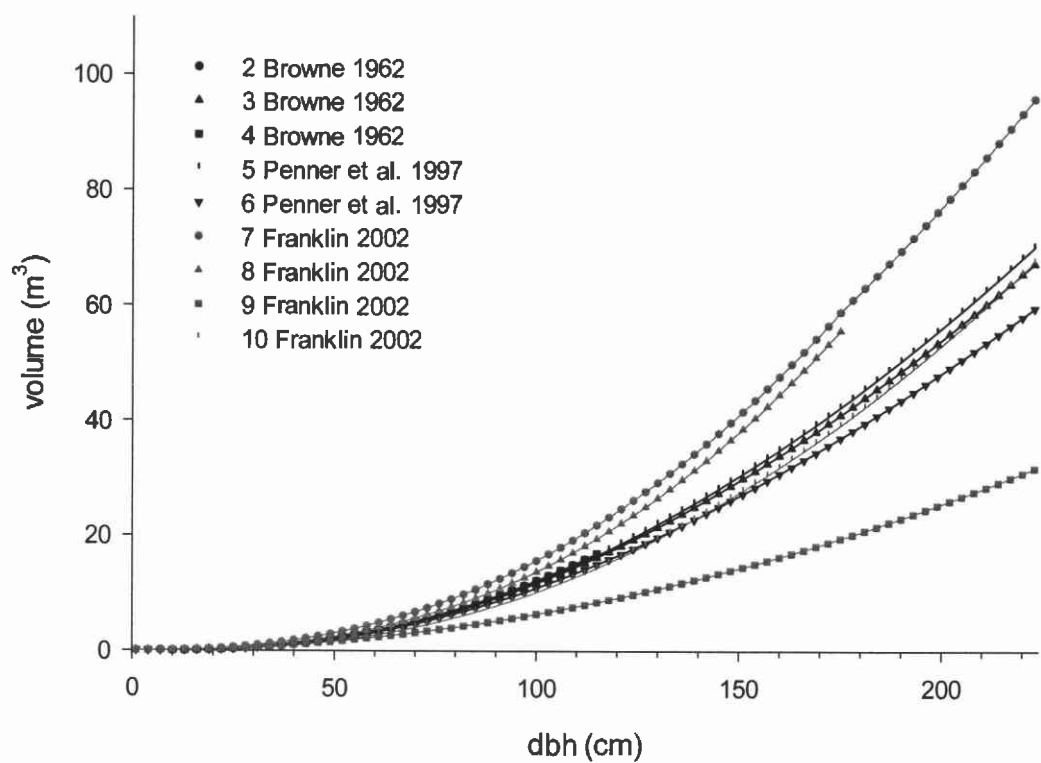
Figure B.1. *Picea sitchensis* stem wood volume equations plotted.
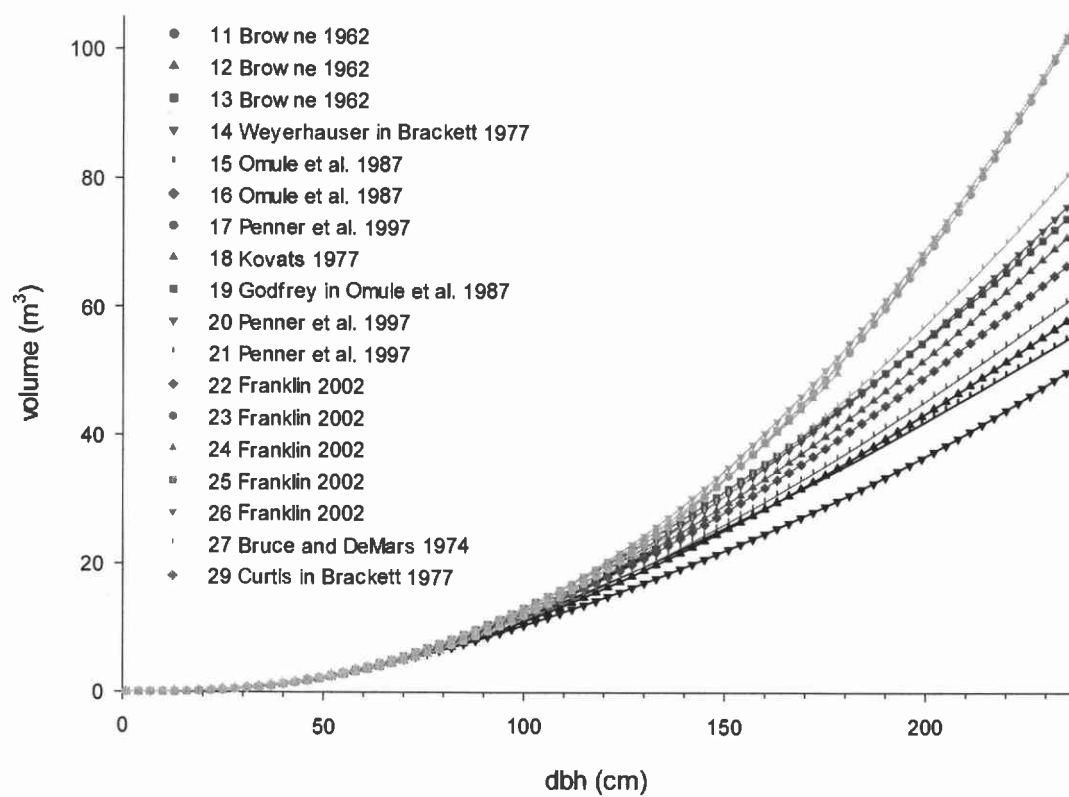
Figure B.2. *Pseudotsuga menziesii* stem wood volume equations plotted.
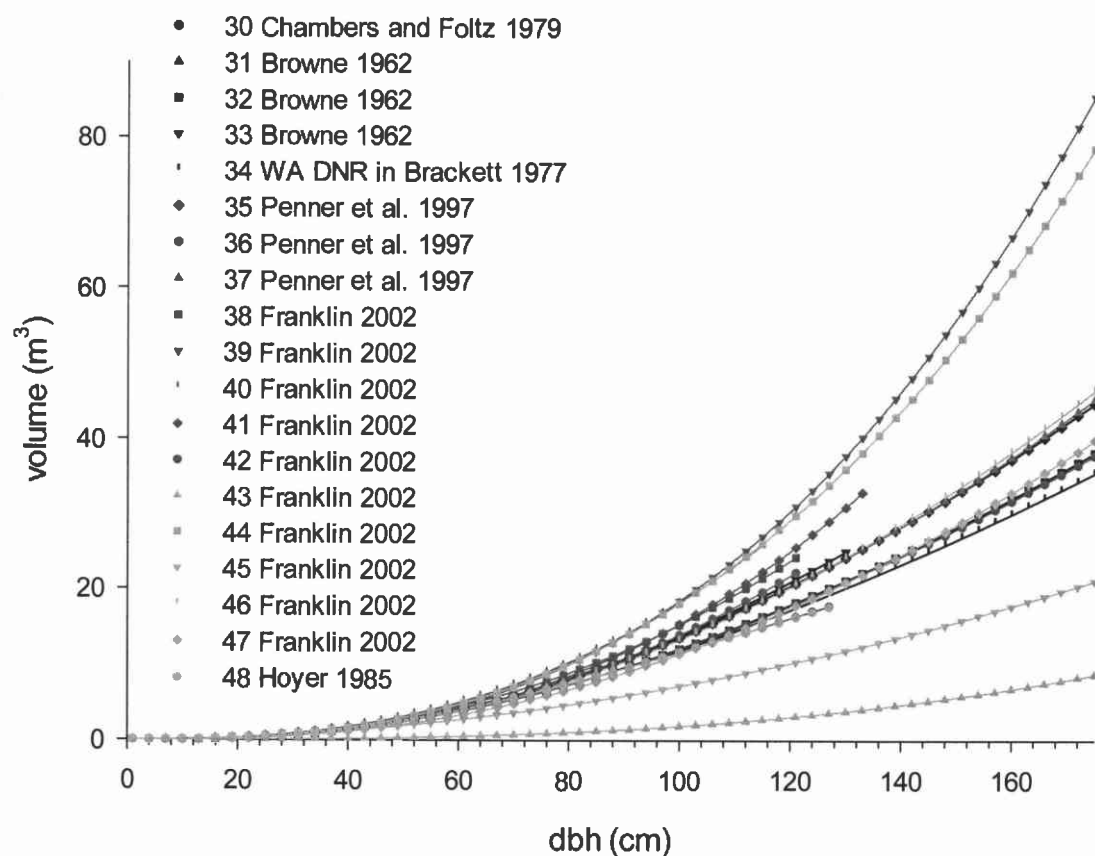
Figure B.3. *Tsuga heterophylla* stem wood volume equations plotted.
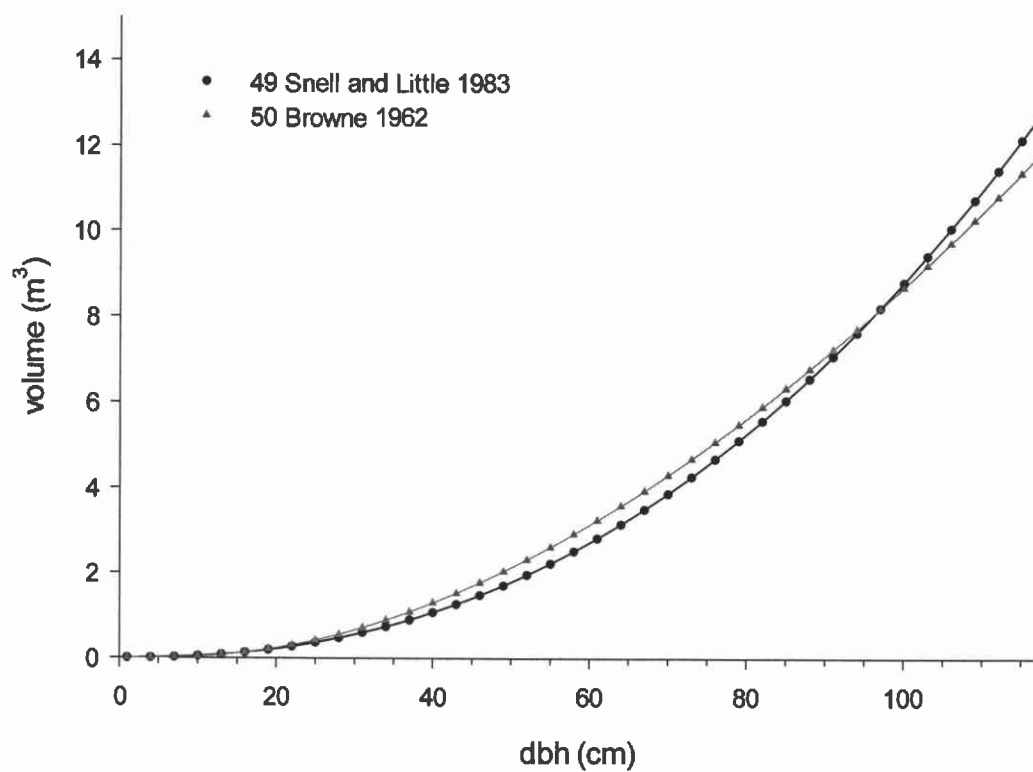
Figure B.4. *Acer macrophyllum* stem wood volume equations plotted.
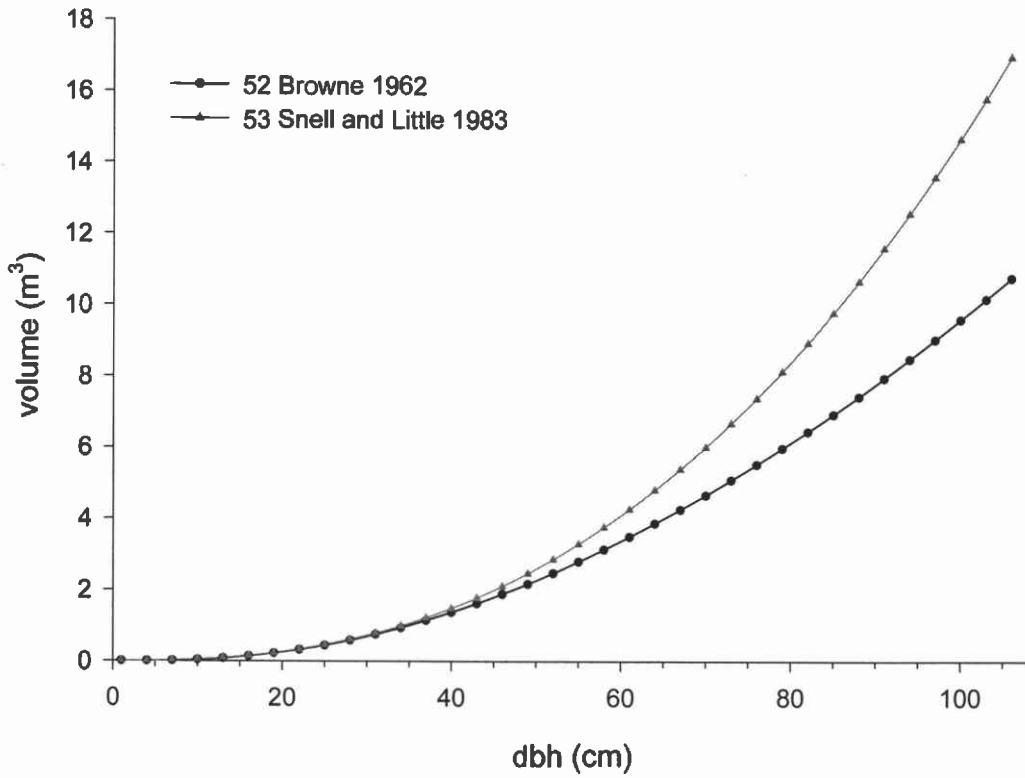
Figure B.5. *Alnus rubra* stem wood volume equations plotted.

Appendix C Biomass Equations

Table C.1. Biomass equations for NW OR by species and component. Spc is the species code (the first two letters of the code are the first two letters of the genus name, the second two are the first two letters of the species name, i.e. *Picea sitchensis* is PISI), # is the equation number given in this study, n is the number of observations, Rsqr is the R squared value, MSE is the mean squared error from regression, and CF? indicates whether a correction factor was incorporated into the equations by the authors. Equations numbered in the form xxxx.xxx indicate an equation that was applied to more than one target species (98 = *Picea sitchensis*, 202 = *Pseudotsuga menziesii*, 263 = *Tsuga heterophylla*, 312 = *Acer macrophyllum*, and 351 = *Alnus rubra*). Occasionally an equation will appear in two forms. This commonly occurs when authors convert an equation created by a previous researcher into different units, or report it on the regular versus the transformed scale. In general, such duplicate equations were discarded unless the transformation resulted in obvious differences in predicted values. Within the Component column, lt = less than, gt = greater than. References appear in the general bibliography.

Spc	#	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
PISI	255	aboveground total	$y = 17.6 + 172.1 * x^2 * z$	kg	dbh (m)	ht (m)	0.053	0.451	40	0.96	385.7	
PISI	2090.098	aboveground total	$\ln(y) = -2.7152 + 2.3323 * \ln(x)$	kg	dbh (cm)		1	250			0.06271	no
PISI	2022	branch dead	$y = 1 + 1.8 * x^2 * z$	kg	dbh (m)	ht (m)	0.053	0.451	40	0.27		
PISI	234	branch live	$y = 9.7 + 22 * (x/100)^2 * z$	kg	dbh (cm)	ht (m)					unk	
PISI	1393	branch live	$\ln(y) = 1.71866 + 2.518 * \ln(x)$	g	dbh (cm)		3.0	77.7	28	0.8	0.0169	no
PISI	250	branch live large (gt2.5cm)	$y = 0.3 + 6.7 * x^2 * z$	kg	dbh (m)	ht (m)	0.053	0.451	40	0.42	25.0	
PISI	251	branch live med (0.5to2.5cm) plus top	$y = 6.7 + 10.5 * x^2 * z$	kg	dbh (m)	ht (m)	0.053	0.451	40	0.41	30.6916	
PISI	252	branch live small (lt0.5cm) plus top	$y = 2.7 + 4.8 * x^2 * z$	kg	dbh (m)	ht (m)	0.053	0.451	40	0.41	11.83	
PISI	63	branch total	$\ln(y) = -5.1891 + 2.518 * \ln(x)$	kg	dbh (cm)		3	77.7	28	0.8	0.0169	no
PISI	734	crown total	$y = 5.77 + (0.0212788 ((x^3)/z)) + (0.000143485 ((x^3)/z)^2) + (-1.05941E-007((x^3)/z)^3) + (1.58349E-011 ((x^3)/z)^4)$	kg	dbh (cm)	ht (m)			38	0.94	186.46449	
PISI	746.098	crown total	$y = 0.41 + (0.0490137 ((x^3)/z)) + (-2.34327E-006 ((x^3)/z)^2) + (3.10136E-010((x^3)/z)^3) + (-2.53319E-014 ((x^3)/z)^4)$	kg	dbh (cm)	ht (m)			6733	0.77	450.33933	
PISI	62	foliage total	$\ln(y) = -5.822 + 2.78 * \ln(x)$	kg	dbh (cm)		3	77.7	28	0.81	0.0169	no
PISI	254	foliage total	$y = 7.6 + 20.1 * x^2 * z$	kg	dbh (m)	ht (m)	0.053	0.451	40	0.46	74.64	
PISI	2020.098	roots coarse	$\ln(y) = -4.691 + 2.6929 * \ln(x)$	kg	dbh (cm)		2.3	135	26	0.96	0.127	yes
PISI	2082.098	roots coarse	$\ln(y) = -4.352 + 2.579 * \ln(x)$	kg	dbh (cm)		15	50	33	0.9	0.208	yes
PISI	2083.098	roots coarse	$\ln(y) = -4.643 + 2.652 * \ln(x)$	kg	dbh (cm)		51	135	3	0.94	0.2	yes
PISI	2099.098	roots coarse	$\log10(y) = -1.2417 + 2.1514 * \log10(x)$	kg	dbh (cm)				15	0.97	unk	no
PISI	2115.098	roots coarse	$\log10(y) = -2.074 + 0.8946 * \log10(x^2 * z)$	kg	dbh (cm)	ht (m)	15	38	3	0.99	unk	no
PISI	233	stem bark	$y = 1.3 + 12.6 * (x/100)^2 * z$	kg	dbh (cm)	ht (m)					unk	
PISI	716	stem bark	$y = 0.57 + (0.000845391 * x^2 * z) + (7.27353E-005 * x^3 * z) + (-1.55959E-006 * x^4 * z)$	kg	dbh (cm)	ht (m)			38	0.93	6.07524	

Table C.1. (Continued)

Spc	#	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
PISI	728.098	stem bark	y = 1.38 + (0.00141769 * x^2 * z) + (6.77791E-006 * x^3 * z) + (-8.91979E-008 * x^4 * z)	kg	dbh (cm)	ht (m)			6856	0.87	65.24116	
PISI	1404	stem bark	ln(y) = 3.200874 + 2.0887 * ln(x)	g	dbh (cm)		20.7	176.0	27	0.91	0.14724	yes
PISI	1405	stem bark	ln(y) = 4.731108 + 1.7059 * ln(x)	g	dbh (cm)		35.4	283.0	41	0.82	0.10538	yes
PISI	1406	stem bark	ln(y) = 2.712394 + 2.1245 * ln(x)	g	dbh (cm)		24.3	41.5	14	0.66	0.05815	yes
PISI	249	stem bark (notoplt2.5cm)	y = 1.3 + 12.6 * x^2 * z	kg	dbh (m)	ht (m)	0.053	0.451	40	0.93	7.45	
PISI	698	stem wood	y = 6.55 + (0.00297651 * x^2 * z) + (0.0005404 * x^3 * z) + (-8.62033E-006 * x^4 * z)	kg	dbh (cm)	ht (m)			38	0.96	192.00813	
PISI	710.098	stem wood	y = -0.8 + (0.0150905 * x^2 * z) + (5.53425E-005 * x^3 * z) + (-3.76558E-006 * x^4 * z)	kg	dbh (cm)	ht (m)			6856	0.86	2214.74713	
PISI	1412	stem wood	ln(y) = 3.905154 + 2.4995 * ln(x)	g	dbh (cm)		20.7	176.0	27	0.93	0.14799	yes
PISI	1413	stem wood	ln(y) = 4.664733 + 2.3633 * ln(x)	g	dbh (cm)		35.4	283.0	41	0.95	0.04685	yes
PISI	1414	stem wood	ln(y) = 5.433522 + 2.0004 * ln(x)	g	dbh (cm)		24.3	41.5	14	0.88	0.01415	yes
PISI	248	stem wood (notoplt2.5cm)	y = -1 + 117.4 * x^2 * z	kg	dbh (m)	ht (m)	0.053	0.451	40	0.98	182.53	
PISI	61	stem wood plus bark	ln(y) = -3.215 + 2.552 * ln(x)	kg	dbh (cm)		3	77.7	28	0.97	0.0025	no
PISI	1409	stem wood plus bark	ln(y) = 4.085144 + 2.4765 * ln(x)	g	dbh (cm)		20.7	176.0	27	0.93	0.14427	yes
PISI	1410	stem wood plus bark	ln(y) = 4.871437 + 2.3320 * ln(x)	g	dbh (cm)		35.4	283.0	41	0.95	0.04391	yes
PISI	1411	stem wood plus bark	ln(y) = 5.483533 + 2.0120 * ln(x)	g	dbh (cm)		24.3	41.5	14	0.87	0.01475	yes
PSME	154	aboveground total	y = 1054 + 0.02057 * (x^2) * z	g	dbh (cm)	ht (cm)	1	220.7	144	0.69	0.00024	
PSME	204	aboveground total	ln(y) = -3.9371 + 2.8427 * ln(x)	kg	dbh (cm)		16	30	40	0.93	0.0529	yes
PSME	239	aboveground total	log10(y) = -0.85223 + 2.30609 * log10(x)	kg	dbh (cm)		5	30		0.99	unk	unk
PSME	247	aboveground total	y = 37.3 + 139.3 * x^2 * z	kg	dbh (m)	ht (m)	0.045	0.66	49	0.99	2376.6	
PSME	271	aboveground total	y = 61.9 + 133.5 * x^2 * z	kg	dbh (m)	ht (m)	0.031	0.632	41	0.84	26589.0	
PSME	1459	aboveground total	ln(y) = -0.6484 + 1.848 * ln(x) + 0.924 * ln(z)	g	dbh (cm)	ht (cm)	8.9	26.1	240	0.95	0.081	no
PSME	1465	aboveground total	ln(y) = -6.135 + 2.355 * ln(x)	g	ht (cm)		3.0	24.0	11	0.94	0.21	no
PSME	1931	aboveground total	y = 0.059265 * x^2 * z	lb	dbh (in)	ht (ft)	1	48	112	0.96	3048516.0	
PSME	2088	aboveground total	ln(y) = -2.2304 + 2.4435 * ln(x)	kg	dbh (cm)		1	250			0.04783	no
PSME	2206	aboveground total	ln(y) = ln(119.42) + 2.36 * ln(x)	g	dbh (cm)		5	25	24	0.99	0.0115	no
PSME	2207	aboveground total	ln(y) = ln(117.2) + 2.36 * ln(x)	g	dbh (cm)		5	25	24	0.98	0.0101	no
PSME	2208	aboveground total	ln(y) = ln(111.6) + 2.38 * ln(x)	g	dbh (cm)		5	25	24	0.96	0.0085	no
PSME	2209	aboveground total	ln(y) = ln(95.64) + 2.43 * ln(x)	g	dbh (cm)		5	25	24	0.99	0.0043	no
PSME	223	abovestump (10cm) stem bark	ln(y) = -4.3209 + 2.2124 * ln(x)	kg	dbh (cm)		9	26		0.87	0.0201	yes
PSME	222	abovestump (10cm) stem wood	ln(y) = -2.475 + 2.2691 * ln(x)	kg	dbh (cm)		9	26		0.92	0.0114	yes
PSME	221	abovestump (10cm) stem wood plus bark	ln(y) = -2.329 + 2.2621 * ln(x)	kg	dbh (cm)		9	26		0.93	0.0105	yes
PSME	220	abovestump (10cm) total	ln(y) = -2.1253 + 2.2985 * ln(x)	kg	dbh (cm)		9	26		0.93	0.011	yes
PSME	2245	abovestump (15cm) stem bark	y = 0.0113 * x^2.5772	kg	dbh (cm)		5	54	60	0.96	0.126	

Table C.1. (Continued)

Spc	#	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
PSME	2244	abovestump (15cm) stem wood	y = 0.0336 * x^2.6518	kg	dbh (cm)		5	54	60	0.96	0.14	
PSME	144	abovestump (15cm) stem wood plus bark	ln(y) = 4.63891 + 2.11972 * ln(x)	g	dbh (cm)		1.4	13.4	18	0.97	0.05971	no
PSME	2246	abovestump (15cm) stem wood plus bark	y = 0.0451 * x^2.6343	kg	dbh (cm)		5	54	60	0.96	0.132	
PSME	145	abovestump (15cm) total	ln(y) = 4.98412 + 2.18584 * ln(x)	g	dbh (cm)		1.4	13.4	18	0.97	0.07422	no
PSME	2243	abovestump (15cm) total	y = 0.08 * x^2.5282	kg	dbh (cm)		5	54	60	0.97	0.08	
PSME	116	branch dead	ln(y) = -3.529 + 1.7503 * ln(x)	kg	dbh (cm)		1.8	162	85	0.84	0.53	yes
PSME	246	branch dead	y = 1.6 + 1 * x^2 * z	kg	dbh (m)	ht (m)	0.045	0.66	49	0.69		
PSME	270	branch dead	y = 2.4 + 2.2 * x^2 * z	kg	dbh (m)	ht (m)	0.031	0.632	41	0.44		
PSME	1981	branch dead	ln(y) = -10.595 + 3.648 * ln(x)	kg	dbh (cm)		5	56	75	0.1		no
PSME	1986	branch dead	ln(y) = -5.596 + 1.866 * ln(x)	kg	dbh (cm)		6	29	48	0.08		no
PSME	2023	branch dead	ln(y) = -4.016 + 2.132 * ln(x)	kg	dbh (cm)		9	30	26	0.22	0.8	yes
PSME	2060	branch dead	ln(y) = -2.455 + 1.4 * ln(x)	kg	dbh (cm)		25.9	163	17	0.86	0.53	yes
PSME	2222	branch dead	ln(y) = ln(8.75) + 2.2 * ln(x)	g	dbh (cm)		5	25	24	0.86	0.0894	no
PSME	2223	branch dead	ln(y) = ln(7.89) + 2.23 * ln(x)	g	dbh (cm)		5	25	24	0.97	0.1453	no
PSME	2224	branch dead	ln(y) = ln(0.36) + 3.06 * ln(x)	g	dbh (cm)		5	25	24	0.84	0.1944	no
PSME	2225	branch dead	ln(y) = ln(0.04) + 3.69 * ln(x)	g	dbh (cm)		5	25	24	0.80	0.3373	no
PSME	209	branch large plus med total	ln(y) = -5.7108 + 2.6788 * ln(x)	kg	dbh (cm)		16	30	40	0.92	0.0576	yes
PSME	115	branch live	ln(y) = -3.6941 + 2.1382 * ln(x)	kg	dbh (cm)		1.8	162	123	0.92	0.399	yes
PSME	214	branch live	ln(y) = -4.456 + 2.469 * ln(x)	kg	dbh (cm)		9	30	26	0.86	0.86	yes
PSME	225	branch live	ln(y) = -4.4216 + 2.4394 * ln(x)	kg	dbh (cm)		9	26		0.74	0.0539	yes
PSME	228	branch live	y = 0.626 + 0.00079 * x^2 * z	kg	dbh (cm)	ht (m)					unk	
PSME	1472	branch live	ln(y) = -3.0332 + 1.92 * ln(x) + 0.96 * ln(z)	g	dbh (cm)	ht (cm)	8.9	26.1	240	0.73	0.0572	no
PSME	1970	branch live	ln(y) = -7.915 + 2.488 * ln(x)	g	ht (cm)		80	220	10	0.84		no
PSME	1975	branch live	ln(y) = -11.842 + 3.385 * ln(x)	g	ht (cm)		39	171	16	0.83		no
PSME	1980	branch live	ln(y) = -1.466 + 1.566 * ln(x)	kg	dbh (cm)		5	56	10	0.96		no
PSME	1985	branch live	ln(y) = -2.946 + 1.904 * ln(x)	kg	dbh (cm)		6	29	8	0.78		no
PSME	1990	branch live	ln(y) = -2.829 + 1.937 * ln(x)	kg	dbh (cm)		5	64	46	0.83	0.25402	no
PSME	1994	branch live	ln(y) = -2.914 + 1.97 * ln(x)	kg	dbh (cm)		5	35	42	0.76	0.25	no
PSME	2008	branch live	ln(y) = -3.108 + 2.063 * ln(x)	kg	dbh (cm)		11	64	14	0.83	0.31248	no
PSME	2012	branch live	ln(y) = -3.073 + 2.007 * ln(x)	kg	dbh (cm)		7	28	17	0.76	0.1608	no
PSME	2059	branch live	ln(y) = -4.786 + 2.389 * ln(x)	kg	dbh (cm)		25.9	163	29	0.97	0.188	yes
PSME	2218	branch live	ln(y) = ln(1.64) + 2.96 * ln(x)	g	dbh (cm)		5	25	24	0.90	0.1164	no
PSME	2219	branch live	ln(y) = ln(1.14) + 3.15 * ln(x)	g	dbh (cm)		5	25	24	0.88	0.0611	no
PSME	2220	branch live	ln(y) = ln(4.95) + 2.71 * ln(x)	g	dbh (cm)		5	25	24	0.95	0.0434	no

Table C.1. (Continued)

Spc	#	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
PSME	2221	branch live	$\ln(y) = \ln(9.99) + 2.49 * \ln(x)$	g	dbh (cm)		5	25	24	0.88	0.0234	no
PSME	242	branch live large (gt2.5cm)	$y = 1.4 + 6 * x^2 * z$	kg	dbh (m)	ht (m)	0.045	0.66	49	0.64	389.2729	
PSME	266	branch live large (gt2.5cm)	$y = -0.2 + 11.8 * x^2 * z$	kg	dbh (m)	ht (m)	0.031	0.632	41	0.56	1188.8704	
PSME	243	branch live med (0.5to2.5cm) plus top	$y = 9 + 2.2 * x^2 * z$	kg	dbh (m)	ht (m)	0.045	0.66	49	0.45	55.8009	
PSME	267	branch live med (0.5to2.5cm) plus top	$y = 10.9 + 6.4 * x^2 * z$	kg	dbh (m)	ht (m)	0.031	0.632	41	0.31	616.0324	
PSME	244	branch live small (lt0.5cm) plus top	$y = 3.2 + 1.2 * x^2 * z$	kg	dbh (m)	ht (m)	0.045	0.66	49	0.56	10.69	
PSME	268	branch live small (lt0.5cm) plus top	$y = 1.9 + 5.3 * x^2 * z$	kg	dbh (m)	ht (m)	0.031	0.632	41	0.45	226.2	
PSME	211	branch small total	$\ln(y) = -6.802 + 2.7361 * \ln(x)$	kg	dbh (cm)		16	30	40	.90+	0.0529	yes
PSME	143	branch total	$\ln(y) = 2.85568 + 2.50332 * \ln(x)$	g	dbh (cm)		1.4	13.4	18	0.94	0.19322	no
PSME	156	branch total	$y = 0.626 + 0.000798 * (x^2) * z$	kg	dbh (cm)	ht (m)	1	220.7	171	0.77	0.00024	
PSME	2247	branch total	$y = 0.0088 * x^{2.584}$	kg	dbh (cm)		5	54	60	0.91	0.298	
PSME	196	crown dead	$y = 22.46 + 0.001 * 9.8^3 + 0.2425 * (x^2 - 9.8^2)$	lb	dbh (in)		1	10	90	0.97		
PSME	197	crown dead	$y = 22.46 + 0.001 * x^3$	lb	dbh (in)		11	90	90	0.97		
PSME	202	crown dead	$\ln(y) = -10.6294 + 3.2692 * \ln(x)$	kg	dbh (cm)		30	157	32	0.79	0.25	unk
PSME	192	crown live	$\ln(y) = 0.0623 + 1.949 * \ln(x)$	lb	dbh (in)		1	87	173	0.91	51574.41	yes
PSME	193	crown live	$\ln(y) = -0.7224 + 1.888 * \ln(z) - 0.3873 (z/x)$	lb	dbh (in)	ht (ft)	1	87	108	0.97	56548.84	yes
PSME	200	crown live	$\ln(y) = 4.0068 + 0.0206 * x$	kg	dbh (cm)		30	157	32	0.73	0.14	unk
PSME	224	crown live	$\ln(y) = -3.7604 + 2.4059 * \ln(x)$	kg	dbh (cm)		9	26		0.78	0.0421	yes
PSME	1486	crown live	$\ln(y) = -2.3458 + 1.902 * \ln(x) + 0.951 * \ln(z)$	g	dbh (cm)	ht (cm)	8.9	26.1	240	0.77	0.044	no
PSME	208	crown total	$\ln(y) = -5.0145 + 2.706 * \ln(x)$	kg	dbh (cm)		16	30	40	0.93	0.0529	yes
PSME	737	crown total	$y = 4.06 + (0.0512793 ((x^3)/z)) + (4.54407E\text{-}006 ((x^3)/z)^2) + (1.21177E\text{-}009((x^3)/z)^3) + (-3.52394E\text{-}013 ((x^3)/z)^4)$	kg	dbh (cm)	ht (m)			49	0.85	981.50624	
PSME	746.202	crown total	$y = 0.41 + (0.0490137 ((x^3)/z)) + (-2.34327E\text{-}006 ((x^3)/z)^2) + (3.10136E\text{-}010((x^3)/z)^3) + (-2.53319E\text{-}014 ((x^3)/z)^4)$	kg	dbh (cm)	ht (m)			6733	0.77	450.33933	
PSME	2226	foliage new	$\ln(y) = \ln(0.68) + 2.74 * \ln(x)$	g	dbh (cm)		5	25	24	0.99	0.1371	no
PSME	2227	foliage new	$\ln(y) = \ln(0.72) + 2.73 * \ln(x)$	g	dbh (cm)		5	25	24	0.99	0.0688	no
PSME	2228	foliage new	$\ln(y) = \ln(3.91) + 2.2 * \ln(x)$	g	dbh (cm)		5	25	24	0.90	0.0483	no
PSME	2229	foliage new	$\ln(y) = \ln(0.37) + 2.98 * \ln(x)$	g	dbh (cm)		5	25	24	0.99	0.0608	no
PSME	2230	foliage old	$\ln(y) = \ln(1.82) + 2.84 * \ln(x)$	g	dbh (cm)		5	25	24	0.99	0.1107	no
PSME	2231	foliage old	$\ln(y) = \ln(2.16) + 2.8 * \ln(x)$	g	dbh (cm)		5	25	24	0.88	0.0732	no
PSME	2232	foliage old	$\ln(y) = \ln(13.08) + 2.24 * \ln(x)$	g	dbh (cm)		5	25	24	0.94	0.0373	no
PSME	2233	foliage old	$\ln(y) = \ln(13.9) + 2.24 * \ln(x)$	g	dbh (cm)		5	25	24	0.83	0.0477	no
PSME	114	foliage total	$\ln(y) = -2.8462 + 1.7009 * \ln(x)$	kg	dbh (cm)		1.8	162	123	0.86	0.483	yes

Table C.1. (Continued)

Spc #	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
PSME 142	foliage total	$\ln(y) = 3.32861 + 2.03097 * \ln(x)$	g	dbh (cm)		1.4	13.4	18	0.94	0.1212	no
PSME 155	foliage total	$y = 0.543 + 0.00082 * (x^2) * z$	kg	dbh (cm)	ht (m)	1	220.7	171	0.8	0.00018	
PSME 210	foliage total	$\ln(y) = -6.0934 + 2.7229 * \ln(x)$	kg	dbh (cm)		16	30	40	0.93	0.0576	yes
PSME 215	foliage total	$\ln(y) = -4.791 + 2.502 * \ln(x)$	kg	dbh (cm)		9	30	26	0.92	0.16	yes
PSME 226	foliage total	$\ln(y) = -4.4698 + 2.3603 * \ln(x)$	kg	dbh (cm)		9	26		0.76	0.0475	yes
PSME 245	foliage total	$y = 10.3 + 3.9 * x^2 * z$	kg	dbh (m)	ht (m)	0.045	0.66	49	0.56	101.6	
PSME 269	foliage total	$y = 11.1 + 6 * x^2 * z$	kg	dbh (m)	ht (m)	0.031	0.632	41	0.4	241.8	
PSME 1500	foliage total	$\ln(y) = -3.0295 + 1.978 * \ln(x) + 0.936 * \ln(z)$	g	dbh (cm)	ht (cm)	8.9	26.1	240	0.76	0.0475	no
PSME 1505	foliage total	$\ln(y) = 8.6918 + 0.711272 * \ln(x)$	g	dbh (cm)		110	190	7	0.60	0.01589	no
PSME 1971	foliage total	$\ln(y) = -4.384 + 1.876 * \ln(x)$	g	ht (cm)		80	220	10	0.77		no
PSME 1976	foliage total	$\ln(y) = -9.381 + 3.005 * \ln(x)$	g	ht (cm)		39	171	16	0.93		no
PSME 1982	foliage total	$\ln(y) = -1.239 + 1.285 * \ln(x)$	kg	dbh (cm)		5	56	10	0.96		no
PSME 1987	foliage total	$\ln(y) = -2.029 + 1.46 * \ln(x)$	kg	dbh (cm)		6	29	8	0.87		no
PSME 1991	foliage total	$\ln(y) = -2.203 + 1.636 * \ln(x)$	kg	dbh (cm)		5	64	43	0.87	0.1325	no
PSME 1995	foliage total	$\ln(y) = -2.515 + 1.76 * \ln(x)$	kg	dbh (cm)		5	35	39	0.85	0.10956	no
PSME 2009	foliage total	$\ln(y) = -2.408 + 1.674 * \ln(x)$	kg	dbh (cm)		11	64	13	0.94	0.06401	no
PSME 2013	foliage total	$\ln(y) = -2.784 + 1.899 * \ln(x)$	kg	dbh (cm)		7	28	17	0.77	0.13396	no
PSME 2061	foliage total	$\ln(y) = -4.151 + 1.982 * \ln(x)$	kg	dbh (cm)		25.9	163	29	0.96	0.176	yes
PSME 2248	foliage total	$y = 0.0423 * x^{1.8619}$	kg	dbh (cm)		5	54	60	0.86	0.246	
PSME 2204	roots <1cm	$y = -2.982E\text{-}006 + 0.00846496 * x$	kg	dbh (mm)		30	50	9	0.04	unk	
PSME 2202	roots >4cm	$y = 8.5234E\text{-}005 * x^2 + -0.0633035 * x$	kg	dbh (mm)		30	50	9	0.8	unk	
PSME 2203	roots 1to4cm	$y = 1.0785E\text{-}005 * x^2 + -0.0051797 * x$	kg	dbh (mm)		30	50	9	0.79	unk	
PSME 119	roots coarse	$\ln(y) = -4.691 + 2.6929 * \ln(x)$	kg	dbh (cm)		2.3	135	26	0.96	0.127	yes
PSME 160	roots coarse	$y = 0.421 + 0.00362 * (x^2) * z$	kg	dbh (cm)	ht (m)	1	220.7	13	0.99	0.00001	
PSME 2082.202	roots coarse	$\ln(y) = -4.352 + 2.579 * \ln(x)$	kg	dbh (cm)		15	50	33	0.90	0.208	yes
PSME 2083.202	roots coarse	$\ln(y) = -4.643 + 2.652 * \ln(x)$	kg	dbh (cm)		51	135	3	0.94	0.2	yes
PSME 2108	roots coarse	$\log10(y) = -2.3807 + 2.9108 * \log10(x)$	kg	dbh (cm)		4	18	14	0.91	unk	no
PSME 2250	roots coarse	$\ln(y) = -3.55 + 2.33 * \ln(x)$	kg	dbh (cm)		21	55	52	0.86	0.05912	yes
PSME 2251	roots coarse	$\ln(y) = -3.98 + 2.48 * \ln(x)$	kg	dbh (cm)		22.0	42.0	23	0.72	0.07844	yes
PSME 2252	roots coarse	$\ln(y) = -4.02 + 2.44 * \ln(x)$	kg	dbh (cm)		21.0	55.0	29	0.94	0.03961	yes
PSME 118	stem bark	$\ln(y) = -4.3103 + 2.43 * \ln(x)$	kg	dbh (cm)		1.8	162	99	0.99	0.104	yes
PSME 158	stem bark	$y = -0.114 + 0.0041 * (x^2) * z$	kg	dbh (cm)	ht (m)	1	220.7	120	0.68	0.00002	
PSME 207	stem bark	$\ln(y) = -5.6097 + 2.7009 * \ln(x)$	kg	dbh (cm)		16	30	40	0.85	0.1156	yes
PSME 213	stem bark	$\ln(y) = -4.906 + 2.53 * \ln(x)$	kg	dbh (cm)		9	30	26	0.94	0.13	yes
PSME 227	stem bark	$y = (e^{(2.18317 + 2.661 * \ln(x))})/1000$	kg	dbh (cm)						unk	unk

Table C.1. (Continued)

Spc #	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
PSME 719	stem bark	y = -0.4 + (0.00285953 * x^2 * z) + (-2.52361E-005 * x^3 * z) + (8.55488E-008 * x^4 * z)	kg	dbh (cm)	ht (m)			49	0.99	80.61167	
PSME 728.202	stem bark	y = 1.38 + (0.00141769 * x^2 * z) + (6.77791E-006 * x^3 * z) + (-8.91979E-008 * x^4 * z)	kg	dbh (cm)	ht (m)		130	6856	0.87	65.24116	
PSME 1511	stem bark	ln(y) = -2.6432 + 1.778 * ln(x) + 0.889 * ln(z)	g	dbh (cm)	ht (cm)	8.9	26.1	240	0.88	0.0174	no
PSME 1517	stem bark	ln(y) = 2.887035 + 2.4785 * ln(x)	g	dbh (cm)		17.0	212.7	215	0.92	0.2087	yes
PSME 1518	stem bark	ln(y) = 1.589661 + 2.7023 * ln(x)	g	dbh (cm)		24.6	206.5	34	0.96	0.16611	yes
PSME 1519	stem bark	ln(y) = 4.275131 + 2.2136 * ln(x)	g	dbh (cm)		31.5	215.0	45	0.84	0.22183	yes
PSME 1520	stem bark	ln(y) = 2.902625 + 2.4818 * ln(x)	g	dbh (cm)		17.2	177.4	116	0.93	0.16021	yes
PSME 1521	stem bark	ln(y) = 4.608186 + 2.0687 * ln(x)	g	dbh (cm)		38.6	161.0	20	0.80	0.10765	yes
PSME 1933	stem bark	y = 0.007908 * x^2 * z	lb	dbh (in)	ht (ft)	1	48	112	0.98	23409.0	
PSME 1969	stem bark	ln(y) = -4.992 + 1.663 * ln(x)	g	ht (cm)		80	220	10	0.75		no
PSME 1974	stem bark	ln(y) = -10.862 + 3 * ln(x)	g	ht (cm)		39	171	16	0.94		no
PSME 1979	stem bark	ln(y) = -6.088 + 2.853 * ln(x)	kg	dbh (cm)		5	56	10	0.97		no
PSME 1984	stem bark	ln(y) = -5.394 + 2.853 * ln(x)	kg	dbh (cm)		6	29	8	0.98		no
PSME 1989	stem bark	ln(y) = -5.456 + 2.659 * ln(x)	kg	dbh (cm)		5	64	46	0.96	0.08821	no
PSME 1993	stem bark	ln(y) = -5.505 + 2.678 * ln(x)	kg	dbh (cm)		5	35	42	0.94	0.09486	no
PSME 2007	stem bark	ln(y) = -5.626 + 2.702 * ln(x)	kg	dbh (cm)		11	64	14	0.97	0.0841	no
PSME 2011	stem bark	ln(y) = -5.598 + 2.696 * ln(x)	kg	dbh (cm)		7	28	17	0.91	0.0906	no
PSME 2058	stem bark	ln(y) = -4.108 + 2.39 * ln(x)	kg	dbh (cm)		25.9	163	29	0.99	0.083	yes
PSME 2214	stem bark	ln(y) = ln(16.31) + 2.3 * ln(x)	g	dbh (cm)		5	25	24	0.99	0.0163	no
PSME 2215	stem bark	ln(y) = ln(27.16) + 2.09 * ln(x)	g	dbh (cm)		5	25	24	0.99	0.0084	no
PSME 2216	stem bark	ln(y) = ln(15.9) + 2.28 * ln(x)	g	dbh (cm)		5	25	24	0.90	0.0203	no
PSME 2217	stem bark	ln(y) = ln(15.23) + 2.28 * ln(x)	g	dbh (cm)		5	25	24	0.94	0.011	no
PSME 241	stem bark (notoplt2.5cm)	y = 3.1 + 15.6 * x^2 * z	kg	dbh (m)	ht (m)	0.045	0.66	49	0.98	87.61	
PSME 265	stem bark (notoplt2.5cm)	y = 3.6 + 18.2 * x^2 * z	kg	dbh (m)	ht (m)	0.031	0.632	41	0.80	823.7	
PSME 117	stem wood	ln(y) = -3.0396 + 2.5951 * ln(x)	kg	dbh (cm)		1.8	162	99	0.99	0.096	yes
PSME 157	stem wood	y = -0.001 + 0.01486 * (x^2) * z	kg	dbh (cm)	ht (m)	1	220.7	120	0.88	0.00002	
PSME 206	stem wood	ln(y) = -4.747 + 2.9674 * ln(x)	kg	dbh (cm)		16	30	40	0.89	0.1024	yes
PSME 212	stem wood	ln(y) = -2.603 + 2.367 * ln(x)	kg	dbh (cm)		9	30	26	0.97	0.08	yes
PSME 701	stem wood	y = -6.87 + (0.0214979 * x^2 * z) + (-0.000327462 * x^3 * z) + (2.61359E-006 * x^4 * z)	kg	dbh (cm)	ht (m)			49	1.00	1221.30679	
PSME 710.202	stem wood	y = -0.8 + (0.0150905 * x^2 * z) + (5.53425E-005 * x^3 * z) + (-3.76558E-006 * x^4 * z)	kg	dbh (cm)	ht (m)	4	55	6856	0.86	2214.74713	
PSME 1536	stem wood	ln(y) = -1.0164 + 1.838 * ln(x) + 0.919 * ln(z)	g	dbh (cm)	ht (cm)	8.9	26.1	240	0.93	0.0065	no
PSME 1542	stem wood	ln(y) = 4.462817 + 2.4153 * ln(x)	g	dbh (cm)		17.0	212.7	215	0.97	0.0655	yes
PSME 1543	stem wood	ln(y) = 3.98298 + 2.5030 * ln(x)	g	dbh (cm)		24.6	206.5	34	0.99	0.04176	yes

Table C.1. (Continued)

Spc #	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
PSME 1544	stem wood	$\ln(y) = 4.032171 + 2.4930 * \ln(x)$	g	dbh (cm)		31.5	215.0	45	0.95	0.06919	yes
PSME 1545	stem wood	$\ln(y) = 4.841987 + 2.3323 * \ln(x)$	g	dbh (cm)		17.2	177.4	116	0.97	0.06125	yes
PSME 1546	stem wood	$\ln(y) = 5.594456 + 2.2145 * \ln(x)$	g	dbh (cm)		38.6	161.0	20	0.93	0.04	yes
PSME 1932	stem wood	$y = 0.044119 * x^2 * z$	lb	dbh (in)	ht (ft)	1	48	112	0.98	857476.0	
PSME 1968	stem wood	$\ln(y) = -6.826 + 2.285 * \ln(x)$	g	ht (cm)		80	220	10	0.92		no
PSME 1973	stem wood	$\ln(y) = -11.195 + 3.232 * \ln(x)$	g	ht (cm)		39	171	16	0.97		no
PSME 1978	stem wood	$\ln(y) = -4.146 + 2.895 * \ln(x)$	kg	dbh (cm)		5	56	10	0.96		no
PSME 1983	stem wood	$\ln(y) = -4.014 + 2.927 * \ln(x)$	kg	dbh (cm)		6	29	8	0.98		no
PSME 1988	stem wood	$\ln(y) = -4.194 + 2.827 * \ln(x)$	kg	dbh (cm)		5	64	46	0.97	0.07236	no
PSME 1992	stem wood	$\ln(y) = -4.291 + 2.866 * \ln(x)$	kg	dbh (cm)		5	35	42	0.96	0.0784	no
PSME 2006	stem wood	$\ln(y) = -4.761 + 3.002 * \ln(x)$	kg	dbh (cm)		11	64	14	0.98	0.06101	no
PSME 2010	stem wood	$\ln(y) = -4.123 + 2.793 * \ln(x)$	kg	dbh (cm)		7	28	17	0.94	0.06452	no
PSME 2057	stem wood	$\ln(y) = -2.656 + 2.53 * \ln(x)$	kg	dbh (cm)		25.9	163	29	0.99	0.088	yes
PSME 2210	stem wood	$\ln(y) = \ln(99.61) + 2.28 * \ln(x)$	g	dbh (cm)		5	25	24	0.99	0.0136	no
PSME 2211	stem wood	$\ln(y) = \ln(101.78) + 2.26 * \ln(x)$	g	dbh (cm)		5	25	24	0.98	0.011	no
PSME 2212	stem wood	$\ln(y) = \ln(80.64) + 2.34 * \ln(x)$	g	dbh (cm)		5	25	24	0.94	0.0108	no
PSME 2213	stem wood	$\ln(y) = \ln(59.41) + 2.44 * \ln(x)$	g	dbh (cm)		5	25	24	0.99	0.0067	no
PSME 240	stem wood (notoplt2.5cm)	$y = 10.3 + 110.4 * x^2 * z$	kg	dbh (m)	ht (m)	0.045	0.66	49	0.99	1270.9	
PSME 264	stem wood (notoplt2.5cm)	$y = 34.5 + 85.8 * x^2 * z$	kg	dbh (m)	ht (m)	0.031	0.632	41	0.8	17675.7	
PSME 159	stem wood plus bark	$y = -0.115 + 0.01896 * (x^2) * z$	kg	dbh (cm)	ht (m)	1	220.7	144	0.74	0.00882	
PSME 205	stem wood plus bark	$\ln(y) = -4.4346 + 2.9216 * \ln(x)$	kg	dbh (cm)		16	30	40	0.89	0.1024	yes
PSME 1525	stem wood plus bark	$\ln(y) = -0.8420 + 1.83 * \ln(x) + 0.915 * \ln(z)$	g	dbh (cm)	ht (cm)	8.9	26.1	240	0.96	0.0059	no
PSME 1530	stem wood plus bark	$\ln(y) = 4.660412 + 2.4247 * \ln(x)$	g	dbh (cm)		17.0	212.7	215	0.973	0.0583	yes
PSME 1531	stem wood plus bark	$\ln(y) = 4.073402 + 2.5277 * \ln(x)$	g	dbh (cm)		24.6	206.5	34	0.99	0.03175	yes
PSME 1532	stem wood plus bark	$\ln(y) = 4.598476 + 2.4367 * \ln(x)$	g	dbh (cm)		31.5	215.0	45	0.96	0.06086	yes
PSME 1533	stem wood plus bark	$\ln(y) = 4.96253 + 2.3602 * \ln(x)$	g	dbh (cm)		17.2	177.4	116	0.97	0.0592	yes
PSME 1534	stem wood plus bark	$\ln(y) = 5.877232 + 2.1901 * \ln(x)$	g	dbh (cm)		38.6	161.0	20	0.94	0.03273	yes
PSME 2052.202	stump (10cm)	$y = ((x/(100 - 1.77)) 100) - x$	kg	abovestump (10cm) stem wood plus bark (kg)							
PSME 2053.202	stump (15cm)	$y = ((x/(100 - 2.61)) 100) - x$	kg	abovestump (15cm) stem wood plus bark (kg)							
PSME 2234	twigs live	$\ln(y) = \ln(0.29) + 2.51 * \ln(x)$	g	dbh (cm)		5	25	24	0.99	0.1439	no
PSME 2235	twigs live	$\ln(y) = \ln(0.15) + 2.79 * \ln(x)$	g	dbh (cm)		5	25	24	0.78	0.2639	no

Table C.1. (Continued)

Spc	#	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
PSME	2236	twigs live	ln(y) = ln(0.98) + 2.12 * ln(x)	g	dbh (cm)		5	25	24	0.90	0.0732	no
PSME	2237	twigs live	ln(y) = ln(0.41) + 2.44 * ln(x)	g	dbh (cm)		5	25	24	0.86	0.0704	no
TSHE	168	aboveground total	y = 0.497 + 0.02113 * (x^2) * z	kg	dbh (cm)	ht (m)	0.2	118	47	0.88	0.00012	
TSHE	287	aboveground total	y = 29.8 + 155.8 * x^2 * z	kg	dbh (m)	ht (m)	0.031	0.705	70	0.98	3570.1	
TSHE	1963	aboveground total	y = 0.071955 * x^2 * z	lb	dbh (in)	ht (ft)	1	36	89	0.98	599076.0	
TSHE	2089.263	aboveground total	ln(y) = -2.5384 + 2.4814 * ln(x)	kg	dbh (cm)		1	210			0.03324	no
TSHE	1962	abovestump (30cm) stem bark	log10(y) = 3.06 + 1.197 * log10(((x/2)^2) * 3.14)	kg	dbh (cm)		0.16	0.49	8	0.94	unk	unk
TSHE	1961	abovestump (30cm) stem wood	log10(y) = 2.112 + 0.87 * log10(x^2 * z)	kg	dbh (m)	ht (m)	0.16	0.49	8	0.99	unk	unk
TSHE	2240	abovestump (30cm) stem wood	log10(y) = 3.455 + 2.12 * log10(x)	kg	dbh (m)		16	49	8	0.98	unk	no
TSHE	1951	abovestump (30cm) total	y = 79.458 + 136.626 * (x^2) * z	kg	dbh (m)	ht (m)	0.1524	1.27	8	0.96	unk	
TSHE	1952	abovestump (30cm) total	log10(y) = 2.304 + 0.845 * log10(x^2 * z)	kg	dbh (m)	ht (m)	0.1524	1.27	8	0.99	unk	unk
TSHE	2239	abovestump (30cm) total	log10(y) = 3.68 + 2.135 * log10(x)	kg	dbh (m)		16	49	8	0.97	unk	no
TSHE	122	branch dead	ln(y) = -2.409 + 1.312 * ln(x)	kg	dbh (cm)		15.3	78	18	0.62	0.641	yes
TSHE	286	branch dead	y = 3.5 + 0.8 * x^2 * z	kg	dbh (m)	ht (m)	0.031	0.705	70	0.18		
TSHE	1793	branch dead	ln(y) = -0.65124 + 2.805 * ln(x)	g	dbh (cm)		9.9	47.8	21	0.93	0.134	no
TSHE	1794	branch dead	ln(y) = -0.17724 + 2.805 * ln(x)	g	dbh (cm)		9.9	47.8	21	0.93	0.134	no
TSHE	1953	branch large (gt2.5cm) total	log10(y) = 0.825 + 1.57 * log10(x^2 * z)	kg	dbh (m)	ht (m)	0.1524	1.27	8	0.77	unk	unk
TSHE	1957	branch large (gt2.5cm) total	log10(y) = 3.27 + 3.868 * log10(x)	kg	dbh (m)		0.16	0.49	8	0.78	unk	unk
TSHE	121	branch live	ln(y) = -5.149 + 2.778 * ln(x)	kg	dbh (cm)		15.3	78	18	0.98	0.177	yes
TSHE	125	branch live	ln(y) = -5.0317 + 2.616 * ln(x)	kg	dbh (cm)		2.1	13.4	9	0.97	0.022	yes
TSHE	230	branch live	y = 0.047 + 0.00413 * x^2 * z	kg	dbh (cm)	ht (m)					unk	
TSHE	1797	branch live	y = e^(-4.57 + (2.271 * ln(x))) + e^(-6.611 + (2.431 * ln(x)))	kg	dbh (cm)		9.9	47.8	21	0.89	0.139	no
TSHE	1798	branch live	y = e^(-4.876 + (2.271 * ln(x))) + e^(-6.611 + (2.431 * ln(x)))	kg	dbh (cm)		9.9	47.8	21	0.89	0.139	no
TSHE	282	branch live large (gt2.5cm)	y = 1 + 5.8 * x^2 * z	kg	dbh (m)	ht (m)	0.031	0.705	70	0.67	118.81	
TSHE	283	branch live med (0.5to2.5cm) plus top	y = 8.2 + 3.9 * x^2 * z	kg	dbh (m)	ht (m)	0.031	0.705	70	0.55	86.3041	
TSHE	284	branch live small (lt0.5cm) plus top	y = 4.2 + 2.5 * x^2 * z	kg	dbh (m)	ht (m)	0.031	0.705	70	0.52	35.49	
TSHE	1954	branch med (0.64to2.5cm) total	log10(y) = 1.427 + 0.62 * log10(x^2 * z)	kg	dbh (m)	ht (m)	0.1524	1.27	8	0.9	unk	unk
TSHE	1958	branch med (0.64to2.5cm) total	log10(y) = 2.366 + 1.477 * log10(x)	kg	dbh (m)		0.1524	1.27	8	0.85	unk	unk
TSHE	1955	branch small (lt0.64cm) plus foliage total	log10(y) = 0.125 + 0.774 * log10(x^2 * z)	kg	dbh (m)	ht (m)	0.1524	1.27	8	0.92	unk	unk
TSHE	1959	branch small (lt0.64cm) plus foliage total	log10(y) = 2.42 + 1.837 * log10(x)	kg	dbh (m)		0.1524	1.27	8	0.86	unk	unk
TSHE	170	branch total	y = 0.047 + 0.00413 * (x^2) * z	kg	dbh (cm)	ht (m)	0.2	118	74	0.98	0.00018	
TSHE	203	crown dead	ln(y) = -5.4241 + 2.2577 * ln(x)	kg	dbh (cm)		14	140	29	0.73	0.24	unk

Table C.1. (Continued)

Spc	#	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
TSHE	194	crown live	ln(y) = 0.3157 + 1.907 * ln(x)	lb	dbh (in)		1	47	58	0.94	38416.0	yes
TSHE	195	crown live	ln(y) = 4.577 + 3.228 * ln(x) + -1.76 * ln(z)	lb	dbh (in)	ht (ft)	1	47	32	0.97	17344.89	yes
TSHE	201	crown live	ln(y) = 3.8886 + 0.0338 * x	kg	dbh (cm)		14	140	29	0.82	0.13	unk
TSHE	742	crown total	y = -1.75 + (0.0783124 ((x^3)/z)) + (-1.79677E-005 ((x^3)/z)^2) + (5.20382E-009((x^3)/z)^3) + (-4.3442E-013 ((x^3)/z)^4)	kg	dbh (cm)	ht (m)			70	0.85	1114.92549	
TSHE	746.263	crown total	y = 0.41 + (0.0490137 ((x^3)/z)) + (-2.34327E-006 ((x^3)/z)^2) + (3.10136E-010((x^3)/z)^3) + (-2.53319E-014 ((x^3)/z)^4)	kg	dbh (cm)	ht (m)			6733	0.77	450.33933	
TSHE	120	foliage total	ln(y) = -4.13 + 2.218 * ln(x)	kg	dbh (cm)		15.3	78	18	0.96	0.189	yes
TSHE	124	foliage total	ln(y) = -4.4351 + 2.3886 * ln(x)	kg	dbh (cm)		2.1	13.4	9	0.96	0.103	yes
TSHE	169	foliage total	y = 0.113 + 0.00421 * (x^2) * z	kg	dbh (cm)	ht (m)	0.2	118	66	0.99	0.00031	
TSHE	285	foliage total	y = 8 + 4.3 * x^2 * z	kg	dbh (m)	ht (m)	0.031	0.705	70	0.57	73.96	
TSHE	1815	foliage total	ln(y) = 0.38376 + 2.659 * ln(x)	g	dbh (cm)		9.9	47.8	21	0.91	0.157	no
TSHE	1956	foliage total	log10(y) = 0.951 + 1.022 * log10(x^2 * z)	kg	dbh (m)	ht (m)	0.1524	1.27	8	0.92	unk	unk
TSHE	2242	foliage total	log10(y) = 2.508 + 2.454 * log10(x)	kg	dbh (m)		16	49	8	0.89	unk	no
TSHE	2020.263	roots coarse	ln(y) = -4.691 + 2.6929 * ln(x)	kg	dbh (cm)		2.3	135	26	0.96	0.127	yes
TSHE	2082.263	roots coarse	ln(y) = -4.352 + 2.579 * ln(x)	kg	dbh (cm)		15	50	33	0.9	0.208	yes
TSHE	2083.263	roots coarse	ln(y) = -4.643 + 2.652 * ln(x)	kg	dbh (cm)		51	135	3	0.94	0.2	yes
TSHE	127	stem bark	ln(y) = -4.373 + 2.258 * ln(x)	kg	dbh (cm)		15.3	78	18	0.99	0.019	yes
TSHE	172	stem bark	y = -0.025 + 0.00134 * (x^2) * z	kg	dbh (cm)	ht (m)	0.2	118	37	0.73	0.00221	
TSHE	724	stem bark	y = 3.71 + (-0.00265814 * x^2 * z) + (0.000220228 * x^3 * z) + (-2.32018E-006 * x^4 * z)	kg	dbh (cm)	ht (m)			70	0.99	56.71295	
TSHE	728.263	stem bark	y = 1.38 + (0.00141769 * x^2 * z) + (6.77791E-006 * x^3 * z) + (-8.91979E-008 * x^4 * z)	kg	dbh (cm)	ht (m)			6856	0.87	65.24116	
TSHE	1821	stem bark	ln(y) = 2.53676 + 2.259 * ln(x)	g	dbh (cm)		9.9	47.8	19	0.97	0.035	no
TSHE	1822	stem bark	ln(y) = 3.383997 + 2.0831 * ln(x)	g	dbh (cm)		19.3	121.6	41	0.94	0.06745	yes
TSHE	1823	stem bark	ln(y) = 5.418532 + 1.5855 * ln(x)	g	dbh (cm)		27.5	73.4	31	0.59	0.11352	yes
TSHE	1824	stem bark	ln(y) = 3.559969 + 2.0166 * ln(x)	g	dbh (cm)		19.6	172.3	47	0.90	0.11484	yes
TSHE	1825	stem bark	ln(y) = 5.616217 + 1.3129 * ln(x)	g	dbh (cm)		25.6	45.7	25	0.29	0.10822	yes
TSHE	1828	stem bark	ln(y) = 0.787286 + 2.7876 * ln(x)	g	dbh (cm)		15.3	134.7	21	0.96	0.11465	yes
TSHE	1830	stem bark	ln(y) = 2.450465 + 2.4109 * ln(x)	g	dbh (cm)		8.9	134.7	207	0.84	0.3121	yes
TSHE	1831	stem bark	ln(y) = 2.562767 + 2.3623 * ln(x)	g	dbh (cm)		8.9	113.3	80	0.87	0.24886	yes
TSHE	1832	stem bark	ln(y) = 2.766209 + 2.3474 * ln(x)	g	dbh (cm)		14.4	114.8	91	0.78	0.43634	yes
TSHE	1833	stem bark	ln(y) = 0.779614 + 2.8795 * ln(x)	g	dbh (cm)		24.7	56.0	15	0.86	0.0597	yes
TSHE	1965	stem bark	y = 0.008406 * x^2 * z	lb	dbh (in)	ht (ft)	1	36	89	0.93	34225.0	
TSHE	281	stem bark (notoplt2.5cm)	y = 3 + 16 * x^2 * z	kg	dbh (m)	ht (m)	0.031	0.705	70	0.92	203.3	

Table C.1. (Continued)

Spc	#	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
TSHE	123	stem wood	$\ln(y) = -2.172 + 2.257 * \ln(x)$	kg	dbh (cm)		15.3	78	18	0.99	0.014	yes
TSHE	171	stem wood	$y = 0.362 + 0.01145 * (x^2) * z$	kg	dbh (cm)	ht (m)	0.2	118	37	0.98	0.00001	
TSHE	706	stem wood	$y = 4.56 + (0.00686442 * x^2 * z) + (0.000327054 * x^3 * z) + (-3.59338E\text{-}006 * x^4 * z)$	kg	dbh (cm)	ht (m)			70	1	883.60535	
TSHE	710.263	stem wood	$y = -0.8 + (0.0150905 * x^2 * z) + (5.53425E\text{-}005 * x^3 * z) + (-3.76558E\text{-}006 * x^4 * z)$	kg	dbh (cm)	ht (m)			6856	0.86	2214.74713	
TSHE	1849	stem wood	$\ln(y) = 4.2268 + 2.447 * \ln(x)$	g	dbh (cm)		9.9	47.8	19	0.98	0.032	no
TSHE	1850	stem wood	$\ln(y) = 4.438266 + 2.4215 * \ln(x)$	g	dbh (cm)		19.3	121.6	41	0.98	0.02721	yes
TSHE	1851	stem wood	$\ln(y) = 3.544438 + 2.1130 * \ln(x)$	g	dbh (cm)		27.5	73.4	31	0.88	0.03764	yes
TSHE	1852	stem wood	$\ln(y) = 4.523059 + 2.4222 * \ln(x)$	g	dbh (cm)		19.6	172.3	47	0.96	0.06319	yes
TSHE	1853	stem wood	$\ln(y) = 6.063223 + 1.9237 * \ln(x)$	g	dbh (cm)		25.6	45.7	25	0.85	0.01713	yes
TSHE	1856	stem wood	$\ln(y) = 3.412996 + 2.6648 * \ln(x)$	g	dbh (cm)		15.3	134.7	21	0.98	0.06784	yes
TSHE	1858	stem wood	$\ln(y) = 3.756174 + 2.6253 * \ln(x)$	g	dbh (cm)		8.9	134.7	207	0.95	0.1097	yes
TSHE	1859	stem wood	$\ln(y) = 3.23288 + 2.7429 * \ln(x)$	g	dbh (cm)		8.9	113.3	80	0.88	0.05795	yes
TSHE	1860	stem wood	$\ln(y) = 4.176308 + 2.5353 * \ln(x)$	g	dbh (cm)		14.4	114.8	91	0.92	0.15577	yes
TSHE	1861	stem wood	$\ln(y) = 2.278515 + 3.0358 * \ln(x)$	g	dbh (cm)		24.7	56.0	15	0.91	0.04254	yes
TSHE	1964	stem wood	$y = 0.056537 * x^2 * z$	lb	dbh (in)	ht (ft)	1	36	89	0.99	190096.0	
TSHE	280	stem wood (notoplt2.5cm)	$y = 5.5 + 123.3 * x^2 * z$	kg	dbh (m)	ht (m)	0.031	0.705	70	0.99	1081.1	
TSHE	126	stem wood plus bark	$\ln(y) = -2.0849 + 2.3275 * \ln(x)$	kg	dbh (cm)		2.1	13.4	9	0.99	0.011	yes
TSHE	173	stem wood plus bark	$y = 0.337 + 0.01279 * (x^2) * z$	kg	dbh (cm)	ht (m)	0.2	118	37	0.97	0.00002	
TSHE	1835	stem wood plus bark	$\ln(y) = 4.635161 + 2.3938 * \ln(x)$	g	dbh (cm)		19.3	121.6	41	0.98	0.02662	yes
TSHE	1836	stem wood plus bark	$\ln(y) = 6.096668 + 2.0696 * \ln(x)$	g	dbh (cm)		27.5	73.4	31	0.88	0.03843	yes
TSHE	1837	stem wood plus bark	$\ln(y) = 4.740136 + 2.3863 * \ln(x)$	g	dbh (cm)		19.6	172.3	47	0.96	0.05581	yes
TSHE	1838	stem wood plus bark	$\ln(y) = 6.308001 + 1.8743 * \ln(x)$	g	dbh (cm)		25.6	45.7	25	0.84	0.01693	yes
TSHE	1843	stem wood plus bark	$\ln(y) = 3.483012 + 2.6741 * \ln(x)$	g	dbh (cm)		15.3	134.7	21	0.98	0.06339	yes
TSHE	1844	stem wood plus bark	$\ln(y) = 3.968674 + 2.5989 * \ln(x)$	g	dbh (cm)		8.9	134.7	207	0.94	0.1158	yes
TSHE	1845	stem wood plus bark	$\ln(y) = 3.526139 + 2.7017 * \ln(x)$	g	dbh (cm)		8.9	113.3	80	0.98	0.05854	yes
TSHE	1846	stem wood plus bark	$\ln(y) = 4.386886 + 2.5095 * \ln(x)$	g	dbh (cm)		14.4	114.8	91	0.91	0.17236	yes
TSHE	1847	stem wood plus bark	$\ln(y) = 2.45444 + 3.0203 * \ln(x)$	g	dbh (cm)		24.7	56.0	15	0.92	0.03745	yes
TSHE	2018.263	stump (30cm)	$y = ((x/(100 - 5.36)) 100) - x$	kg	abovestump (30cm) stem wood plus bark (kg)				592			
TSHE	2019.263	stump (30cm)	$y = ((x/(100 - 5.03)) 100) - x$	kg	abovestump (30cm) stem wood plus bark (kg)				218			
ACMA	2085	aboveground total	$\ln(y) = -1.9123 + 2.3651 * \ln(x)$	kg	dbh (cm)		1	66			0.24175	no

Table C.1. (Continued)

Spc	#	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
ACMA	78	branch dead	ln(y) = -2.116 + 1.092 * ln(x)	kg	dbh (cm)		7.60	35.3	18	0.15	1.862	yes
ACMA	691	branch dead	ln(y) = -6.4918 + 2.5033 * ln(x)	kg	dbh (cm)		5.08	45.72	16	0.78	0.7131	no
ACMA	77	branch live	ln(y) = -4.236 + 2.43 * ln(x)	kg	dbh (cm)		7.60	35.3	18	0.88	0.225	yes
ACMA	686	crown live	ln(y) = -2.8534 + 2.1505 * ln(x)	kg	dbh (cm)		5.08	45.72	16	0.93	0.1495	no
ACMA	76	foliage total	ln(y) = -3.765 + 1.617 * ln(x)	kg	dbh (cm)		7.60	35.3	18	0.87	0.101	yes
ACMA	2020.312	roots coarse	ln(y) = -4.691 + 2.6929 * ln(x)	kg	dbh (cm)		2.3	135	26	0.96	0.127	yes
ACMA	2082.312	roots coarse	ln(y) = -4.352 + 2.579 * ln(x)	kg	dbh (cm)		15	50	33	0.9	0.208	yes
ACMA	2083.312	roots coarse	ln(y) = -4.643 + 2.652 * ln(x)	kg	dbh (cm)		51	135	3	0.94	0.2	yes
ACMA	2092.312	roots coarse	ln(y) = -4.1303 + 2.6099 * ln(x)	kg	dbh (cm)		2.4	22.7	16	0.99		unk
ACMA	2109.312	roots coarse	log10(y) = -1.9837 + 1.9463 * log10(x)	kg	dbh (cm)				7	0.99	unk	no
ACMA	2110.312	roots coarse	log10(y) = -1.1453 + 2.1478 * log10(x)	kg	dbh (cm)				14	0.99	unk	no
ACMA	2111	roots coarse	log10(y) = -1.2632 + 2.2006 * log10(x)	kg	dbh (cm)				14	0.99	unk	no
ACMA	2112	roots coarse	log10(y) = -0.9691 + 1.7992 * log10(x)	kg	dbh (cm)				15	0.93	unk	no
ACMA	2113.312	roots coarse	log10(y) = -1.4 + 2.3156 * log10(x)	kg	dbh (cm)				14	0.98	unk	no
ACMA	2114.312	roots coarse	log10(y) = -1.3244 + 2.3547 * log10(x)	kg	dbh (cm)				3	0.98	unk	no
ACMA	2120.312	roots coarse	log10(y) = -1.8274 + 0.9308 * log10(x^2 * z)	kg	dbh (cm)	ht (m)			3	1.00	unk	no
ACMA	2121.312	roots coarse	log10(y) = -1.0003 + 0.6816 * log10(x^2 * z)	kg	dbh (cm)	ht (m)			7	0.97	unk	no
ACMA	2122.312	roots coarse	log10(y) = -2.8434 + 1.104 * log10(x^2 * z)	kg	dbh (cm)	ht (m)	12	64	3	1	unk	no
ACMA	2249.312	roots total	ln(y) = -0.8911 + 1.9428 * ln(x)	kg	dbh (cm)		2.5	60	10	0.93	unk	no
ACMA	80	stem bark	ln(y) = -4.574 + 2.574 * ln(x)	kg	dbh (cm)		7.60	35.3	18	0.98	0.058	yes
ACMA	79	stem wood	ln(y) = -3.493 + 2.723 * ln(x)	kg	dbh (cm)		7.60	35.3	18	0.99	0.014	yes
ALRU	295	aboveground total	y = 4.8 + 195.5 * x^2 z	kg	dbh (m)	ht (m)	0.058	0.348	40	0.94	86.8624	
ALRU	1904	aboveground total	y = 0.4 (1942.91 + (93.4572 * x^2 * z))	g	dbh (in)	ht (ft)	0.118	5.866	230	0.86	unk	
ALRU	1909	aboveground total	y = 0.4 ((1634.34 + (428724 * ((x/2)^2 * 3.14)))/1000)	g	dbh (cm)		0.3	14.9	230	0.81	unk	
ALRU	1912	aboveground total	y = 0.02 + (2.09 ((x^2 * z)/100)) + (-0.0015 ((x^2 * z)/100)^2)	kg	dbh (cm)	ht(m)	1.25	152.5	119	0.98	unk	
ALRU	2084	aboveground total	ln(y) = -2.2094 + 2.3867 * ln(x)	kg	dbh (cm)		1	70			0.2575	no
ALRU	82	aboveground wood plus bark	y = 0.02 + 2.09 * (x^2 * z/100) + -0.00015 * (x^2 * z/100)^2	kg	dbh (cm)	ht (m)	5	300	119	0.98	unk	
ALRU	140	abovestump (15cm) stem wood plus bark	ln(y) = 4.71633 + 2.09759 * ln(x)	g	dbh (cm)		1.7	13.2	18	0.96	0.06477	no
ALRU	141	abovestump (15cm) total	ln(y) = 5.13118 + 2.15046 * ln(x)	g	dbh (cm)		1.7	13.2	18	0.95	0.08717	no
ALRU	294	branch dead	y = -0.6 + 8.5 * x^2 * z	kg	dbh (m)	ht (m)	0.06	0.348	40	0.87		
ALRU	689	branch dead	ln(y) = -7.6156 + 2.6243 * ln(x)	kg	dbh (cm)		2.54	63.5	53	0.63	2.7976	unk
ALRU	866	branch dead	ln(y) = -6.014345 + 4.3225 * ln(x)	g	dbh (cm)		9.1	39.6	10	0.72	1.78974	no
ALRU	236	branch live	y = e^(-4.5648 + (2.6232 * ln(x))) - ((1/(2.7638 + (0.062 * x^1.3364))) * e^(-4.5648 + (2.6232 * ln(x))))	kg	dbh (cm)						unk	unk

Table C.1. (Continued)

Spc	#	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
ALRU	867	branch live	ln(y) = 2.20 + 2.70 * ln(x)	g	dbh (cm)		6.0	20.0	12	0.91	0.1183	unk
ALRU	871	branch live	ln(y) = -0.911945 + 3.4886 * ln(x)	g	dbh (cm)		9.1	39.6	10	0.92	0.26384	no
ALRU	889	branch live	ln(y) = 4.238755 + 2.4618 * ln(x)	g	dbh (cm)		9.1	39.6	10	0.99	0.02321	no
ALRU	290	branch live large (gt10cm)	y = 1.2 + 8.1 * x^2 * z	kg	dbh (m)	ht (m)	0.06	0.348	40	0.42	15.8404	
ALRU	291	branch live med (6to10cm)	y = 5.9 + 15.1 * x^2 * z	kg	dbh (m)	ht (m)	0.06	0.348	40	0.26	16.4836	
ALRU	292	branch live small (2to6cm) plus top	y = 1 + 3 * x^2 * z	kg	dbh (m)	ht (m)	0.06	0.348	40	0.49	0.67	
ALRU	139	branch total	ln(y) = 3.41463 + 2.38276 * ln(x)	g	dbh (cm)		1.7	13.2	18	0.91	0.21234	no
ALRU	1908	branch total	y = (251.325 + 98022.2 ((x/2)^2 * 3.14))/1000	g	dbh (cm)		0.3	14.9	230	0.7	unk	
ALRU	684	crown live	ln(y) = -4.5648 + 2.6232 * ln(x)	kg	dbh (cm)		2.54	63.5	53	0.94	0.3202	no
ALRU	745	crown total	y = 5.7 + (-0.0209476 ((x^3)/z)) + (0.000326784 ((x^3)/z)^2) + (-3.30112E-007((x^3)/z)^3) + (8.93569E-011 ((x^3)/z)^4)	kg	dbh (cm)	ht (m)			41	0.87	47.40873	
ALRU	747.351	crown total	y = -0.19 + (0.0582004 ((x^3)/z)) + (3.97768E-006 ((x^3)/z)^2) + (-5.45215E-010((x^3)/z)^3) + (1.32978E-014 ((x^3)/z)^4)	kg	dbh (cm)	ht (m)			3743	0.73	2031.41307	
ALRU	1910	crown total	y = 0.01 + (0.48 ((x^2 * z)/100)) + (-0.0009 ((x^2 * z)/100)^2)	kg	dbh (cm)	ht(m)	1.25	152.5	91	0.75	unk	
ALRU	84	foliage total	y = 0.5124 + 0.1298 * ((x^2 * z)/100)	kg	dbh (cm)	ht (m)	1.3	40.8	66	0.64	0.545	
ALRU	138	foliage total	ln(y) = 3.39718 + 1.93319 * ln(x)	g	dbh (cm)		1.7	13.2	18	0.93	0.10864	no
ALRU	293	foliage total	y = 2.5 + 4 * x^2 * z	kg	dbh (m)	ht (m)	0.06	0.348	40	0.37	2.7556	
ALRU	875	foliage total	ln(y) = 3.20 + 1.89 * ln(x)	g	dbh (cm)		6.0	20.0	10	0.85	0.1096	unk
ALRU	880	foliage total	ln(y) = -2.4473 + 3.2434 * ln(x)	g	dbh (cm)		9.1	39.6	10	0.96	0.1023	no
ALRU	1906	foliage total	y = (454.086 + 53578 ((x/2)^2 * 3.14))/1000	g	dbh (cm)		0.3	14.9	230	0.52	unk	
ALRU	83	roots coarse	y = 0.1 + 0.48 * (x^2 * z/100) + -0.0005 * (x^2 * z/100)^2	kg	dbh (cm)	ht (m)	5	300	28		unk	
ALRU	1913	roots coarse	y = 0.01 + (0.48 ((x^2 * z)/100)) + (-0.0005 ((x^2 * z)/100)^2)	kg	dbh (cm)	ht(m)	1.25	152.5	est	est	unk	
ALRU	2020.351	roots coarse	ln(y) = -4.691 + 2.6929 * ln(x)	kg	dbh (cm)		2.3	135	26	0.96	0.127	yes
ALRU	2082.351	roots coarse	ln(y) = -4.352 + 2.579 * ln(x)	kg	dbh (cm)		15	50	33	0.9	0.208	yes
ALRU	2083.351	roots coarse	ln(y) = -4.643 + 2.652 * ln(x)	kg	dbh (cm)		51	135	3	0.94	0.2	yes
ALRU	2092.351	roots coarse	ln(y) = -4.1303 + 2.6099 * ln(x)	kg	dbh (cm)		2.4	22.7	16	0.99		unk
ALRU	2109.351	roots coarse	log10(y) = -1.9837 + 1.9463 * log10(x)	kg	dbh (cm)				7	0.99	unk	no
ALRU	2110.351	roots coarse	log10(y) = -1.1453 + 2.1478 * log10(x)	kg	dbh (cm)				14	0.99	unk	no
ALRU	2113.351	roots coarse	log10(y) = -1.4 + 2.3156 * log10(x)	kg	dbh (cm)				14	0.98	unk	no
ALRU	2114.351	roots coarse	log10(y) = -1.3244 + 2.3547 * log10(x)	kg	dbh (cm)				3	0.98	unk	no
ALRU	2120.351	roots coarse	log10(y) = -1.8274 + 0.9308 * log10(x^2 * z)	kg	dbh (cm)	ht (m)			3	1.00	unk	no
ALRU	2121.351	roots coarse	log10(y) = -1.0003 + 0.6816 * log10(x^2 * z)	kg	dbh (cm)	ht (m)			7	0.97	unk	no

Table C.1. (Continued)

Spc	#	Component	Equation	y	x	z	low x	high x	n	Rsqr	MSE	CF?
ALRU	2122.351	roots coarse	$\log 10(y) = -2.8434 + 1.104 * \log 10(x^2 * z)$	kg	dbh (cm)	ht (m)	12	64	3	1.00	unk	no
ALRU	2249.351	roots total	$\ln(y) = -0.8911 + 1.9428 * \ln(x)$	kg	dbh (cm)		2.5	60	10	0.93	unk	no
ALRU	235	stem bark	$y = e^{\wedge}(-4.6424 + 2.4617 * \ln(x))$	kg	dbh (cm)						unk	unk
ALRU	727	stem bark	$y = -0.03 + (0.00112859 * x^2 * z) + (5.68821E\text{-}005 * x^3 * z) + (-4.5796E\text{-}007 * x^4 * z)$	kg	dbh (cm)	ht (m)			41	0.99	1.51832	
ALRU	729.351	stem bark	$y = 0.34 + (0.00360306 * x^2 * z) + (-4.89182E\text{-}005 * x^3 * z) + (3.06466E\text{-}007 * x^4 * z)$	kg	dbh (cm)	ht (m)			3746	0.84	110.77984	
ALRU	883	stem bark	$\ln(y) = 2.265355 + 2.4617 * \ln(x)$	g	dbh (cm)		9.1	39.6	10	0.99	0.02321	no
ALRU	289	stem bark (notoplt2.5cm)	$y = -1.2 + 27.6 * x^2 * z$	kg	dbh (m)	ht (m)	0.06	0.348	40	0.94	1.1025	
ALRU	709	stem wood	$y = -0.82 + (0.0143242 * x^2 * z) + (-2.10993E\text{-}006 * x^3 * z) + (2.21776E\text{-}006 * x^4 * z)$	kg	dbh (cm)	ht (m)			40	1.00	16.47223	
ALRU	711.351	stem wood	$y = -2.46 + (0.0156714 * x^2 * z) + (0.000181728 * x^3 * z) + (-5.66014E\text{-}006 * x^4 * z)$	kg	dbh (cm)	ht (m)			3750	0.85	3591.89257	
ALRU	288	stem wood (notoplt2.5cm)	$y = -4.6 + 137.7 * x^2 * z$	kg	dbh (m)	ht (m)	0.06	0.348	40	0.98	12.0409	
ALRU	81	stem wood plus bark	$y = 0.02 + 1.6 * (x^2 * z/100) + -0.0005 * (x^2 * z/100)^2$	kg	dbh (cm)	ht (m)	5	300	91	0.99	unk	
ALRU	884	stem wood plus bark	$\ln(y) = 3.97 + 2.56 * \ln(x)$	g	dbh (cm)		6.0	20.0	12	0.98	0.0128	unk
ALRU	1907	stem wood plus bark	$y = (933.984 + 277680 ((x/2)^2 * 3.14))/1000$	g	dbh (cm)		0.3	14.9	230	0.78	unk	
ALRU	1911	stem wood plus bark	$y = 0.02 + (4.6 ((x^2 * z)/100)) + (-0.0005 ((x^2 * z)/100)^2)$	kg	dbh (cm)	ht(m)	1.25	152.5	91	0.99	unk	
ALRU	2053.351	stump (15cm)	$y = ((x/(100 - 2.61)) 100) - x$	kg	abovestump (15cm) stem wood plus bark (kg)							

Table C.2. Biomass equation metadata, all species. Equations used by the FIA appear with a gray background. Spc is the species code (the first two letters of the code are the first two letters of the genus name, the second two are the first two letters of the species name, i.e. *Picea sitchensis* is PISI). The references to BIOPAK is Means et al. (1994). Multiple sources indicates the some form of the equation appeared in each author or database.

#	Source	Area	Notes
61	BIOPAK #464, Bormann 1990	southeast AK	
62	BIOPAK #465, Bormann 1990, Harmon 1996	southeast AK, mature	BT Bormann, Forest Science Dept OSU
63	Bormann 1990	southeast AK	
76	BIOPAK #31; Gholz et al. 1979; Grier & Logan 1977	west of Cascades, old-growth	
77	BIOPAK #32; Gholz et al. 1979; Grier & Logan 1977; Harmon 1996	west of Cascades, old-growth	
78	BIOPAK #33; Gholz et al. 1979; Grier & Logan 1977; Harmon 1996	west of Cascades, old-growth	
79	BIOPAK #34; Gholz et al. 1979; Grier & Logan 1977; Harmon 1996	west of Cascades, old-growth	
80	BIOPAK #35; Gholz et al. 1979; Grier & Logan 1977; Harmon 1996	west of Cascades, old-growth	
81	BIOPAK #36, Gholz et al. 1979	Coast Range, young	
82	BIOPAK #37; Gholz et al. 1979	Coast Range, young	
83	BIOPAK #38, Gholz et al. 1979	Coast Range, young	BIOPAK says only for live roots
84	BIOPAK #39, Gholz et al. 1979	Coast Range, young	
114	BIOPAK #1, Gholz et al. 1979, Harmon 1996		
115	BIOPAK #2, Gholz et al. 1979, Harmon 1996	West of Cascades, G	
116	BIOPAK #3, Gholz et al. 1979, Harmon 1996	west of Cascades, combo or unknown	
117	BIOPAK #4, Gholz et al. 1979		
118	BIOPAK #5, Gholz et al. 1979		
119	BIOPAK #6, Gholz et al. 1979, Harmon et al. 1996		
120	BIOPAK #8, Grier & Logan 1977, Gholz et al. 1979, Harmon 1996	west of Cascades, old-growth	
121	BIOPAK #9, Gholz et al. 1979; Grier & Logan 1977, Harmon 1996	west of Cascades, old-growth	
122	BIOPAK #10, Gholz et al. 1979; Grier & Logan 1977	west of Cascades, old-growth	
123	BIOPAK #11, Grier & Logan 1977, Gholz et al. 1979	west of Cascades, old-growth	
124	BIOPAK #128, Gholz et al. 1979	Otis, OR 49m elevation	small trees only
125	BIOPAK # 129, Gholz et al. 1979	Otis, OR 49m elevation	small trees only
126	BIOPAK #130, Gholz et al. 1979	Otis, OR 49m elevation	small trees only
127	BIOPAK #12, Grier & Logan 1977, Gholz et al. 1979	west of Cascades, old-growth	
138	BIOPAK #280, Helgerson et al. 1988	Coast Range, young	stump 15 cm tall; trees about 16 years old
139	BIOPAK # 284, Helgerson et al. 1988	Coast Range, young	stump 15 cm tall; trees about 16 years old
140	BIOPAK #287, Helgerson et al. 1988	Coast Range, young	stump 15 cm tall; trees about 16 years old; added 1 to b_1
141	BIOPAK #288; Helgerson et al. 1988	Coast Range, young	stump 15 cm tall; trees about 16 years old

Table C.2. (Continued)

#	Source	Area	Notes
142	BIOPAK #297, Helgerson et al. 1988	Coast Range, young	stump 15 cm tall; trees about 16 years old
143	BIOPAK #298, Helgerson et al. 1988	Coast Range, young	stump 15 cm tall; trees about 16 years old
144	BIOPAK #300, Helgerson et al. 1988	Coast Range, young	stump 15 cm tall; trees about 16 years old
145	BIOPAK #301, Helgerson et al. 1988	Coast Range, young	stump 15 cm tall; trees about 16 years old
154	BIOPAK #444, Shaw 1979	Several places in NW	got #s from other studies
155	BIOPAK #445, Shaw 1979	Several places in NW	got #s from other studies
156	BIOPAK #446, Shaw 1979	Several places in NW	got #s from other studies; BIOPAK says these are live branches
157	BIOPAK #447, Shaw 1979	Several places in NW	got #s from other studies; errors from BIOPAK
158	BIOPAK #448, Shaw 1979	Several places in NW	got #s from other studies
159	BIOPAK #449, Shaw 1979	Several places in NW	got #s from other studies; errors from BIOPAK
160	BIOPAK #450, Dice 1970 in Santantonio (log10 form), Shaw 1979	Several places in NW	got #s from other studies
168	BIOPAK #451, Shaw 1979	Several places in NW	got #s from other studies; errors from BIOPAK
169	BIOPAK #452, Shaw 1979	Several places in NW	got #s from other studies; errors from BIOPAK
170	BIOPAK #453, Shaw 1979	Several places in NW	got #s from other studies; errors from BIOPAK
171	BIOPAK #454, Shaw 1979	Several places in NW	got #s from other studies; errors from BIOPAK
172	BIOPAK #455, Shaw 1979, FIA Biomass documentation	Several places in NW	got #s from other studies; errors from BIOPAK
173	BIOPAK #456, Shaw 1979	Several places in NW	got #s from other studies; errors from BIOPAK
192	Snell & Anholt 1981	western WA, ID, MT	most values from literature
193	Snell & Anholt 1981	western WA, ID, MT	most values from literature
194	Snell & Anholt 1981	western WA, ID, MT	most values from literature
195	Snell & Anholt 1981	western WA, ID, MT	most values from literature
196	Snell & Anholt 1981	western WA	for trees dbh <= 9.8 inches
197	Snell & Anholt 1981	western WA	for trees dbh > 9.8 inches
200	BIOPAK # 417, Snell & Max 1985	Wind River WA	
201	BIOPAK #418, Snell & Max 1985	Wind River WA	
202	BIOPAK #419, Snell & Max 1985	Wind River WA	
203	BIOPAK #420, Snell & Max 1985	Wind River WA	
204	BIOPAK #830, Espinosa et al. 1987	Coast Range OR 250-300m elevation	age 22
205	BIOPAK #829, Espinosa et al. 1987	Coast Range OR, young	age 22
206	BIOPAK #827, Espinosa et al. 1987	Coast Range OR, young	age 22
207	BIOPAK #828, Espinosa et al. 1987	Coast Range OR, young	age 22
208	BIOPAK #826, Espinosa et al. 1987	Coast Range OR, young	age 22
209	BIOPAK #825, Espinosa et al. 1987	Coast Range OR, young	age 22
210	BIOPAK #823, Espinosa et al. 1987	Coast Range OR, young	age 22
211	Espinosa et al. 1987	Coast Range OR, young	age 22

Table C.2. (Continued)

#	Source	Area	Notes
212	Grier et al. 1984	Puget Sound WA	plantation age 23; fertilized and non-fertilized trees
213	Grier et al. 1984	Puget Sound WA	plantation age 23; fertilized and non-fertilized trees
214	Grier et al. 1984	Puget Sound WA	plantation age 23; fertilized and non-fertilized trees
215	Grier et al. 1984	Puget Sound WA	plantation age 23; fertilized and non-fertilized trees
220	BIOPAK #750, St.Clair 1993	Coast Range, OR 100m elevation	stump 10 cm; age 18
221	BIOPAK #751, St.Clair 1993	Coast Range, OR 100m elevation	stump 10 cm; age 18
222	BIOPAK #753, St.Clair 1993	Coast Range, OR 100m elevation	stump 10 cm; age 18
223	BIOPAK #754, St.Clair 1993	Coast Range, OR 100m elevation	stump 10 cm; age 18
224	BIOPAK #752, St.Clair 1993	Coast Range, young	stump 10 cm; age 18
225	BIOPAK #755, St.Clair 1993	Coast Range, OR 100m elevation	stump 10 cm; age 18
226	BIOPAK #756, St.Clair 1993	Coast Range, OR 100m elevation	stump 10 cm; age 18
227	cited in FIA Biomass documentation		
228	cited in FIA Biomass documentation		
230	cited in FIA Biomass documentation		
233	cited in FIA Biomass documentation		
234	cited in FIA Biomass documentation		
235	cited in FIA Biomass documentation		
236	cited in FIA Biomass documentation		
239	Long & Turner 1975	partly from West-central WA	estimated dbh range, partially from Dice 1970 data
240	BIOPAK #839, Standish et al. 1985	coastal BC	age 9-86
241	BIOPAK #840, Standish et al. 1985	coastal BC	age 9-86
242	Standish et al. 1985	coastal BC	age 9-86
243	Standish et al. 1985	coastal BC	age 9-86
244	BIOPAK #841, Standish et al. 1985	coastal BC	age 9-86
245	BIOPAK #843, Standish et al. 1985	coastal BC	age 9-86
246	Standish et al. 1985	coastal BC	age 9-86
247	BIOPAK #838, Standish et al. 1985	coastal BC	age 9-86; BIOPAK says total aboveground
248	BIOPAK #844, Standish et al. 1985	BC	age 9-86
249	BIOPAK #845, Standish et al. 1985	BC	age 9-86
250	Standish et al. 1985	BC	age 9-86
251	Standish et al. 1985	BC	age 9-86
252	BIOPAK #846, Standish et al. 1985	BC	age 9-86
254	maybe BIOPAK #848, Standish et al. 1985	BC	age 9-86
255	BIOPAK #849, Standish et al. 1985	BC	age 13-78; BIOPAK says total aboveground
264	BIOPAK #856, Standish et al. 1985	Interior BC	age 9-86
265	BIOPAK #857, Standish et al. 1985	Interior BC	age 9-86

Table C.2. (Continued)

#	Source	Area	Notes
266	Standish et al. 1985	Interior BC	age 9-86
267	Standish et al. 1985	Interior BC	age 15-254
268	BIOPAK #858, Standish et al. 1985	Interior BC	age 15-254
269	BIOPAK #860, Standish et al. 1985	Interior BC	age 15-254
270	Standish et al. 1985	Interior BC	age 15-254
271	BIOPAK #861, Standish et al. 1985	Interior BC	age 15-254; BIOPAK says total aboveground
280	BIOPAK #868, Standish et al. 1985	BC	age 11-253
281	BIOPAK #869, Standish et al. 1985	BC	age 11-253
282	Standish et al. 1985	BC	age 11-253
283	Standish et al. 1985	BC	age 11-253
284	BIOPAK #872, Standish et al. 1985	BC	age 11-253
285	BIOPAK #870, Standish et al. 1985	BC	age 11-253
286	Standish et al. 1985	BC	age 11-253
287	BIOPAK #873, Standish et al. 1985	BC	age 11-253; BIOPAK says total aboveground
288	BIOPAK #935, Standish et al. 1985	BC	age 7-92
289	BIOPAK #936, Standish et al. 1985	BC	age 7-92
290	Standish et al. 1985	BC	age 7-92
291	Standish et al. 1985	BC	age 7-92
292	BIOPAK #937, Standish et al. 1985	BC	age 7-92
293	Standish et al. 1985	BC	age 7-92
294	Standish et al. 1985	BC	age 7-92
295	BIOPAK #940, Standish et al. 1985	BC	age 7-92
684	BIOPAK #421, Snell & Little 1983	Western OR & WA, G	18 locations, age 5-95
686	BIOPAK #427; Snell & Little 1983	Western WA	8 locations, age 12-114
689	BIOPAK #422; Snell & Little 1983; Harmon 1996	Western OR & WA	18 locations, age 5-95
691	BIOPAK #428; Snell & Little 1983; Harmon 1996	Western WA	8 locations, age 12-114
698	Newnham in Evert 1985	BC	
701	Newnham in Evert 1985	BC	
706	Newnham in Evert 1985	BC	
709	Newnham in Evert 1985	BC	
710	Newnham in Evert 1985	BC	
711	Newnham in Evert 1985	BC	
716	Newnham in Evert 1985	BC	
719	Newnham in Evert 1985	BC	
724	Newnham in Evert 1985	BC	
727	Newnham in Evert 1985	BC	

Table C.2. (Continued)

#	Source	Area	Notes
728	Newnham in Evert 1985	BC	
729	Newnham in Evert 1985	BC	
734	Newnham in Evert 1985	BC	
737	Newnham in Evert 1985	BC	
742	Newnham in Evert 1985	BC	
745	Newnham in Evert 1985	BC	
746	Newnham in Evert 1985	BC	
747	Newnham in Evert 1985	BC	
866	BIOPAK #273	west of Cascades, mature	FSDB TV008
867	BIOPAK #265, Binkley 1983 in Forest Science Databank	Coast Ranges, mature	FSDB
871	BIOPAK #274, Harmon 1996?	west of Cascades, mature	FSDB TV008
875	BIOPAK #264, Binkley 1983 in Forest Science Databank	Coast Ranges, mature	FSDB
880	BIOPAK #272, Harmon 1996	west of Cascades, mature	FSDB TV008
883	BIOPAK #275, Harmon 1996	west of Cascades, mature	FSDB TV008
884	BIOPAK #266, Binkley 1983 in Forest Science Databank	Coast Ranges, mature	Forest Science Data Bank
889	BIOPAK #276, Harmon 1996	west of Cascades, mature	FSDB TV008
1393	BIOPAK #466, Bormann data, Harmon 1996	southeast AK, mature	BT Bormann, Forest Science Dept OSU.
1404	BIOPAK #370, Harmon	Coast Ranges, mature	TV009 Dataset, Forest Science Dept OSU
1405	BIOPAK #310, Harmon 1996	Coast Ranges, old-growth	TV009 Dataset, Forest Science Dept OSU
1406	BIOPAK #403, Harmon	Coast Ranges, young	TV009 Dataset, Forest Science Dept OSU
1409	BIOPAK #371, Harmon	Coast Ranges, mature	TV009 Dataset, Forest Science Dept OSU
1410	BIOPAK #311, Harmon	Coast Ranges, old-growth	TV009 Dataset, Forest Science Dept OSU
1411	BIOPAK #404, Harmon	Coast Ranges, young	TV009 Dataset, Forest Science Dept OSU
1412	BIOPAK #369, Harmon	Coast Ranges, mature	TV009 Dataset, Forest Science Dept OSU
1413	BIOPAK #309, Harmon 1996	Coast Ranges, old-growth	TV009 Dataset, Forest Science Dept OSU
1414	BIOPAK #402, Harmon	Coast Ranges, young	TV009 Dataset, Forest Science Dept OSU
1459	BIOPAK #759, St Clair 1992	Coast Ranges, young	Brad St.Clair. OSU
1465	BIOPAK #1095, Halpern	west of Cascades, early seral	Charles Halpern, UW
1472	BIOPAK #764	Coast Ranges, young	Brad St.Clair, OSU
1486	BIOPAK #761	Coast Ranges, young	Brad St.Clair. OSU
1500	BIOPAK #765	Coast Ranges, young	Brad St.Clair. OSU
1505	BIOPAK #247	west of Cascades, old-growth	
1511	BIOPAK #763	Coast Ranges, young	Brad St.Clair. OSU
1517	BIOPAK #254, Harmon	west of Cascades, mature	TV009 Dataset, Forest Science Dept OSU
1518	BIOPAK #364, Harmon	west of Cascades, mature	TV009 Dataset, Forest Science Dept OSU
1519	BIOPAK #328, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU

Table C.2. (Continued)

#	Source	Area	Notes
1520	BIOPAK #343, Harmon 1996	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1521	BIOPAK #352, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1525	BIOPAK #760	Coast Ranges, young	Brad St.Clair, OSU.
1530	BIOPAK #256, Harmon	west of Cascades, mature	TV009 Dataset, Forest Science Dept OSU
1531	BIOPAK #365, Harmon	west of Cascades, mature	TV009 Dataset, Forest Science Dept OSU
1532	BIOPAK #329, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1533	BIOPAK #344, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1534	BIOPAK #353, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1536	BIOPAK #762	Coast Ranges, young	Brad St.Clair, OSU
1542	BIOPAK #255, Harmon	west of Cascades, mature	TV009 Dataset, Forest Science Dept OSU
1543	BIOPAK #363, Harmon	west of Cascades, mature	TV009 Dataset, Forest Science Dept OSU
1544	BIOPAK #327, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1545	BIOPAK #342, Harmon 1996	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1546	BIOPAK #351, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1793	BIOPAK #544, Sachs 1983	Coast Ranges, mature, thinned	
1794	BIOPAK #545, Sachs 1983, Harmon 1996	Coast Ranges, mature, unthinned	
1797	BIOPAK #542, Sachs 1983	Coast Ranges, thinned, mature, branches + twigs	
1798	BIOPAK #543, Sachs 1983	Coast Ranges, mature, branches + twigs	
1815	BIOPAK #175, Sachs 1983	Coast Ranges, mature	D. Sachs, For. Sc., OSU; TP721 seq. Nos. 1350-71; Data set codes for raw data TP84.
1821	BIOPAK #174, Sachs 1983	Coast Ranges, mature	D. Sachs, For. Sc., OSU; TP721 seq. Nos. 1350-54, 1357-60, 1362-70; Data set codes TP84.
1822	BIOPAK #373, Harmon	Coast Ranges, mature	TV009 Dataset, Forest Science Dept OSU
1823	BIOPAK #376, Harmon	Coast Ranges, mature	TV009 Dataset, Forest Science Dept OSU
1824	BIOPAK #313, Harmon	Coast Ranges, old-growth	TV009 Dataset, Forest Science Dept OSU
1825	BIOPAK #406, Harmon	Coast Ranges, young	TV009 Dataset, Forest Science Dept OSU
1828	BIOPAK #367, Harmon	west of Cascades, mature	TV009 Dataset, Forest Science Dept OSU
1830	BIOPAK #257, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1831	BIOPAK #334, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1832	BIOPAK #349, Harmon 1996	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1833	BIOPAK #358, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1835	BIOPAK #374, Harmon	Coast Ranges, mature	TV009 Dataset, Forest Science Dept OSU
1836	BIOPAK #377, Harmon	Coast Ranges, mature	TV009 Dataset, Forest Science Dept OSU
1837	BIOPAK #314, Harmon	Coast Ranges, old-growth	TV009 Dataset, Forest Science Dept OSU
1838	BIOPAK #407, Harmon	Coast Ranges, young	TV009 Dataset, Forest Science Dept OSU
1843	BIOPAK #368 , Harmon	west of Cascades, mature	TV009 Dataset, Forest Science Dept OSU
1844	BIOPAK #259, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU

Table C.2. (Continued)

#	Source	Area	Notes
1845	BIOPAK #335, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1846	BIOPAK #350, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1847	BIOPAK #359, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1849	BIOPAK #173, Sachs 1983	Coast Ranges, mature	D. Sachs, Forest Science Dept OSU; TP721 seq. Nos. 1350-54, 1357-60; Data set codes TP84.
1850	BIOPAK #372, Harmon	Coast Ranges, mature	TV009 Dataset, Forest Science Dept OSU
1851	BIOPAK #375, Harmon	Coast Ranges, mature	TV009 Dataset, Forest Science Dept OSU
1852	BIOPAK #312, Harmon	Coast Ranges, old-growth	TV009 Dataset, Forest Science Dept OSU
1853	BIOPAK #405, Harmon	Coast Ranges, young	TV009 Dataset, Forest Science Dept OSU
1856	BIOPAK #366, Harmon	west of Cascades, mature	TV009 Dataset, Forest Science Dept OSU
1858	BIOPAK #258, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1859	BIOPAK #333, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1860	BIOPAK #348, Harmon 1996	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1861	BIOPAK #357, Harmon	west of Cascades, old-growth	TV009 Dataset, Forest Science Dept OSU
1904	Smith 1972 in Stanek 1979	PNW	fresh weight - multiply by 0.4 for dry
1906	Smith 1972 in Stanek 1979	PNW	fresh weight - multiply by 0.4 for dry
1907	Smith 1972 in Stanek 1979	PNW	fresh weight - multiply by 0.4 for dry
1908	Smith 1972 in Stanek 1979	PNW	fresh weight - multiply by 0.4 for dry
1909	Smith 1972 in Stanek 1979	PNW	fresh weight - multiply by 0.4 for dry
1910	BIOPAK #652, Zavitkovski 1972 in Stanek 1979		
1911	Zavitkovski 1972 in Stanek 1979		
1912	Zavitkovski 1972 in Stanek 1979		
1913	Zavitkovski 1972 in Stanek 1979		
1931	Kurucz 1969	Coastal BC	MSE in lbs
1932	Kurucz 1969	Coastal BC	MSE in lbs
1933	Kurucz 1969	Coastal BC	MSE in lbs
1951	Krumlik 1974 in Stanek 1979		
1952	Krumlik 1974 in Stanek 1979		
1953	Krumlik 1974 in Stanek 1979		
1954	Krumlik 1974 in Stanek 1979		
1955	Krumlik 1974 in Stanek 1979		
1956	Krumlik 1974 in Stanek 1979		
1957	Krumlik 1974 in Stanek 1979		
1958	Krumlik 1974 in Stanek 1979		
1959	Krumlik 1974 in Stanek 1979		
1961	Krumlik 1973 in Stanek 1979		

Table C.2. (Continued)

#	Source	Area	Notes
1962	Krumlik 1973 in Stanek 1979		
1963	Kurucz 1969	Coastal BC	MSE in lbs
1964	Kurucz 1969	Coastal BC	MSE in lbs
1965	Kurucz 1969	Coastal BC	MSE in lbs
1968	Feller 1992	Vancouver Island, BC, good sites	
1969	Feller 1992	Vancouver Island, BC, good sites	
1970	Feller 1992	Vancouver Island, BC, good sites	
1971	Feller 1992	Vancouver Island, BC, good sites	
1973	Feller 1992	Vancouver Island, BC, poor sites	
1974	Feller 1992	Vancouver Island, BC, poor sites	
1975	Feller 1992	Vancouver Island, BC, poor sites	
1976	Feller 1992	Vancouver Island, BC, poor sites	
1978	Feller 1992	Vancouver Island, BC, good sites	
1979	Feller 1992	Vancouver Island, BC, good sites	
1980	Feller 1992	Vancouver Island, BC, good sites	
1981	Feller 1992	Vancouver Island, BC, good sites	
1982	Feller 1992	Vancouver Island, BC, good sites	
1983	Feller 1992	Vancouver Island, BC, poor sites	
1984	Feller 1992	Vancouver Island, BC, poor sites	
1985	Feller 1992	Vancouver Island, BC, poor sites	
1986	Feller 1992	Vancouver Island, BC, poor sites	
1987	Feller 1992	Vancouver Island, BC, poor sites	
1988	Feller 1992 with Standish data	coastal BC	
1989	Feller 1992 with Standish data	coastal BC	
1990	Feller 1992 with Standish data	coastal BC	
1991	Feller 1992 with Standish data	coastal BC	
1992	Feller 1992 with Standish data	coastal BC	
1993	Feller 1992 with Standish data	coastal BC	
1994	Feller 1992 with Standish data	coastal BC	
1995	Feller 1992 with Standish data	coastal BC	
2006	Feller 1992 with Standish data	coastal BC, assumed good sites	
2007	Feller 1992 with Standish data	coastal BC, assumed good sites	
2008	Feller 1992 with Standish data	coastal BC, assumed good sites	
2009	Feller 1992 with Standish data	coastal BC, assumed good sites	
2010	Feller 1992 with Standish data	coastal BC, assumed poor sites	
2011	Feller 1992 with Standish data	coastal BC, assumed poor sites	

Table C.2. (Continued)

#	Source	Area	Notes
2012	Feller 1992 with Standish data	coastal BC, assumed poor sites	
2013	Feller 1992 with Standish data	coastal BC, assumed poor sites	
2018	Alemdag 1982	Ontario	Ontario species; apply to PNW because information limited
2019	Alemdag 1982	Ontario	Ontario species; apply to PNW because information limited
2020	BIOPAK #6, Gholz et al. 1979, Harmon et al. 1996	PNW	originally for *Pseudotsuga menziesii*
2022	Standish et al. 1985	BC	
2023	Grier et al. 1984	Puget Sound WA	plantation age 23; fertilized and non-fertilized trees
2052	Alemdag 1982	Ontario	originally for *P. banksiana* in Ontario
2053	Alemdag 1982	Ontario	originally for *P. banksiana* in Ontario
2057	Grier & Logan 1977	watershed 10, HJ Andrews	
2058	Grier & Logan 1977	watershed 10, HJ Andrews	
2059	Grier & Logan 1977	watershed 10, HJ Andrews	
2060	Grier & Logan 1977	watershed 10, HJ Andrews	
2061	Grier & Logan 1977	watershed 10, HJ Andrews	
2082	Grier & Logan 1977 (Dice 1970 in Santantonio 1977, Riekirk 1967 in Santantonio 1977)	watershed 10, HJ Andrews	
2083	Grier & Logan 1977 (Santantonio 1977)	watershed 10, HJ Andrews	
2084	Jenkins et al. 2003	all USA	developed from many references
2085	Jenkins et al. 2003	all USA	developed from many references
2088	Jenkins et al. 2003	all USA	developed from many references
2089	Jenkins et al. 2003	all USA	developed from many references
2090	Jenkins et al. 2003	all USA	developed from many references
2092	Le Goff & Ottorini 2001	NE France	developed for beech, max/min dbh from mean & SD; assume b_0 does not contain CF
2099	Whittaker et al. 1974 in Santantonio 1977	Hubbard Brook	developed for *P. rubens*
2108	Riekirk 1967 in Santantonio	somewhere in a *Pseudotsuga menziesii* ecosystem	dbh range estimated
2109	Kira & Ogawa 1968 in Santantonio		developed for *F. crenata*
2110	Whittaker et al. 1974 in Santantonio 1977	Hubbard Brook	developed for *F. grandifolia*
2111	Whittaker et al. 1974 in Santantonio 1977	Hubbard Brook	developed for *A. saccharum*
2112	Whittaker et al. 1974 in Santantonio 1977	Hubbard Brook	developed for *A. spicatum*
2113	Whittaker et al. 1974 in Santantonio 1977	Hubbard Brook	developed for *B. lutea*
2114	Ovington & Madgwick 1959 in Santantonio 1977		developed for *B. verrucosa*
2115	Nihlgard 1972 in Santantonio 1977	Sweden	developed for *P. abies*
2120	Ovington & Madgwick 1959 in Santantonio 1977		developed for *B. verrucosa*
2121	Kira & Ogawa 1968 in Santantonio		developed for *F. crenata*
2122	Nihlgard 1972 in Santantonio 1977	Sweden	developed for *F. silvatica*

Table C.2. (Continued)

#	Source	Area	Notes
2202	Ranger & Gelhaye 2001	France	age 47; , assume dbh range from 30-50cm
2203	Ranger & Gelhaye 2001	France	age 47; assume dbh range from 30-50cm
2204	Ranger & Gelhaye 2001	France	age 47; assume dbh range from 30-50cm
2206	Barclay et al. 1986	Victoria, BC	not thinned, not fertilized; trees felled at ground level
2207	Barclay et al. 1986	Victoria, BC	not thinned, fertilized; trees felled at ground level
2208	Barclay et al. 1986	Victoria, BC	thinned, not fertilized; trees felled at ground level
2209	Barclay et al. 1986	Victoria, BC	thinned and fertilized; trees felled at ground level
2210	Barclay et al. 1986	Victoria, BC	not thinned, not fertilized; trees felled at ground level; no top given
2211	Barclay et al. 1986	Victoria, BC	not thinned, fertilized; trees felled at ground level; no top given
2212	Barclay et al. 1986	Victoria, BC	thinned, not fertilized; trees felled at ground level; no top given
2213	Barclay et al. 1986	Victoria, BC	thinned and fertilized; trees felled at ground level; no top given
2214	Barclay et al. 1986	Victoria, BC	not thinned, no fertilizer, used overall dbh range; no top given
2215	Barclay et al. 1986	Victoria, BC	not thinned, fertilizer, used overall dbh range; no top given
2216	Barclay et al. 1986	Victoria, BC	thin, no fertilizer, used overall dbh range; no top given
2217	Barclay et al. 1986	Victoria, BC	thinned, fertilizer, used overall dbh range; no top given
2218	Barclay et al. 1986	Victoria, BC	not thinned, not fertilized
2219	Barclay et al. 1986	Victoria, BC	not thinned, fertilized
2220	Barclay et al. 1986	Victoria, BC	thinned, not fertilized
2221	Barclay et al. 1986	Victoria, BC	thinned and fertilized
2222	Barclay et al. 1986	Victoria, BC	not thinned, not fertilized
2223	Barclay et al. 1986	Victoria, BC	not thinned, fertilized
2224	Barclay et al. 1986	Victoria, BC	thinned, not fertilized
2225	Barclay et al. 1986	Victoria, BC	thinned and fertilized
2226	Barclay et al. 1986	Victoria, BC	not thinned, not fertilized
2227	Barclay et al. 1986	Victoria, BC	not thinned, fertilized
2228	Barclay et al. 1986	Victoria, BC	thinned, not fertilized
2229	Barclay et al. 1986	Victoria, BC	thinned and fertilized
2230	Barclay et al. 1986	Victoria, BC	not thinned, not fertilized
2231	Barclay et al. 1986	Victoria, BC	not thinned, fertilized
2232	Barclay et al. 1986	Victoria, BC	thinned, not fertilized
2233	Barclay et al. 1986	Victoria, BC	thinned and fertilized
2234	Barclay et al. 1986	Victoria, BC	not thinned, not fertilized; add to branch live
2235	Barclay et al. 1986	Victoria, BC	not thinned, fertilized; add to branch live

Table C.2. (Continued)

#	Source	Area	Notes
2236	Barclay et al. 1986	Victoria, BC	thinned, not fertilized; add to branch live
2237	Barclay et al. 1986	Victoria, BC	thinned and fertilized; add to branch live
2239	Krumlik 1974 in Jenkins 2004		Jenkins says cm, seems like m works better
2240	Krumlik 1974 in Jenkins 2004		Jenkins says cm, seems like m works better
2242	Krumlik 1974 in Jenkins 2004		Jenkins says cm, seems like m works better
2243	Marshall & Wang 1995 in Jenkins 2004	BC	
2244	Marshall & Wang 1995 in Jenkins 2004	BC	
2245	Marshall & Wang 1995 in Jenkins 2004	BC	
2246	Marshall & Wang 1995 in Jenkins 2004	BC	
2247	Marshall & Wang 1995 in Jenkins 2004	BC	
2248	Marshall & Wang 1995 in Jenkins 2004	BC	
2249	Ramseur 1981 in Jenkins 2004	Tennessee	
2249	Ramseur 1981 in Jenkins 2004	Tennessee	upper end of dbh estimated from site description in text; stem cut at ground level; root crown to 100 cm radius from stem; mix of hardwood species in 2 Tennessee deciduous stands
2250	Thies & Cunningham 1996	western OR	two plantations ages 40 & 70 years
2251	Thies & Cunningham 1996	Cascades, OR	plantation age 40, dbh range from graph
2252	Thies & Cunningham 1996	Coast Range, OR	plantation age 70, dbh range from graph
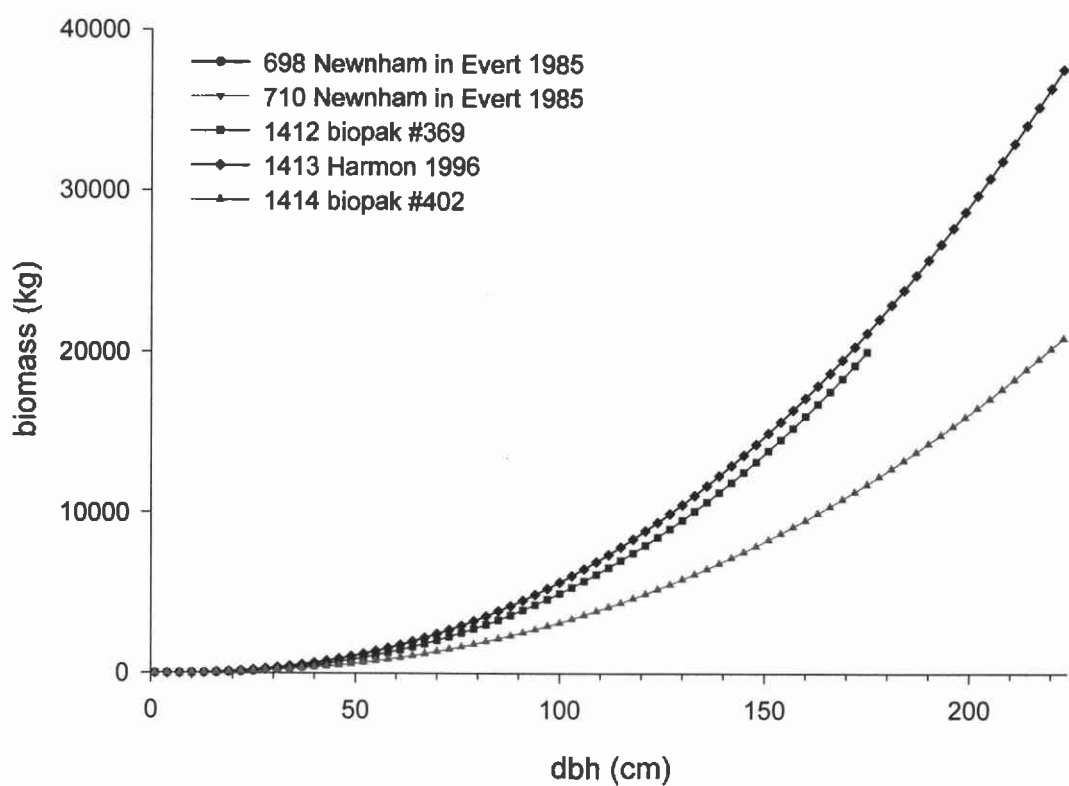
Figure C.1 Stem wood biomass plotted for *Picea sitchensis*. Equation numbers correspond to those in Table C.1.
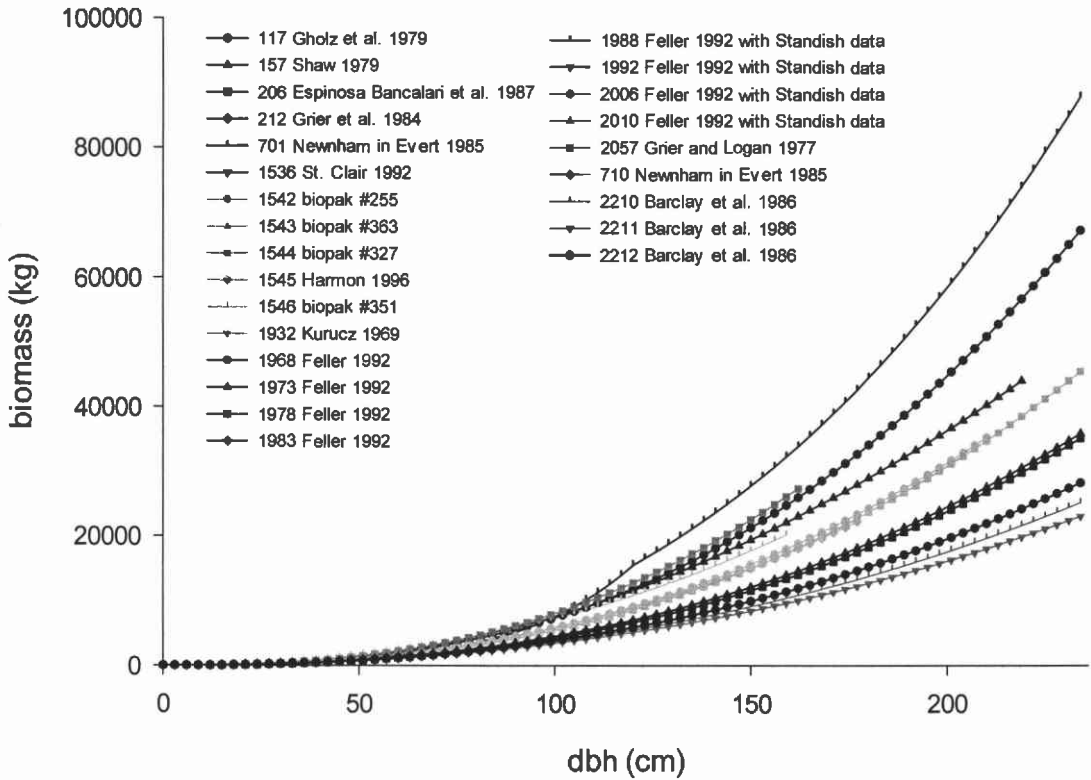
Figure C.2. Stem wood biomass plotted for *Pseudotsuga menziesii*. Equation numbers correspond to those in Table C.1.
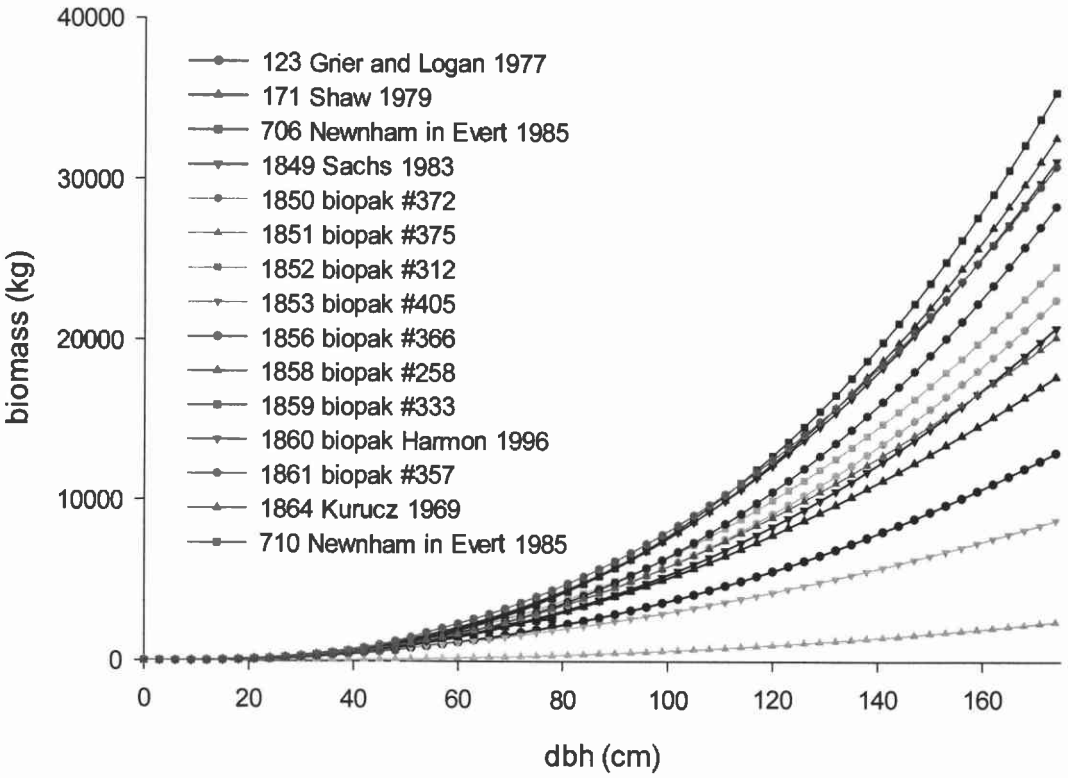
Figure C.3. Stem wood biomass plotted for *Tsuga heterophylla*. Equation numbers correspond to those in Table C.1.
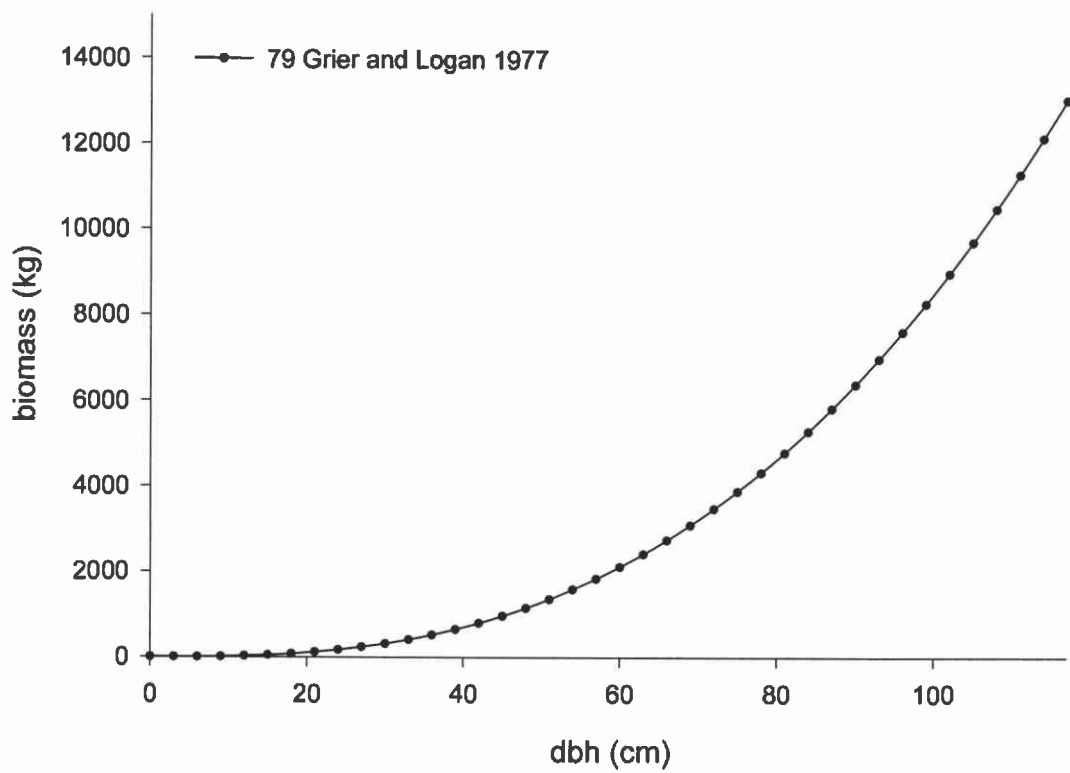
Figure C.4. Stem wood biomass plotted for *Acer macrophyllum*. Equation numbers correspond to those in Table C.1.
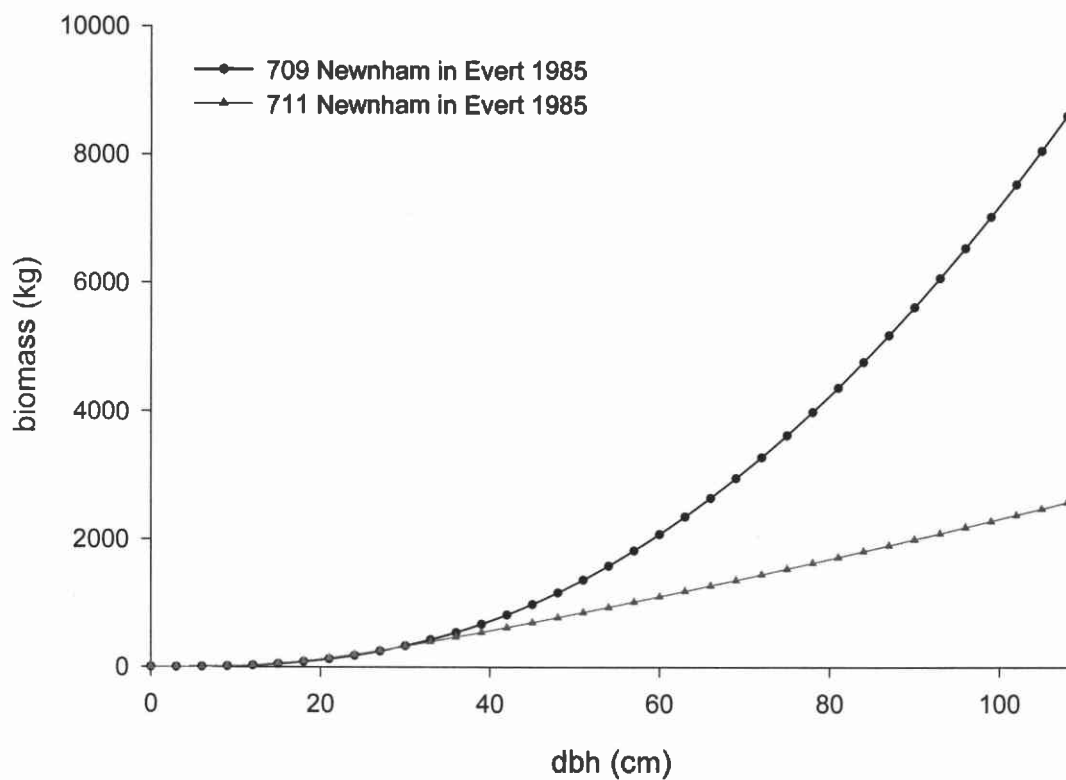
Figure C.5. Stem wood biomass plotted for *Alnus rubra*. Equation numbers correspond to those in Table C.1.

Appendix D Density Values

Table D.1. Density values collected from the literature along with estimates of variance. SG = specific gravity, SE = standard error, n = number of observations, CV = coefficient of variation. References are included in the general bibliography.

Species	Component	SG	SE	n	Source	Location	Type (weight/volume)	Notes
PISI	bark	0.539	0.02353	17	Smith and Kozack 1971	BC	dry/green	weighted average of inner & outer bark for specific gravity and SE, SE based on PSMEs
PISI	bark	0.538	0.01701	10	Franklin 2002	PNW	"green"	n assumed 10; SE from CV; CV assumed 10%
PISI	wood	0.330	0.00330	100	Forest Products Laboratory 1999	US	dry/green	SE from CV; n unknown so assumed 100
PISI	wood	0.370	0.00740	25	Markwardt and Wilson 1935 in Gonzalez 1990	AK OR & WA	dry/green	SE from CV; CV assumed 10%
PISI	wood	0.347	0.00937	14	Jessome 1977 in Gonzalez 1990	BC	dry/green	SE from CV
PISI	wood	0.412	0.01088	34	Standish 1983 in Gonzalez 1990	BC	dry/green	SE from CV; 15-78 yrs; 5-45 cm dbh
PISI	wood	0.360	0.01138	10	Franklin 2002	PNW	"green"	n assumed 10; SE from CV; CV assumed 10%
PISI	wood + bark	0.369	0.01167	10	Franklin 2002	PNW	"green"	n assumed 10; SE from CV; CV assumed 10%
PSME	bark	0.435	0.00993	98	Smith and Kozack 1971	BC	dry/green	weighted average of inner & outer bark for specific gravity and SE
PSME	bark	0.438	0.01385	10	Franklin 2002	PNW	"green"	n assumed 10; SE from CV; CV assumed 10%
PSME	wood	0.452	0.00160	1861	USDA 1965	WOR	dry/green	
PSME	wood	0.437	0.00220	962	USDA 1965	WWA	dry/green	
PSME	wood	0.450	0.00450	100	Forest Products Laboratory 1999	US	dry/green	SE from CV; n unknown so assumed 100
PSME	wood	0.422	0.00135	711	Smith 1970	BC interior	dry/green	
PSME	wood	0.445	0.01054	24	Drow 1957 in Gonzalez 1990	BC	dry/green	SE from CV
PSME	wood	0.430	0.01356	14	Drow 1957 in Gonzalez 1990	BC	dry/green	SE from CV
PSME	wood	0.421	0.00780	42	Standish 1983 in Gonzalez 1990	BC coast	dry/green	SE from CV; 16-86 yrs; 8-66 cm dbh
PSME	wood	0.446	0.00851	37	Drow 1957 in Gonzalez 1990	US west coast	dry/green	SE from CV
PSME	wood	0.423	0.00464	112	Drow 1957 in Gonzalez 1990	OR & WA coast	dry/green	SE from CV
PSME	wood	0.436	0.00509	36	McKimmy 1959 in Gonzalez 1990	OR & WA coast	dry/green	SE from CV; 55-150 yrs; 29-88 cm dbh
PSME	wood	0.453	0.02026	5	Littleford 1961 in Gonzalez 1990	BC coast	dry/green	SE from CV; CV assumed 10%; 76-81 yrs; 94-104 cm dbh
PSME	wood	0.450	0.00822	30	Markwardt and Wilson 1935 in Gonzalez 1990	CA OR & WA coast	dry/green	SE from CV; CV assumed 10%
PSME	wood	0.452	0.01429	10	Franklin 2002	PNW	"green"	n assumed 10; SE from CV; CV assumed 10%
PSME	wood + bark	0.449	0.01420	10	Franklin 2002	PNW	"green"	n assumed 10; SE from CV; CV assumed 10%
TSHE	bark	0.501	0.01591	29	Smith and Kozack 1971	BC	dry/green	weighted average of inner & outer bark for specific gravity and SE
TSHE	bark	0.415	0.01312	10	Franklin 2002	PNW	"green"	n assumed 10; SE from CV; CV assumed 10%
TSHE	wood	0.422	0.00340	261	USDA 1965	WOR	dry/green	
TSHE	wood	0.420	0.00230	645	USDA 1965	WWA	dry/green	
TSHE	wood	0.420	0.00420	100	Forest Products Laboratory 1999	US	dry/green	SE from CV; n unknown so assumed 100
TSHE	wood	0.424	0.00195	398	Smith 1970	BC coast	dry/green	
TSHE	wood	0.380	0.00896	18	Markwardt and Wilson 1935 in Gonzalez 1990	AK OR & WA	dry/green	SE from CV; CV assumed 10%
TSHE	wood	0.409	0.00839	21	Jessome 1977 in Gonzalez 1990	BC	dry/green	SE from CV
TSHE	wood	0.427	0.00158	605	Kennedy and Swann 1969 in Gonzalez 1990	BC	dry/green	SE from CV; 43 cm avg dbh
TSHE	wood	0.436	0.00783	59	Standish 1983 in Gonzalez 1990	BC	dry/green	SE from CV; 15-253 yrs; 5-71 cm dbh
TSHE	wood	0.403	0.01315	12	Krahmer 1966 in Gonzalez 1990	OR	dry/green	SE from CV; 34-243 yrs; 29-78 cm dbh

Table D.1. (Continued)

Species	Component	SG	SE	n	Source	Location	Type (weight/volume)	Notes
TSHE	wood	0.380	0.01327	12	Krahmer 1966 in Gonzalez 1990	OR	dry/green	SE from CV; 34-243 yrs; 29-78 cm dbh
TSHE	wood	0.421	0.01331	10	Franklin 2002	PNW	"green"	n assumed 10; SE from CV; CV assumed 10%
TSHE	wood + bark	0.420	0.01328	10	Franklin 2002	PNW	"green"	n assumed 10; SE from CV; CV assumed 10%
ACMA	bark	0.592	0.03152	6	Smith and Kozack 1971	BC	dry/green	weighted average of inner & outer bark for specific gravity and SE, SE based on cottonwood
ACMA	wood	0.440	0.00440	100	Forest Products Laboratory 1999	US	dry/green	SE from CV; n unknown so assumed 100
ACMA	wood	0.440	0.01968	5	Markwardt and Wilson 1935 in Gonzalez 1990	WA	dry/green	SE from CV; CV assumed 10%
ACMA	wood	0.466	0.00894	6	Jessome 1977 in Gonzalez 1990	BC	dry/green	weighted average of inner & outer bark for specific gravity and SE, SE based on cottonwood
ALRU	bark	0.562	0.02301	9	Smith and Kozack 1971	BC	dry/green	SE from CV
ALRU	wood	0.370	0.00370	100	Forest Products Laboratory 1999	US	dry/green	SE from CV; CV assumed 10%; n unknown so assumed 100
ALRU	wood	0.370	0.01511	6	Markwardt and Wilson 1935 in Gonzalez 1990	WA	dry/green	SE from CV
ALRU	wood	0.373	0.01051	6	Jessome 1977 in Gonzalez 1990	BC	dry/green	SE from CV; 5-48 yrs; 6-33 cm dbh
ALRU	wood	0.395	0.00793	40	Standish 1983 in Gonzalez 1990	BC	dry/green	SE from CV

Table D.2. Final density ranges by species and component.

Species	Component	Maximum Range Density		Mid-Range Density		Source of Mid-Range Density
		low	high	low	high	
		$(kg\ m^{-3})$	$(kg\ m^{-3})$	$(kg\ m^{-3})$	$(kg\ m^{-3})$	
Picea sitchensis	wood	323	434	323	337	Forest Products Laboratory 1999
Picea sitchensis	bark	489	588	489	588	Smith and Kozack 1971
Picea sitchensis	stem wood + bark	342	395	342	395	Franklin 2002
Pseudotsuga menziesii	wood	397	509	423	467	Drow 1957 in Gonzalez 1990
Pseudotsuga menziesii	bark	407	469	415	454	Smith and Kozack 1971
Pseudotsuga menziesii	stem wood + bark	417	481	417	481	Franklin 2002
Tsuga heterophylla	wood	351	452	415	425	USDA 1965
Tsuga heterophylla	bark	385	534	468	534	Smith and Kozack 1971
Tsuga heterophylla	stem wood + bark	390	450	390	450	Franklin 2002
Acer macrophyllum	wood aboveground	385	494	431	449	Forest Products Laboratory 1999 used average of 3 wood & 1 bark specific gravity
Acer macrophyllum	wood+bark	443	526	443	526	
Alnus rubra	wood	331	411	346	400	Jessome 1977 in Gonzalez 1990

Appendix E Lookup Tables

Lookup Tables

The lookup tables which follow were created from equations specific to the Pacific Northwest (Oregon and Washington states west of the Cascade crest and north of the Siskiyou range) and British Columbia. Data in these lookup tables should only be applied to trees growing within those areas. Furthermore, a number of equations were dependent on height as well as dbh, so lookup tables were developed using dbh-height relationships from the northwest corner of Oregon state. The most appropriate area for application to these tables is therefore the six counties in northwest Oregon named in Chapter 3.

These lookup tables represent the base case reported in Objective 2. They do not include the effect of height variation.

Table E.1. *Picea sitchensis* total tree C lookup table. Values excluding dbh are in kg C.

dbh	Positive Correlation		Zero Correlation		Negative Correlation	
(cm)	minimum	maximum	minimum	maximum	minimum	maximum
0	0.00107	3.00870	0.00883	2.35240	0.01629	1.77185
1	0.01299	3.82558	0.05040	2.95107	0.06314	2.05470
2	0.08170	4.86016	0.24772	3.78855	0.30022	2.78091
3	0.24405	6.46327	0.63067	5.14663	0.74869	4.08458
4	0.52701	9.19609	1.22294	7.53391	1.43294	5.98789
5	0.94939	14.01323	2.04107	11.81725	2.37194	10.62510
6	1.54291	15.11408	3.09711	12.72221	3.58149	11.51305
7	2.33275	16.99202	4.40704	14.17594	5.07530	12.69712
8	3.38126	20.00864	5.98355	16.17117	6.86551	14.21558
9	4.68893	24.37527	7.84874	19.90032	8.96312	16.10563
10	6.27553	29.45824	10.00887	24.23358	11.37818	19.52496
11	8.15914	35.37685	12.47512	29.24101	14.11999	24.32058
12	10.35684	42.30854	15.25831	35.03859	17.19722	29.73017
13	12.88540	50.51794	18.36907	41.81839	20.61801	35.77133
14	15.76163	57.29805	21.80761	48.53772	24.39002	42.46067
15	19.00266	65.42448	25.58943	56.11682	28.52053	49.81389
16	22.62605	74.30870	29.72128	64.43341	33.01644	57.84594
17	26.64990	83.96956	34.21058	73.50314	37.88436	66.57104
18	31.09288	94.42524	39.06442	83.34220	43.13059	76.00276
19	35.97431	105.69333	44.29399	94.60682	48.76121	86.15410
20	41.31425	132.29943	49.96263	118.25764	54.78205	103.53769
21	47.13369	148.05052	55.95665	132.51018	61.19872	116.10741
22	53.45475	164.71028	62.34020	147.65079	68.01666	129.51280
23	60.30106	182.21559	69.11895	163.65145	75.24112	143.76734
24	67.69830	200.48479	76.29834	180.47427	82.87717	158.88412
25	75.67490	219.41682	83.88366	198.07231	90.92977	174.87576
26	84.18303	239.28856	91.88066	216.59285	99.40370	191.58326
27	93.13532	260.01497	100.29430	236.00400	108.30363	209.10996
28	101.51074	281.60615	109.12945	256.31928	117.63409	227.46741
29	110.30369	304.07195	118.39059	277.34508	127.39951	246.66681
30	119.51916	327.63968	128.17955	299.24701	137.82189	266.71909
31	129.16199	352.77086	138.70297	322.39600	149.35750	287.63491
32	139.23687	378.91507	149.71492	346.49264	161.45083	309.42463
33	149.74839	406.56891	161.22162	371.54937	174.11054	332.09843
34	160.70096	436.52904	173.22916	397.57835	187.34514	355.66620
35	172.09890	467.81533	185.74674	425.46010	201.16306	380.13759
36	183.94641	500.42576	198.77856	454.67060	215.57259	405.52209
37	196.24758	534.37788	212.32976	485.03812	230.58194	431.82895
38	209.00637	569.68899	226.40605	516.57741	246.19921	459.06722
39	222.54478	606.37610	241.19276	549.44141	262.43238	487.56388
40	236.58745	644.45598	256.53827	583.52244	279.28938	517.04848
41	251.14010	683.94517	272.44923	618.83538	296.77801	547.53158
42	266.20835	725.02962	288.93258	655.48722	314.90601	579.02353
43	281.79777	768.27411	305.99619	693.79042	333.68104	611.53460
44	297.91386	813.03956	323.64491	733.40258	353.11065	645.07490
45	314.56206	859.34179	341.88508	774.33782	373.20234	679.65437
46	331.74774	907.19638	360.72298	816.61004	393.96353	715.28290
47	349.47623	956.61851	380.16482	860.23286	415.40157	751.97019
48	367.75278	1007.62310	400.21676	905.21858	437.52372	789.72586
49	386.58261	1060.22477	420.88482	951.57100	460.33721	829.07763
50	405.97088	1114.43779	442.17491	999.27802	483.84916	875.02468
51	425.92268	1170.27619	464.09301	1048.35392	508.06667	922.49893
52	446.44308	1227.75370	486.64515	1098.83482	532.99675	971.51570
53	467.53709	1286.88372	509.83719	1150.73243	558.64636	1022.08995
54	489.20966	1347.67945	533.67492	1204.05830	585.02239	1074.23631
55	511.46572	1410.15372	558.16411	1258.82374	612.13170	1127.96911
56	534.31013	1474.31916	583.31045	1315.03989	639.98108	1183.30238
57	557.74773	1540.18811	609.11960	1372.71769	668.57725	1240.24981
58	581.78331	1607.77265	635.59718	1431.86787	697.92691	1298.82483
59	606.42161	1677.08455	662.74874	1492.50097	728.03669	1359.04059
60	631.66734	1748.13543	690.57980	1554.62738	758.91318	1420.90993
61	657.52519	1820.93655	719.09583	1618.25727	790.56290	1484.44546
62	681.09847	1895.49898	748.30227	1683.40066	822.99236	1549.65950
63	704.49769	1971.83352	778.20451	1750.06738	856.20800	1616.56414

Table E.1. (Continued)

dbh (cm)	Positive Correlation minimum	maximum	Zero Correlation minimum	maximum	Negative Correlation minimum	maximum
64	728.34151	2049.95078	808.81309	1819.18314	890.21621	1685.17121
65	752.63237	2129.86105	840.15984	1895.40230	925.02336	1755.49230
66	777.37275	2211.57444	872.22037	1973.49583	960.63575	1827.53879
67	802.56515	2295.10079	904.99993	2053.47518	997.05967	1901.32181
68	828.21199	2380.44979	938.50377	2135.35155	1034.30134	1976.85231
69	854.31571	2467.63077	972.73708	2219.13580	1072.36696	2054.14099
70	880.87875	2556.65298	1007.70502	2304.83856	1111.26268	2133.19839
71	907.90349	2647.52533	1043.41271	2392.47017	1150.99462	2214.03484
72	935.39233	2740.25660	1079.86525	2482.04071	1191.56886	2296.66048
73	963.34767	2834.85532	1117.06769	2573.55999	1232.99144	2381.08528
74	991.77185	2931.32977	1155.02506	2667.03758	1275.26836	2467.31905
75	1020.66725	3029.68809	1193.74235	2762.48279	1318.40561	2555.37140
76	1050.03621	3130.23568	1233.22463	2859.92290	1362.40911	2644.96639
77	1079.88103	3232.77542	1273.47676	2959.35454	1407.28477	2736.30986
78	1110.20405	3337.24782	1314.50362	3060.78228	1453.03847	2829.47523
79	1140.57467	3443.66108	1356.06164	3164.03010	1499.67605	2924.03782
80	1169.40540	3556.84239	1397.24249	3268.42969	1547.20330	3018.41597
81	1198.60300	3674.27175	1439.14323	3374.80127	1595.62602	3114.52213
82	1228.16779	3793.92248	1481.76745	3483.15194	1644.94994	3212.36220
83	1258.10007	3915.80198	1525.11867	3593.48858	1695.18079	3311.94197
84	1288.40015	4039.91733	1569.20041	3705.81788	1746.32425	3413.26716
85	1319.06833	4166.27534	1614.01615	3820.14634	1798.38598	3516.34337
86	1350.10490	4294.88250	1659.56937	3936.48029	1851.37161	3621.17615
87	1381.51014	4425.74502	1705.86348	4054.82585	1905.28674	3727.77097
88	1413.28434	4558.86881	1752.90191	4175.18899	1960.13696	3836.13323
89	1445.42779	4694.25949	1800.68805	4297.57547	2015.92780	3946.26828
90	1477.94078	4831.92237	1849.22525	4421.99092	2072.66479	4058.18143
91	1510.82354	4971.86249	1898.51685	4548.44078	2130.35343	4171.87796
92	1544.07636	5114.08457	1948.56618	4676.93032	2188.99919	4287.36312
93	1577.69950	5258.59304	1999.37653	4807.46469	2248.60752	4404.64213
94	1611.69321	5405.39201	2050.95116	4940.04885	2309.18382	4523.72023
95	1646.05777	5554.77558	2103.29362	5074.72947	2370.73351	4644.32416
96	1680.79341	5707.13091	2156.40755	5211.56650	2433.26195	4766.09107
97	1715.90037	5861.86354	2210.29555	5350.47825	2496.77450	4889.59964
98	1751.37890	6018.98022	2264.96081	5491.46956	2561.27647	5014.85147
99	1787.22924	6178.48759	2320.40651	5634.54517	2626.77318	5141.84803
100	1823.45163	6340.39210	2376.63580	5779.70968	2693.26991	5270.59066
101	1860.04630	6504.70012	2433.65180	5926.96758	2760.77190	5401.08059
102	1897.01348	6671.41783	2491.45763	6076.32325	2829.28441	5533.31895
103	1934.35338	6840.55132	2550.05637	6227.78094	2898.81264	5667.30675
104	1972.06625	7012.10654	2609.45110	6381.34482	2969.36178	5803.04491
105	2010.15227	7186.08931	2669.64486	6537.01893	3040.93702	5940.53423
106	2048.61168	7362.50533	2730.64070	6694.80721	3113.54351	6079.77543
107	2087.44471	7541.36020	2792.44162	6854.71351	3187.18637	6220.76911
108	2126.65153	7722.65939	2855.05062	7016.74158	3261.87072	6363.51580
109	2166.23238	7906.40826	2918.47067	7180.89507	3337.60165	6508.01591
110	2206.18744	8092.61207	2982.70474	7347.17755	3414.38423	6654.26981
111	2246.51692	8281.27597	3047.75578	7515.59248	3492.22353	6802.27773
112	2287.22103	8472.40502	3113.62669	7686.14326	3571.12457	6952.03985
113	2326.61124	8626.68041	3180.05700	7826.31602	3651.09236	7074.67253
114	2366.37645	8782.90316	3247.26142	7968.22409	3732.13192	7198.71872
115	2406.51686	8941.07629	3315.29967	8111.86948	3814.24821	7324.17839
116	2447.03265	9101.20298	3384.15537	8257.25415	3897.44620	7451.05143
117	2487.92400	9263.28627	3453.83112	8404.38002	3981.73084	7579.33769
118	2529.19113	9427.32914	3524.32952	8553.24895	4067.10704	7709.03697
119	2570.83418	9593.33452	3595.65315	8703.86275	4153.57972	7840.14900
120	2612.85333	9761.30522	3667.80457	8856.22319	4241.15377	7972.67346
121	2655.24878	9931.24405	3740.78632	9010.33199	4329.83406	8106.61000
122	2698.02069	10103.15371	3814.60093	9166.19083	4419.62546	8241.95820
123	2741.16924	10277.03686	3889.25091	9323.80133	4510.53280	8378.71760
124	2784.69460	10452.89611	3964.73875	9483.16511	4602.56091	8516.88772
125	2828.59691	10631.25785	4041.06787	9644.36633	4695.71460	8655.96536
126	2872.87640	10811.82174	4118.24024	9807.35944	4789.99867	8796.24050
127	2917.53316	10994.38944	4183.26211	9971.96068	4885.41788	8937.90515

Table E.1. (Continued)

dbh (cm)	Positive Correlation		Zero Correlation		Negative Correlation	
	minimum	maximum	minimum	maximum	minimum	maximum
128	2962.56737	11178.96342	4245.43850	10138.27575	4981.97701	9080.95854
129	3007.97915	11365.54612	4308.16257	10306.34535	5079.68081	9225.39984
130	3053.76885	11554.13996	4371.43679	10476.17072	5178.53399	9371.22822
131	3099.93645	11744.74726	4435.26345	10647.75301	5278.54129	9518.44279
132	3146.48211	11937.37031	4499.64529	10821.09338	5379.70740	9667.04262
133	3193.40598	12132.01137	4564.58465	10996.19296	5482.03701	9817.02679
134	3240.70820	12328.67266	4630.08350	11173.05283	5585.53479	9968.39430
135	3288.38909	12527.35632	4696.14462	11351.67405	5690.20540	10121.14416
136	3336.44864	12728.06448	4762.76988	11532.05765	5796.05349	10275.27532
137	3384.88700	12930.79923	4829.96145	11714.20464	5903.08369	10430.78674
138	3433.70429	13135.56260	4897.72182	11898.11598	6011.30061	10587.67731
139	3482.90084	13342.35661	4966.05292	12083.79265	6120.70886	10745.94594
140	3532.47646	13551.18322	5034.95679	12271.23555	6231.31302	10905.59147
141	3582.43177	13762.04438	5104.43547	12460.44561	6343.11768	11066.61277
142	3632.76643	13974.94198	5174.49110	12651.42370	6456.12739	11229.00864
143	3683.48073	14189.87790	5245.12547	12844.17070	6570.34671	11392.77789
144	3734.57497	14406.85398	5316.34066	13038.68743	6685.78016	11557.91930
145	3786.04913	14625.87202	5388.13838	13234.97472	6802.43229	11724.43162
146	3837.90350	14846.93381	5460.52084	13433.03338	6920.30758	11892.31360
147	3890.13789	15070.04110	5533.48967	13632.86421	7039.41055	12061.56398
148	3942.75276	15295.19563	5607.04649	13834.46796	7159.74569	12232.18145
149	3995.74823	15522.39908	5681.19341	14037.84539	7281.31745	12404.16471
150	4049.12410	15751.65314	5755.93199	14242.99724	7404.13031	12577.51243
151	4102.88084	15982.95946	5831.26409	14449.92424	7528.18872	12752.22330
152	4157.01840	16216.31969	5907.19140	14658.62711	7653.49710	12928.29596
153	4211.53691	16451.73541	5983.71540	14869.10654	7780.05989	13105.72905
154	4266.43666	16689.20824	6060.83772	15081.36321	7903.63352	13284.52120
155	4321.71759	16928.73972	6138.56028	15295.39782	8006.43323	13464.67103
156	4377.37985	17170.33142	6216.88450	15511.21101	8110.19546	13646.17714
157	4433.42355	17413.98488	6295.81194	15728.80346	8214.92339	13829.03815
158	4489.84897	17659.70159	6375.34412	15948.17581	8320.62023	14013.25262
159	4546.65606	17907.48307	6455.48255	16169.32869	8427.28915	14198.81915
160	4603.84512	18157.33078	6536.22888	16392.26273	8534.93353	14385.73630
161	4661.41608	18409.24623	6617.58459	16616.97858	8643.55652	14574.00266
162	4719.36908	18663.23085	6699.55095	16843.47684	8753.16113	14763.61678
163	4777.70423	18919.28608	6782.12955	17071.75811	8863.75069	14954.57721
164	4836.42179	19177.41335	6865.32180	17301.82302	8975.32836	15146.88251
165	4895.52173	19437.61410	6949.12909	17533.67216	9087.89729	15340.53122
166	4955.00416	19699.88970	7033.55261	17767.30613	9201.46045	15535.52188
167	5014.86935	19964.24157	7118.59407	18002.72553	9316.02133	15731.85302
168	5075.11725	20230.67109	7204.25479	18239.93094	9431.58306	15929.52319
169	5135.74813	20499.17965	7290.53592	18478.92296	9548.14860	16128.53092
170	5196.76195	20769.76860	7377.43876	18719.70217	9665.72107	16328.87474
171	5258.15880	21042.43931	7464.96477	18962.26916	9784.30376	16530.55317
172	5319.93881	21317.19313	7553.11504	19206.62451	9903.89960	16733.56474
173	5382.10224	21594.03140	7641.89100	19452.76880	10024.51188	16937.90797
174	5444.64903	21872.95548	7731.29389	19700.70262	10146.14369	17160.88607
175	5507.57944	22153.96670	7821.32510	19950.42656	10268.79830	17386.78794
176	5570.89345	22437.06636	7911.98550	20201.94118	10392.47846	17614.15135
177	5634.59113	22722.25582	8003.17884	20455.24585	10517.18741	17842.97465
178	5698.67276	23009.53638	8095.00715	20710.34106	10642.92842	18073.25621
179	5763.13829	23298.90935	8187.47132	20967.22943	10769.70438	18304.99438
180	5827.98780	23590.37608	8280.57260	21225.91089	10897.51853	18538.18755
181	5893.22158	23883.93785	8374.31187	21486.38601	11026.37376	18772.83405
182	5958.83956	24179.59596	8468.69018	21748.65540	11156.27313	19008.93230
183	6024.84184	24477.35175	8563.70889	22012.71967	11287.22003	19246.48064
184	6091.22866	24777.20650	8659.36871	22278.57940	11419.21717	19485.47745
185	6158.00019	25079.16151	8755.67081	22546.23521	11552.26775	19725.92114
186	6225.15614	25383.21810	8852.61638	22815.68772	11686.37501	19967.81006
187	6292.69694	25689.37756	8950.20608	23086.93753	11821.54159	20211.14263
188	6360.62271	25997.64120	9048.44106	23359.98528	11957.77073	20455.91723
189	6428.93338	26308.01031	9147.32249	23634.83158	12095.06560	20702.13226
190	6497.62908	26620.48621	9246.85134	23911.47707	12233.42923	20949.78614
191	6566.71000	26935.07019	9347.02823	24189.92240	12372.86428	21198.87725

Table E.1. (Continued)

dbh (cm)	Positive Correlation minimum	maximum	Zero Correlation minimum	maximum	Negative Correlation minimum	maximum
192	6636.17614	27251.76356	9447.85464	24470.16819	12513.37427	21449.40404
193	6706.02755	27570.56764	9549.33118	24752.21512	12654.96187	21701.36491
194	6776.26452	27891.48372	9651.45879	25036.06382	12797.63006	21954.75831
195	6846.88697	28214.51313	9754.23875	25321.71498	12941.38219	22209.58267
196	6917.89517	28539.65716	9857.67165	25609.16925	13086.22090	22465.83642
197	6989.28902	28866.91716	9961.75875	25898.42733	13232.14952	22723.51802
198	7061.06883	29196.29441	10066.50062	26189.48988	13379.17067	22982.62593
199	7133.23447	29527.79028	10171.89851	26482.35762	13527.28769	23243.15863
200	7205.78610	29861.40606	10277.95314	26777.03124	13676.50335	23505.11455
201	7278.72393	30197.14309	10384.66543	27073.51145	13826.82064	23768.49223
202	7352.04807	30535.00271	10492.03641	27371.79895	13978.24268	24033.29011
203	7425.75827	30874.98626	10600.06680	27671.89451	14130.77226	24299.50672
204	7499.85513	31217.09509	10708.75764	27973.79883	14284.41249	24567.14057
205	7574.33824	31561.33054	10818.10962	28277.51267	14439.16615	24836.19015
206	7649.20803	31907.69396	10928.12395	28583.03677	14595.03653	25106.65399
207	7724.46460	32256.18671	11038.80114	28890.37190	14752.02622	25378.53065
208	7800.10784	32606.81017	11150.14221	29199.51884	14910.13833	25651.81866
209	7876.13789	32959.56568	11262.14798	29510.47835	15069.37579	25926.51656
210	7952.55497	33314.45463	11374.81931	29823.25123	15229.74151	26202.62293
211	8029.35903	33671.47842	11488.15719	30137.83829	15391.23860	26480.13633
212	8106.55029	34030.63840	11602.16209	30454.24031	15553.86962	26759.05536
213	8184.12870	34391.93600	11716.83518	30772.45814	15717.63782	27039.37859
214	8262.09453	34755.37260	11832.17710	31092.49260	15882.54596	27321.10464
215	8340.44767	35120.94960	11948.18881	31414.34452	16048.59709	27604.23211
216	8419.18837	35488.66842	12064.87113	31738.01477	16215.79413	27888.75964
217	8498.31659	35858.53048	12182.22466	32063.50416	16384.13979	28174.68585
218	8577.83257	36230.53721	12300.25037	32390.81363	16553.63713	28462.00939
219	8657.73621	36604.69004	12418.94888	32719.94399	16724.28887	28750.72892
220	8738.02764	36980.99040	12538.32128	33050.89618	16896.09824	29040.84307
221	8818.70706	37359.43974	12658.36803	33383.67108	17069.06777	29332.35058
222	8899.77459	37740.03952	12779.09021	33718.26960	17243.20068	29625.25008
223	8981.23017	38122.79121	12900.48826	34054.69266	17418.49950	29919.54030
224	9063.07386	38507.69627	13022.56327	34392.94121	17594.96744	30215.21993

Table E.2. *Pseudotsuga menziesii* total tree C lookup table. Values excluding dbh are in kg C.

dbh (cm)	Positive Correlation minimum	Positive Correlation maximum	Zero Correlation minimum	Zero Correlation maximum	Negative Correlation minimum	Negative Correlation maximum
0	0.00004	3.12132	0.10558	2.67715	0.22037	2.12220
1	0.00417	5.06383	0.12158	4.91101	0.23357	6.52026
2	0.03782	7.91394	0.19629	6.50370	0.31074	4.52012
3	0.13271	15.62596	0.37873	12.91428	0.49385	9.06753
4	0.30920	18.32152	0.71028	15.33414	0.84236	12.26254
5	0.51155	23.75275	1.24675	20.45533	1.48472	17.89623
6	0.80120	28.16894	2.01058	24.36394	2.38992	20.47376
7	1.13483	38.56397	3.03674	33.72928	3.58870	28.74901
8	1.55011	40.05082	4.35624	35.05005	5.11779	29.92510
9	2.06193	41.91350	6.00474	36.70623	7.01296	31.33179
10	2.68065	44.45672	7.91006	38.73290	9.30902	33.03535
11	3.40200	53.16350	9.52322	44.97543	12.03980	38.58684
12	4.19575	62.94560	11.32829	53.72766	15.23818	46.84910
13	5.11654	73.73987	13.32656	63.42986	18.69811	56.01528
14	6.19473	85.56370	15.53064	74.09637	21.22785	66.10503
15	7.41672	98.43358	17.81536	85.64877	24.01936	77.13711
16	8.78998	112.36519	20.20151	98.09940	27.01002	89.12946
17	10.32181	127.37349	22.79365	111.52393	30.33532	102.09931
18	12.01931	143.94303	25.81472	126.18162	34.05539	116.06322
19	13.88941	161.73261	29.11457	141.89960	38.70524	131.03715
20	15.92172	180.90644	32.76026	158.76180	43.71199	147.03653
21	18.05005	201.47347	36.71696	176.74432	49.08371	164.07626
22	20.34784	223.39064	41.04101	195.86416	55.02327	182.17082
23	22.82004	246.81654	46.09021	216.60555	61.64266	200.89625
24	25.47149	271.57390	51.59185	238.64251	68.73222	220.61358
25	28.30691	297.68032	57.49405	261.91127	76.30804	241.34889
26	31.33093	326.16053	63.80727	286.42840	84.79523	263.11118
27	34.54805	356.26367	70.53891	312.20996	93.84415	285.90917
28	37.96272	387.92785	77.70371	339.27160	103.46778	309.75131
29	42.22750	421.17431	85.66669	367.91911	113.67880	335.29404
30	46.72382	456.02369	94.09403	397.88759	124.48960	361.92251
31	51.45441	492.49609	103.00287	429.19068	133.23904	389.64303
32	56.42195	530.61105	112.39436	461.84163	144.94705	418.46173
33	61.62910	570.38758	122.27663	495.85334	157.28158	448.38463
34	67.07851	610.82048	132.19897	530.68380	170.25453	479.41758
35	72.77276	652.84920	142.58153	566.84387	183.87752	511.56633
36	78.71445	696.48893	153.43062	604.34418	198.16197	544.83648
37	84.90613	741.75455	164.75254	643.19511	213.11903	579.23353
38	91.35032	788.66057	176.55346	683.40682	228.75965	614.76284
39	98.04953	837.22121	188.84474	724.98929	245.09456	651.42968
40	105.00625	887.45037	201.62860	767.95222	262.13426	689.23916
41	112.22294	939.36165	214.90989	812.30514	279.88905	728.19629
42	119.70203	992.96837	228.69432	858.05740	298.36905	768.30593
43	127.44595	1048.28355	242.98747	905.21812	317.58416	809.57280
44	135.45710	1105.31996	257.79482	953.79627	337.54411	852.00143
45	143.73786	1164.09013	273.12173	1003.80063	358.25842	895.59618
46	152.29059	1224.60630	288.97347	1055.23981	379.73647	940.36117
47	161.11764	1286.88049	305.08778	1107.93459	401.98743	986.30028
48	170.22133	1350.92448	321.04225	1161.59597	425.02034	1033.41708
49	179.60398	1416.74982	337.50031	1216.69565	448.84405	1081.71481
50	189.26787	1484.36787	354.46792	1273.24234	473.46727	1131.19630
51	199.25872	1553.78972	371.97513	1331.26362	498.89853	1181.90731
52	209.56146	1625.02631	390.01788	1390.76004	525.14625	1233.83234
53	220.17901	1705.97402	408.60199	1451.73987	552.21868	1286.97320
54	231.11422	1790.57482	427.73313	1514.21121	579.73564	1341.33093
55	242.36990	1877.69924	447.43417	1582.70780	605.61379	1396.90565
56	253.94880	1967.37363	467.71466	1658.14778	632.19108	1452.91222
57	265.85363	2059.62406	488.56190	1735.77372	659.47525	1509.71438
58	278.08704	2154.47636	509.98123	1815.60837	687.47404	1567.73797
59	290.48681	2251.95611	531.95736	1897.64383	716.19517	1626.98755
60	303.15041	2352.08867	554.50700	1981.91950	745.64636	1687.46761
61	316.14087	2454.89916	577.61424	2068.44948	775.83528	1749.18260
62	329.46062	2560.41249	601.21857	2157.21169	806.76962	1812.13687
63	343.11207	2668.65334	625.41478	2248.28846	838.45703	1876.33474

Table E.2. (Continued)

dbh (cm)	Positive Correlation minimum	maximum	Zero Correlation minimum	maximum	Negative Correlation minimum	maximum
64	357.09757	2779.64619	650.20756	2341.70129	870.90515	1941.78047
65	371.41946	2893.41531	675.60157	2437.47151	904.12160	2008.47824
66	386.08001	3009.98477	701.60138	2535.62029	938.11401	2077.36500
67	401.08148	3129.37845	728.21154	2636.16864	972.88996	2159.75712
68	416.42608	3251.62003	755.43651	2739.13745	1008.45704	2243.93450
69	432.11601	3376.73302	783.28072	2844.54743	1044.82281	2329.89951
70	448.15342	3504.74074	811.74855	2952.41916	1081.99481	2417.65425
71	464.54042	3637.00235	840.86225	3064.01936	1119.98058	2507.20047
72	481.27911	3773.73006	870.62866	3179.54661	1158.78764	2598.53967
73	497.23295	3913.58848	901.03382	3297.75488	1198.42350	2691.67304
74	513.39387	4056.60393	932.08195	3418.66779	1238.89562	2786.60153
75	529.89047	4203.34060	963.77977	3542.48543	1280.21150	2883.32581
76	546.72510	4353.40826	996.12944	3669.09295	1322.37857	2981.84633
77	563.90014	4506.73588	1029.13461	3798.48163	1365.40429	3082.16327
78	581.41796	4663.34918	1062.79937	3930.67457	1409.29607	3184.27660
79	599.28090	4823.27374	1097.12774	4065.69477	1454.06133	3288.18609
80	617.49134	4986.53498	1132.12374	4203.56512	1499.70745	3393.89127
81	636.05164	5153.15815	1167.79135	4344.30839	1546.24182	3501.39150
82	654.96416	5323.16840	1204.13452	4487.94727	1593.67179	3610.68593
83	674.23127	5496.59071	1241.15716	4634.50432	1642.00472	3721.77353
84	693.85533	5673.44991	1278.86317	4784.00202	1691.24793	3834.65312
85	713.83873	5853.77074	1317.25642	4936.46275	1741.40874	3949.32332
86	734.18384	6037.57775	1356.34075	5091.90882	1792.49444	4065.78261
87	754.89305	6224.89541	1396.11999	5250.36240	1844.51233	4184.65085
88	775.96876	6415.74804	1436.59657	5411.84469	1897.46966	4313.76941
89	797.41337	6610.15985	1477.77732	5576.37979	1951.37370	4445.38730
90	819.22930	6808.15490	1519.66610	5743.98969	2006.23167	4579.52454
91	841.41898	7009.75718	1562.26673	5914.69634	2062.05080	4716.20112
92	863.98484	7214.99052	1605.57412	6088.50851	2118.83830	4855.43701
93	886.92934	7423.87866	1649.59668	6265.45476	2176.60135	4997.25210
94	910.25495	7636.44524	1694.34220	6445.56266	2235.34713	5141.66630
95	933.96414	7852.71375	1739.81446	6628.85383	2295.08279	5288.69944
96	958.05943	8073.52539	1786.02065	6815.60318	2355.81547	5437.58674
97	982.54332	8299.13304	1832.96544	7005.90256	2417.55232	5588.12774
98	1007.41836	8528.59319	1880.64852	7199.47357	2480.30042	5741.26969
99	1032.68710	8761.92909	1929.07363	7396.33754	2544.06689	5897.03219
100	1058.35212	8999.16380	1978.24450	7596.51570	2608.85879	6055.43489
101	1084.41601	9240.32020	2028.16485	7800.02919	2674.68319	6216.49752
102	1110.88141	9485.42097	2078.83842	8006.89905	2741.54714	6380.23988
103	1137.75094	9734.48860	2130.26892	8217.14624	2809.45766	6546.68183
104	1165.02730	9987.54540	2182.46006	8430.79164	2878.42177	6715.84333
105	1192.71317	10245.70388	2235.42003	8648.19656	2948.44648	6886.69824
106	1220.81127	10524.56644	2289.34892	8884.50608	3019.53876	7076.23663
107	1249.32437	10813.92936	2344.12372	9130.24380	3091.70559	7274.63495
108	1278.25523	11108.66685	2399.68440	9380.57619	3164.95390	7476.74401
109	1307.60668	11408.82029	2456.03457	9635.53522	3239.29064	7682.58131
110	1337.38155	11714.43057	2513.17784	9895.15213	3314.72273	7892.16331
111	1367.58272	12025.53810	2571.11781	10159.45754	3391.25706	8105.50548
112	1398.21311	12342.18286	2629.85810	10428.48139	3468.90054	8322.62230
113	1429.27564	12664.40444	2689.39564	10702.24361	3547.66001	8543.52730
114	1460.77331	12992.24210	2749.73753	10980.77795	3627.54235	8768.23307
115	1492.70912	13300.09607	2810.80246	11256.68157	3708.55439	9021.34986
116	1525.08613	13635.38813	2872.75844	11543.78028	3790.70295	9257.42751
117	1557.90744	13976.09374	2935.53211	11835.66026	3873.99484	9497.64383
118	1591.17617	14322.23540	2999.12712	12132.34488	3958.43685	9742.02294
119	1624.89550	14673.83496	3063.54710	12433.85693	4044.03574	9990.58862
120	1659.06864	15030.91360	3128.79574	12740.21874	4130.79829	10243.36433
121	1693.69885	15365.39202	3194.57566	13024.60841	4218.73123	10472.27329
122	1728.78945	15704.38381	3261.18467	13312.90839	4307.84129	10704.43195
123	1764.34377	16047.90864	3328.62665	13605.13920	4398.13517	10939.86316
124	1800.36521	16395.98601	3396.90545	13901.32126	4489.61958	11178.58991
125	1836.85722	16748.63524	3466.02496	14201.47493	4582.30118	11420.63529
126	1873.82330	17105.87544	3535.98910	14505.62055	4676.18664	11666.02254
127	1911.26699	17467.72557	3606.80177	14813.77837	4771.28260	11914.77503

Table E.2. (Continued)

dbh	Positive Correlation		Zero Correlation		Negative Correlation	
(cm)	minimum	maximum	minimum	maximum	minimum	maximum
128	1949.19188	17834.20437	3678.46693	15125.96859	4867.59569	12166.91624
129	1987.60163	18205.33043	3750.98855	15442.21138	4965.13253	12422.46982
130	2026.49994	18581.12212	3824.37061	15762.52684	5063.89970	12681.45953
131	2065.89058	18961.59768	3898.61711	16086.93502	5163.90380	12943.90927
132	2105.75793	19346.77513	3973.73210	16415.45594	5265.15138	13209.84311
133	2143.40304	19736.67232	4049.71963	16748.10956	5367.64900	13479.28522
134	2181.42413	20131.30691	4126.58379	17084.91578	5471.40318	13752.25992
135	2219.82198	20530.69642	4204.32868	17425.89452	5576.42044	14028.79171
136	2258.59741	20936.78532	4282.95843	17771.06557	5682.70728	14308.90519
137	2297.75122	21352.53652	4362.47723	18120.44877	5790.27018	14592.62514
138	2337.28421	21773.34228	4442.88925	18474.06385	5899.11562	14879.97647
139	2377.19719	22199.22276	4524.19873	18831.93058	6009.25004	15170.98425
140	2417.49094	22630.19789	4606.40991	19194.06862	6120.67988	15465.67369
141	2458.16628	23066.28746	4689.52709	19560.49765	6233.41156	15764.07018
142	2499.22400	23508.39247	4773.55705	19931.47514	6347.45148	16065.35353
143	2540.66489	23956.66390	4858.50448	20307.05563	6462.80603	16369.42324
144	2582.48977	24410.17229	4944.37109	20687.00240	6579.48158	16677.21533
145	2624.69943	24868.93807	5031.16133	21071.33525	6697.48449	16988.75446
146	2667.29466	25332.98153	5118.87963	21460.07396	6816.82109	17304.06544
147	2710.27626	25802.32284	5207.53052	21853.23829	6937.49772	17623.17319
148	2753.64503	26276.98200	5297.11852	22250.84799	7059.52067	17946.10274
149	2797.40177	26756.97894	5387.64822	22652.92281	7182.89625	18272.87927
150	2841.54728	27242.33343	5479.12424	23059.48248	7307.63073	18603.52805
151	2880.43079	27673.44959	5545.12877	23439.40483	7433.73036	18925.09359
152	2919.67414	28109.33566	5611.77143	23823.62730	7561.20141	19250.35013
153	2959.27817	28550.00841	5679.05590	24212.16673	7690.05008	19579.31883
154	2999.24368	28995.48456	5746.98584	24605.03993	7820.28260	19912.02093
155	3039.57152	29445.78069	5815.56487	25002.26374	7951.90517	20248.47766
156	3080.26249	29900.91326	5884.79653	25403.85494	8084.92397	20588.71029
157	3121.31743	30360.89865	5954.68437	25809.83035	8219.34516	20932.74011
158	3162.73716	30825.75311	6025.23187	26220.20675	8355.17490	21280.58842
159	3204.52250	31295.49283	6096.44249	26635.00093	8492.41932	21632.27659
160	3246.67429	31770.13389	6168.31964	27054.22967	8631.08455	21987.82597
161	3289.19335	32249.69223	6240.86672	27477.90971	8771.17668	22347.25793
162	3332.08049	32734.18375	6314.08706	27906.05783	8912.70182	22710.59388
163	3375.33655	33223.62424	6387.98400	28338.69076	9055.66603	23077.85523
164	3418.96236	33718.02939	6462.56082	28775.82524	9200.07537	23449.06340
165	3462.95873	34217.41483	6537.82078	29217.47801	9345.93589	23824.23987
166	3507.32650	34721.79606	6613.76711	29663.66578	9493.25361	24203.40606
167	3552.06650	35231.18856	6690.40302	30114.40525	9642.03455	24586.58347
168	3597.17955	35745.60764	6767.73169	30569.71313	9792.28472	24973.79355
169	3642.66648	36265.06863	6845.75625	31029.60614	9944.01008	25365.05780
170	3688.52811	36789.58671	6924.47985	31494.10092	10062.13420	25760.39772
171	3734.76528	37319.17703	7003.90559	31963.21419	10177.26760	26159.83481
172	3781.37882	37853.85463	7084.03653	32436.96259	10293.53451	26563.39056
173	3828.36955	38393.63451	7164.87574	32915.36281	10410.93941	26971.08649
174	3875.73831	38938.53157	7246.42626	33398.43149	10529.48677	27382.94410
175	3923.48593	39488.56067	7328.69109	33886.18529	10649.18105	27798.98491
176	3971.61323	40043.73660	7411.67324	34378.64086	10770.02669	28219.23042
177	4020.12105	40604.07405	7495.37566	34875.81482	10892.02814	28643.70213
178	4069.01023	41169.58771	7579.80132	35377.72381	11015.18983	29072.42155
179	4118.28158	41740.29216	7664.95315	35884.38445	11139.51618	29505.41017
180	4167.93595	42316.20196	7750.83407	36395.81338	11265.01163	29942.68949
181	4217.97417	42897.33157	7837.44697	36912.02720	11391.68056	30384.28098
182	4268.39708	43483.69543	7924.79475	37433.04253	11519.52738	30830.20613
183	4319.20550	44075.30791	8012.88025	37958.87597	11648.55649	31280.48639
184	4370.40027	44672.18334	8101.70635	38489.54413	11778.77228	31735.14321
185	4421.98224	45274.33600	8191.27586	39025.06361	11910.17911	32194.19806
186	4473.95222	45881.78010	8281.59161	39565.45100	12042.78137	32657.67233
187	4526.31107	46494.52981	8372.65641	40110.72288	12176.58341	33125.58744
188	4579.05961	47112.59931	8464.47304	40660.89587	12311.58959	33597.96481
189	4632.19869	47736.00264	8557.04428	41215.98651	12447.80425	34074.82580
190	4685.72913	48364.75390	8650.37290	41776.01145	12585.23175	34556.19179
191	4739.65179	48998.86705	8744.46164	42340.98720	12723.87640	35042.08411

Table E.2. (Continued)

dbh	Positive Correlation		Zero Correlation		Negative Correlation	
(cm)	minimum	maximum	minimum	maximum	minimum	maximum
192	4793.96749	49638.35609	8839.31324	42910.93038	12863.74253	35532.52408
193	4848.67709	50283.23496	8934.93043	43485.85757	13004.83447	36027.53301
194	4903.78140	50933.51753	9031.31592	44065.78532	13147.15653	36527.13217
195	4959.28128	51589.21768	9128.47241	44650.73022	13290.71299	37031.34284
196	5015.17757	52250.34925	9226.40259	45240.70885	13435.50817	37540.18625
197	5071.47111	52916.92603	9325.10915	45835.73776	13581.54636	38053.68360
198	5128.16273	53588.96178	9424.59474	46435.83353	13728.83182	38571.85607
199	5185.25328	54266.47023	9524.86203	47041.01274	13877.36885	39094.72482
200	5242.74360	54949.46512	9625.91367	47651.29195	14027.16171	39622.31100
201	5300.63453	55637.96011	9727.75228	48266.68771	14178.21465	40154.63568
202	5358.92691	56331.96886	9830.38051	48887.21663	14330.53194	40691.71996
203	5417.62160	57031.50502	9933.80097	49512.89525	14484.11782	41233.58487
204	5476.71942	57736.58218	10038.01626	50143.74014	14638.97653	41780.25142
205	5536.22123	58447.21394	10143.02899	50779.76788	14795.11231	42331.74059
206	5596.12786	59163.41387	10248.84175	51420.99503	14952.52937	42888.07336
207	5656.44016	59885.19551	10355.45713	52067.43815	15111.23196	43449.27061
208	5717.15898	60612.57239	10462.87768	52719.11384	15271.22427	44015.35324
209	5778.28516	61345.55802	10571.10599	53376.03863	15432.51051	44586.34210
210	5839.81954	62084.16589	10680.14461	54038.22912	15595.09489	45162.25799
211	5901.76297	62828.40948	10789.99609	54705.70187	15758.98160	45743.12171
212	5964.11630	63578.30227	10900.66297	55378.47345	15924.17483	46328.95400
213	6026.88036	64342.64080	11012.16080	56058.60718	16090.67876	46911.34871
214	6090.05601	65117.97369	11124.48684	56745.30076	16258.49756	47493.65084
215	6153.64409	65899.48514	11237.63645	57437.44212	16427.63540	48080.51433
216	6217.64544	66687.19507	11351.61212	58135.04848	16598.09645	48671.95349
217	6282.06091	67481.12341	11466.41639	58838.13704	16769.88487	49267.98265
218	6346.89136	68281.29002	11582.05175	59546.72497	16943.00479	49868.61610
219	6412.13761	69087.71476	11698.52070	60260.82944	17117.46038	50473.86810
220	6477.80053	69900.41743	11815.82573	60980.46756	17293.25575	51083.75292
221	6543.88095	70719.41785	11933.96934	61705.65646	17470.39506	51698.28480
222	6610.37973	71544.73576	12052.95400	62436.41324	17648.88241	52317.47793
223	6677.29771	72376.39088	12172.78218	63172.75495	17828.72194	52941.34651
224	6744.63573	73214.40294	12293.45636	63914.69866	18009.91775	53569.90474
225	6812.39465	74058.79158	12414.97899	64662.26139	18192.47395	54203.16677
226	6880.57530	74909.57646	12537.35253	65415.46014	18376.39464	54841.14672
227	6949.17854	75766.77721	12660.57942	66174.31191	18561.68393	55483.85872
228	7018.20522	76630.41337	12784.66212	66938.83366	18748.34589	56131.31687
229	7087.65617	77500.50456	12909.60306	67709.04232	18936.38462	56783.53525
230	7157.53225	78377.07027	13035.40468	68484.95484	19125.80419	57440.52793
231	7227.83430	79260.13000	13162.06939	69266.58811	19316.60866	58102.30894
232	7298.56317	80149.70327	13289.59963	70053.95902	19508.80214	58768.89232
233	7369.71971	81045.80946	13417.99781	70847.08440	19702.38864	59440.29205
234	7441.30476	81948.46811	13547.26635	71645.98118	19897.37225	60116.52222
235	7513.31916	82857.69843	13677.40764	72450.66603	20093.75700	60797.59662
236	7585.76378	83773.51998	13808.42409	73261.15592	20291.54694	61483.52939

Table E.3. *Tsuga heterophylla* total tree C lookup table. Values excluding dbh are in kg C.

dbh (cm)	Positive Correlation minimum	Positive Correlation maximum	Zero Correlation minimum	Zero Correlation maximum	Negative Correlation minimum	Negative Correlation maximum
0	0.00028	4.35589	0.00142	3.67400	0.00146	2.39101
1	0.01387	6.62260	0.04526	4.89268	0.04634	3.96922
2	0.09198	11.95579	0.25609	9.23964	0.26140	7.95890
3	0.26577	22.99034	0.39273	18.11538	0.40586	15.94680
4	0.57259	23.40509	0.84685	18.55170	0.87169	16.38191
5	0.98122	24.65270	1.54800	19.54490	1.58942	17.05513
6	1.54826	26.42407	2.54490	20.97123	2.60754	18.01457
7	2.32275	28.74011	3.88407	22.88938	3.97268	19.30587
8	3.24013	31.65193	5.61031	25.36766	5.72968	20.97303
9	4.31318	35.21911	7.76682	28.80607	7.92170	26.58917
10	5.57585	39.50258	10.39536	35.53011	10.59031	33.43455
11	7.03873	46.56257	13.46573	43.11930	13.77555	41.21354
12	8.71197	57.79025	17.21702	53.29266	17.51599	49.95816
13	10.60540	76.47554	21.50694	68.46182	21.84877	59.69630
14	12.72851	106.16962	25.52008	92.86825	26.80966	73.65027
15	15.09050	117.56161	29.01319	103.42347	32.43311	80.56109
16	17.70031	129.78528	32.92297	114.88253	38.75228	90.14100
17	20.56665	142.87602	37.27740	127.25164	45.79909	102.51608
18	23.69800	156.89373	42.09871	140.54120	52.47618	115.74973
19	27.10263	171.77858	47.40631	154.75438	58.77804	129.85046
20	30.78862	187.53974	53.21416	169.85521	65.67408	144.82649
21	34.76386	204.23325	59.56382	185.86560	73.50725	160.68584
22	39.03608	221.88377	66.43939	202.82664	82.01470	177.43627
23	43.61286	240.45826	73.55240	220.72233	90.87366	195.08535
24	48.50160	263.80091	81.27162	239.55791	100.54758	213.64047
25	53.70959	289.92032	89.53047	260.45111	110.88956	233.10883
26	59.12695	317.48302	98.28209	284.46521	121.91277	253.49747
27	64.78442	346.50959	107.54997	309.69715	133.63029	274.81328
28	70.76735	377.01984	117.37059	336.16475	146.42440	297.06302
29	77.08202	409.03290	127.76847	363.88318	159.99175	320.25331
30	83.73461	442.56719	138.75396	392.86713	174.34689	344.39063
31	90.73118	477.64051	150.33709	423.13091	189.50389	369.48140
32	98.07772	514.27000	162.52753	454.68837	205.47635	395.53190
33	105.78008	552.47219	175.31885	487.55891	222.64416	422.54832
34	113.84404	592.26306	188.72111	521.75735	240.94594	450.53680
35	122.27529	633.65793	202.75343	557.29120	260.14244	479.50334
36	131.07943	676.67164	217.42446	594.17295	280.24375	515.49984
37	140.26197	721.31850	232.74260	632.41474	301.25958	553.42519
38	149.82835	767.61229	248.71601	672.02832	322.99997	593.25133
39	159.78393	815.56627	265.35295	715.12116	345.47755	634.99656
40	170.13398	865.19330	282.66170	764.72120	368.87720	678.50570
41	180.88373	918.62670	300.64895	816.35725	393.20684	723.79936
42	191.59885	979.50609	319.22723	869.98323	418.47397	770.73649
43	202.27739	1042.73708	338.43263	925.63857	444.68563	819.38558
44	213.31906	1108.33860	358.33026	983.38221	471.84841	869.86407
45	224.72804	1176.84464	378.44300	1043.73594	499.47313	922.70581
46	236.50844	1248.06193	398.97387	1106.51095	527.76681	977.71802
47	248.66437	1321.75446	420.16456	1171.47711	556.97577	1034.66590
48	261.19986	1397.65242	442.04234	1238.61644	586.81937	1093.83941
49	274.11891	1476.03568	464.59240	1307.97448	617.56737	1154.99952
50	287.42549	1556.91536	487.82007	1379.56494	649.22136	1218.16364
51	302.40235	1640.20540	511.73180	1453.39562	681.76700	1283.36042
52	317.85202	1726.00514	536.33159	1529.48357	715.21926	1350.59590
53	333.77933	1814.32105	561.62456	1607.84021	749.57687	1419.88790
54	350.15185	1905.19270	587.59408	1688.46219	784.87221	1491.18406
55	366.78019	1998.65258	614.14324	1771.26854	821.13106	1564.28071
56	383.87945	2094.71263	641.38450	1856.37201	858.35919	1639.39732
57	401.45360	2192.22433	670.40925	1942.64765	897.67494	1715.38195
58	419.50655	2292.29596	700.19229	2031.17801	938.03075	1793.33955
59	437.87993	2394.93726	730.73769	2121.97126	979.43230	1873.27666
60	456.57220	2500.15747	762.04944	2215.03509	1021.88511	1955.19942
61	475.73896	2607.96532	794.13138	2310.37675	1065.39456	2039.11357
62	495.38389	2718.36907	826.98729	2408.00305	1109.96588	2125.02445
63	515.51060	2831.37652	860.62082	2507.92040	1155.60416	2212.93706

Table E.3. (Continued)

dbh (cm)	Positive Correlation		Zero Correlation		Negative Correlation	
	minimum	maximum	minimum	maximum	minimum	maximum
64	536.12267	2946.99500	895.03556	2610.13482	1202.31436	2302.85602
65	557.22366	3065.23145	930.23498	2714.65195	1250.10129	2394.78564
66	578.81705	3186.09238	966.22251	2821.47705	1298.96969	2488.72988
67	600.90634	3309.58394	1003.00145	2930.61508	1348.92413	2584.69240
68	623.49495	3435.71188	1040.57507	3042.07062	1399.96909	2682.67659
69	646.58630	3564.48161	1078.94653	3155.84797	1452.10897	2782.68553
70	670.18374	3695.89821	1118.11894	3271.95111	1505.34802	2884.72202
71	694.29062	3829.96641	1158.09534	3390.38374	1559.69044	2988.78864
72	718.91026	3966.69067	1198.87872	3511.14928	1615.14030	3094.88770
73	744.04592	4106.07512	1240.47197	3634.25090	1671.70161	3203.02127
74	769.70087	4247.31221	1283.63884	3758.89773	1730.15678	3312.37979
75	795.87832	4391.33374	1327.65725	3885.85496	1789.78609	3423.72612
76	822.58147	4537.99588	1372.53190	4015.11713	1850.57801	3537.07102
77	849.81349	4687.30118	1418.26590	4146.68605	1912.53663	3652.41532
78	877.57752	4839.25228	1464.86230	4280.56333	1975.66599	3769.75964
79	905.87668	4991.94020	1511.48243	4415.85065	2038.21798	3889.11510
80	934.71409	5147.19949	1558.93736	4553.41341	2101.87912	4010.47165
81	964.09277	5305.03121	1607.22958	4693.25231	2166.65242	4133.82947
82	994.01583	5465.43621	1656.36156	4835.36784	2232.54082	4259.18858
83	1024.48623	5628.41522	1706.33571	4979.76039	2299.54720	4386.54891
84	1055.50703	5793.96879	1757.15440	5126.43021	2367.67439	4515.91022
85	1087.08119	5962.09734	1808.81996	5275.37739	2436.92515	4647.27220
86	1119.21169	6132.80114	1861.33469	5426.60193	2507.30221	4780.63441
87	1151.90144	6306.08036	1914.70083	5580.10372	2578.80824	4915.99630
88	1185.15341	6481.93501	1968.92061	5735.88252	2651.44588	5053.35725
89	1213.53299	6628.70818	2007.93095	5874.46066	2697.58734	5184.80427
90	1242.14786	6777.63733	2047.54314	6015.09860	2744.50167	5318.14007
91	1271.18927	6928.72304	2087.76125	6157.79483	2792.19210	5453.36398
92	1300.71584	7081.96581	2128.58929	6302.54784	2840.66187	5590.47526
93	1330.73033	7237.36605	2170.03112	6449.35614	2889.91415	5729.47311
94	1361.23550	7394.92412	2212.09056	6598.21824	2939.95213	5870.35666
95	1392.23409	7554.64033	2254.77129	6749.13268	2990.77896	6013.12502
96	1423.72884	7716.78706	2298.05715	6902.12887	3042.66991	6157.51612
97	1455.72246	7881.19979	2341.96359	7057.18677	3095.46338	6303.68698
98	1488.21766	8047.77993	2386.50126	7214.29377	3149.06371	6451.73132
99	1521.21713	8216.52752	2431.67356	7373.44848	3203.47392	6601.64812
100	1554.72356	8387.44254	2477.48384	7534.64948	3258.69700	6753.43633
101	1588.73961	8560.52498	2523.93538	7697.89542	3314.73591	6907.09489
102	1623.26794	8735.77476	2571.03140	7863.18492	3371.59363	7062.62270
103	1658.31119	8913.19180	2618.77508	8030.51665	3429.27309	7220.01864
104	1693.87200	9092.77598	2667.16952	8199.88929	3487.77723	7379.28158
105	1729.95298	9274.52718	2716.21779	8371.30153	3547.10897	7540.41035
106	1766.55676	9458.44525	2765.92292	8544.75210	3607.27122	7703.40380
107	1803.68592	9644.53002	2816.28787	8720.23975	3668.26687	7868.26075
108	1841.34306	9832.78133	2867.31558	8897.76324	3730.09882	8034.98000
109	1879.53075	10023.19899	2919.00895	9077.32136	3792.76993	8203.56038
110	1918.25157	10215.78283	2971.37083	9258.91294	3856.28309	8374.00068
111	1957.50807	10410.53266	3024.40404	9442.53680	3920.64114	8546.29970
112	1997.30278	10607.44829	3078.11137	9628.19183	3985.84693	8720.45627
113	2037.63826	10806.86242	3132.24842	9816.13758	4051.73767	8896.64832
114	2078.51702	11010.29625	3185.81729	10007.43530	4117.84968	9075.40291
115	2119.94158	11215.96086	3240.02442	10200.80765	4184.79735	9256.03472
116	2161.91444	11423.85642	3294.87230	10396.25382	4252.58346	9438.54267
117	2204.43811	11633.98312	3350.36339	10593.77300	4321.21076	9622.92563
118	2247.51507	11846.34112	3406.50014	10793.36442	4390.68204	9809.18252
119	2291.14779	12060.93064	3463.28500	10995.02733	4461.00005	9997.31227
120	2335.33874	12277.75184	3520.72036	11198.76100	4532.16755	10187.31381
121	2380.09038	12496.80495	3578.80862	11404.56476	4604.18730	10379.18608
122	2425.40516	12718.09019	3637.55217	11612.43794	4677.06205	10572.92806
123	2471.28551	12941.60777	3696.95337	11822.37990	4750.79455	10768.53872
124	2517.73388	13167.35796	3757.01458	12034.39005	4825.38755	10966.01708
125	2564.75267	13395.34099	3817.73812	12248.46781	4900.84380	11165.36213
126	2612.34431	13625.55716	3879.12632	12464.61265	4977.16605	11366.57292
127	2660.51120	13858.00676	3941.18150	12682.82406	5054.35703	11569.64852

Table E.3. (Continued)

dbh	Positive Correlation		Zero Correlation		Negative Correlation	
(cm)	minimum	maximum	minimum	maximum	minimum	maximum
128	2709.25574	14092.69009	4003.90596	12903.10155	5132.41950	11774.58801
129	2758.58030	14329.60750	4067.30199	13125.44469	5211.35620	11981.39048
130	2808.48728	14568.75935	4131.37187	13349.85308	5291.16986	12190.05509
131	2858.97904	14810.14601	4196.11787	13576.32632	5371.86323	12400.58097
132	2910.05794	15053.76788	4261.54226	13804.86408	5453.43905	12612.96730
133	2961.72635	15299.62539	4327.64730	14035.46605	5535.90006	12827.21329
134	3013.98660	15547.71899	4394.43521	14268.13196	5619.24899	13043.31818
135	3066.84104	15798.04915	4461.90826	14502.86155	5703.48860	13261.28121
136	3120.29199	16058.65965	4530.06867	14739.65463	5788.62161	13481.10168
137	3174.34178	16338.39220	4598.91867	14978.51103	5874.65078	13702.77891
138	3228.99273	16621.57500	4668.46046	15219.43061	5961.57883	13926.31224
139	3284.24715	16908.22493	4738.69628	15462.41327	6049.40852	14151.70103
140	3340.10733	17198.35922	4809.62833	15707.45893	6138.14258	14378.94468
141	3396.57556	17491.99516	4881.25881	15954.56760	6227.78376	14608.04264
142	3453.65414	17789.14991	4953.58991	16203.73924	6318.33480	14838.99435
143	3511.34534	18089.84044	5026.62383	16454.97392	6409.79843	15071.79932
144	3569.65144	18394.08419	5100.36276	16708.27171	6502.17742	15306.45705
145	3628.57469	18701.89780	5174.80889	16963.63272	6595.47450	15542.96710
146	3688.11736	19013.29856	5249.96438	17221.05709	6689.69243	15781.32905
147	3748.28169	19328.30341	5325.83143	17480.54502	6784.83393	16059.58711
148	3809.06994	19646.92946	5402.41219	17742.09671	6880.90178	16349.98191
149	3870.48433	19969.19355	5479.70885	18005.71244	6977.89871	16643.69783
150	3932.52709	20295.11262	5557.74704	18294.36945	7075.82748	16940.75028
151	3995.20046	20624.70335	5636.52646	18605.11354	7174.69084	17241.15461
152	4058.50664	20957.98306	5716.03048	18919.38957	7274.49154	17544.92579
153	4122.44784	21294.96850	5796.26131	19237.21313	7375.23233	17852.07942
154	4187.02628	21635.67625	5877.22114	19558.59970	7476.91598	18162.63038
155	4252.24414	21980.12322	5958.91219	19883.56509	7579.54524	18476.59408
156	4318.10362	22328.32637	6041.33665	20212.12515	7683.12286	18793.98540
157	4384.60691	22680.30219	6124.49673	20544.29536	7787.65161	19114.81971
158	4451.75617	23036.06772	6208.39462	20880.09166	7893.13425	19439.11213
159	4519.55358	23395.63937	6293.03252	21219.52944	7999.57353	19766.87755
160	4588.00131	23759.03391	6378.41262	21562.62448	8106.97223	20098.13108
161	4657.10152	24126.26798	6464.53711	21909.39243	8215.33310	20432.88762

Table E.4. *Acer macrophyllum* total tree C lookup table. Values excluding dbh are in kg C.

dbh (cm)	Positive Correlation minimum	Positive Correlation maximum	Zero Correlation minimum	Zero Correlation maximum	Negative Correlation minimum	Negative Correlation maximum
0	0.00005	0.04712	0.00535	0.03593	0.01405	0.01941
1	0.00189	0.36071	0.05307	0.30953	0.15488	0.20772
2	0.06660	1.35352	0.30035	1.19432	0.56809	0.94222
3	0.23863	3.30832	0.83661	2.90584	1.59626	2.19358
4	0.50051	6.14265	1.70225	5.40332	3.17648	3.92909
5	0.97973	10.21942	2.68906	8.92876	5.68895	5.92886
6	1.68910	15.33993	3.99389	13.39732	8.44026	8.95095
7	2.66903	21.17063	5.91660	18.56106	11.83380	12.64386
8	3.96002	28.03904	8.28591	24.66433	15.84100	17.10925
9	5.54880	35.99093	11.11613	31.75000	20.46003	22.40610
10	7.64025	45.06636	14.42156	39.85688	25.69156	28.58688
11	9.66912	55.30041	18.21656	49.02028	31.53854	35.69830
12	12.99735	66.72437	22.51529	59.27268	38.00544	43.78253
13	15.33909	79.36671	27.33142	70.64438	45.09765	52.87815
14	19.82973	93.25371	32.67804	83.16391	52.82104	63.02091
15	22.77532	108.41000	38.46048	96.84713	61.18169	74.24420
16	27.48639	124.85887	44.98731	111.75106	70.18572	86.57941
17	32.80239	142.62248	52.02139	127.87405	79.83922	100.05622
18	38.11874	161.72205	59.18151	145.12067	90.14817	114.15401
19	43.92207	182.17796	66.78752	163.59112	101.11844	129.26019
20	50.21041	204.00988	74.89864	183.31962	112.75577	145.46250
21	56.96843	227.23679	83.52122	204.32497	125.06574	162.78045
22	64.23086	251.87712	92.66140	226.62536	138.05380	181.23296
23	71.41006	277.94872	102.32514	250.23850	151.72529	200.83835
24	78.80052	305.46895	112.51825	275.18157	166.08539	221.61443
25	86.70049	334.45472	123.24638	301.47134	181.13917	243.57855
26	94.99971	364.92249	134.51503	329.12413	196.89158	266.74758
27	103.83977	396.88834	146.32958	358.15589	213.34747	291.13800
28	113.09492	430.36796	158.69525	388.58220	230.51156	316.76588
29	122.92278	465.37667	171.61716	420.41827	248.38850	343.64693
30	133.15419	501.92949	185.10031	453.67903	266.98282	371.79652
31	143.56242	541.28884	199.14960	488.37905	286.29897	401.22968
32	154.30820	585.88359	213.76981	524.53265	306.34131	431.96115
33	165.62174	632.56546	228.96562	562.15385	327.11413	464.00535
34	177.32511	681.56764	244.74165	601.25641	348.62163	497.37644
35	189.62323	732.72384	261.10239	641.85385	370.86793	532.08831
36	202.32122	786.28405	278.25463	687.41505	393.85711	568.15460
37	215.64145	842.06302	296.07398	736.00547	417.59313	605.58872
38	229.37183	900.32787	314.50562	786.68568	442.07994	644.40382
39	243.75238	960.87418	333.55313	839.48252	467.32140	684.61285
40	258.55365	1023.98647	353.22089	894.43897	493.32130	726.22855
41	274.03344	1089.44106	373.51237	951.58091	520.08340	769.26811
42	289.94483	1157.54000	394.43180	1010.95114	547.61138	818.72624
43	306.01859	1228.60823	415.98446	1072.61767	575.90889	869.46102
44	322.43886	1302.49791	438.17283	1136.58926	604.97951	922.24112
45	339.52737	1378.91745	461.00005	1202.88796	634.82678	976.83273
46	356.99963	1458.20679	484.47015	1271.55653	665.45419	1033.57206
47	375.16527	1540.08640	508.58629	1342.61855	696.86519	1092.17641
48	393.72234	1624.91386	533.35237	1416.11657	729.06317	1153.00076
49	412.99880	1712.38995	558.77150	1492.07333	762.05151	1215.74395
50	432.67527	1802.88987	584.84747	1570.53125	795.83350	1280.77981
51	453.09807	1896.09477	611.58330	1651.51223	830.41244	1347.78875
52	473.93048	1992.39742	638.98270	1735.05855	865.79155	1417.16350
53	495.50657	2091.49120	667.04865	1821.19221	901.97404	1488.59804
54	517.47853	2193.77997	695.78476	1909.95516	938.96308	1562.49753
55	540.24728	2298.88698	725.19390	2001.36717	976.76179	1638.48724
56	563.45095	2407.23027	755.27959	2095.47004	1015.37327	1716.98794
57	587.47703	2518.44665	786.04467	2192.28366	1054.80058	1797.63996
58	611.95571	2632.96197	817.49259	2291.84952	1095.04674	1880.87345
59	637.28367	2750.40305	849.62612	2394.18694	1136.11476	1966.32031
60	663.08333	2871.20341	882.44863	2499.33713	1178.00761	2054.41999
61	686.04852	2998.84861	916.05723	2611.04271	1220.72821	2148.66482
62	707.69729	3131.79611	950.40022	2727.44113	1264.27948	2247.51996
63	729.70233	3268.34207	985.44669	2847.29051	1308.66430	2349.29013

Table E.4. (Continued)

dbh (cm)	Positive Correlation minimum	maximum	Zero Correlation minimum	maximum	Negative Correlation minimum	maximum
64	751.63390	3408.97360	1021.20007	2970.66959	1353.88552	2454.47196
65	773.87667	3553.32883	1057.66325	3097.63652	1399.94597	2562.71410
66	795.98904	3701.90688	1094.83961	3228.27455	1446.84844	2674.52716
67	818.35978	3854.34123	1132.73200	3362.64646	1494.59571	2789.55719
68	840.53501	4011.14345	1171.34377	3500.84063	1543.19052	2908.32938
69	862.90694	4171.94309	1210.67775	3642.92518	1592.63560	3030.48801
70	885.00889	4337.26473	1250.43470	3788.98858	1642.62533	3156.57356
71	906.24001	4507.77254	1288.75168	3939.17515	1691.26056	3285.23379
72	926.99959	4683.08825	1327.63086	4093.53278	1740.58431	3417.90468
73	947.67671	4862.84402	1367.07139	4252.14322	1790.59562	3554.22241
74	967.76901	5047.60094	1407.07290	4415.11571	1841.29357	3694.75257
75	987.66549	5236.99096	1447.63464	4582.54007	1892.67726	3839.13204
76	1006.84778	5431.59155	1488.75629	4754.53442	1944.74581	3987.94367
77	1025.70348	5631.03580	1530.43719	4931.19790	1997.49839	4140.82638
78	1057.47235	5821.56208	1572.46755	5098.67920	2050.93417	4284.02475
79	1090.13079	6015.73824	1615.04676	5269.66835	2105.05236	4430.11330
80	1123.22056	6214.07850	1658.17431	5444.20647	2159.85221	4579.61326
81	1157.22419	6416.11645	1701.84932	5622.31023	2215.33298	4732.06568
82	1191.67640	6622.37340	1746.07131	5804.02063	2271.49395	4887.99965
83	1227.06733	6832.37471	1790.83948	5989.35397	2328.33445	5046.94871
84	1262.92470	7046.64870	1836.15339	6178.35113	2385.85380	5209.44970
85	1299.74621	7264.71264	1882.01228	6371.02805	2444.05138	5375.02872
86	1337.05260	7487.10183	1928.41576	6567.42551	2502.92657	5544.23024
87	1375.34901	7713.32553	1975.36312	6767.55910	2562.47877	5716.57299
88	1414.14930	7943.92599	2022.85401	6971.46951	2622.70742	5892.60898
89	1453.96592	8178.40458	2070.88778	7179.17200	2683.61196	6071.84962
90	1494.30587	8417.31044	2119.46409	7390.70718	2745.19188	6254.85434
91	1535.68883	8660.13718	2168.58235	7606.09000	2807.44666	6441.12730
92	1577.61501	8907.44081	2218.24227	7825.36101	2870.37582	6631.23527
93	1620.61120	9158.70727	2268.44328	8048.53483	2933.97887	6824.67519
94	1664.17084	9414.49937	2319.18512	8275.65198	2998.25539	7022.02103
95	1708.82775	9674.29553	2370.46728	8506.72678	3063.20492	7222.76261
96	1754.06866	9938.66534	2422.28953	8741.79971	3128.82705	7427.48102
97	1800.43431	10207.07976	2474.65138	8980.88481	3195.12138	7635.65895
98	1847.40475	10480.11513	2527.55263	9224.02254	3262.08753	7847.88456
99	1894.83236	10730.07848	2580.84046	9455.95993	3329.72512	8059.10886
100	1942.22172	10985.00114	2634.66998	9691.83205	3398.03380	8275.11009
101	1992.15877	11243.93006	2690.02105	9932.30076	3467.01322	8496.58937
102	2043.07039	11506.88479	2745.94349	10176.75553	3536.66306	8721.99473
103	2094.96936	11773.88479	2802.43718	10425.22169	3606.98300	8951.36007
104	2147.86848	12044.94939	2859.50205	10677.72452	3677.97273	9184.71922
105	2201.78053	12320.09782	2917.13802	10934.28933	3749.63197	9422.10595
106	2256.71831	12599.34941	2975.34503	11194.94141	3821.96043	9663.55398
107	2312.69457	12882.72310	3034.12303	11459.70605	3894.95784	9909.09694
108	2367.96963	13170.23799	3093.47199	11728.60851	3968.62394	10158.76842
109	2420.66287	13464.15610	3159.11246	12001.94083	4048.72645	10410.44966
110	2474.03225	13762.47493	3225.53381	12279.48171	4129.70739	10666.11367
111	2528.08021	14065.22097	3292.73811	12561.25677	4211.56855	10925.78643
112	2582.80917	14372.42065	3360.72741	12847.29162	4294.31175	11189.49386
113	2638.22153	14684.10035	3429.50374	13137.61180	4377.93878	11457.26183
114	2694.31968	15000.28636	3499.06915	13432.24283	4462.45141	11729.11612
115	2751.10601	15321.00493	3569.42565	13731.21022	4547.85142	12005.08248
116	2808.58289	15646.28222	3640.57526	14034.53938	4634.14057	12285.18655
117	2866.75266	15976.14435	3712.51998	14342.25574	4721.32062	12569.45396

Table E.5. *Alnus rubra* total tree C lookup table. Values excluding dbh are in kg C.

dbh (cm)	Positive Correlation minimum	maximum	Zero Correlation minimum	maximum	Negative Correlation minimum	maximum
0	0.00037	0.34165	0.02764	0.27458	0.06265	0.19647
1	0.00305	0.78882	0.09829	0.61754	0.23540	0.39203
2	0.04371	1.93848	0.36923	1.53496	0.80734	0.96194
3	0.12164	4.01955	0.85468	3.21215	1.63077	2.17021
4	0.27819	7.57894	1.68336	6.04025	3.26028	3.93117
5	0.60603	13.70114	3.00987	10.89393	6.05880	6.49827
6	1.00687	17.96333	4.14989	14.18297	7.44862	8.56508
7	1.62376	25.31276	6.04976	20.24147	11.32688	11.82792
8	2.64963	34.31836	8.34589	27.66537	15.61961	16.33360
9	4.15098	45.10878	11.03975	36.57662	19.93100	22.47447
10	6.07588	58.42932	14.15701	47.42793	24.75619	29.95848
11	7.29264	73.03510	17.64391	59.56922	30.09177	38.71598
12	9.50906	90.59849	21.56264	73.99647	35.93596	49.00202
13	10.70476	109.31359	25.85306	89.66278	42.28796	60.66100
14	13.52477	131.28432	30.58147	107.87775	49.14755	74.00889
15	14.96958	154.34961	35.69043	127.31860	56.51483	88.79364
16	17.73650	180.94052	41.24174	149.49199	64.39010	105.40644
17	20.56855	208.54280	47.18584	172.96249	72.77376	123.48836
18	23.92368	239.91651	53.57554	199.29564	81.66627	143.51951
19	27.30857	272.19591	60.36590	226.88526	91.06811	165.02391
20	31.29239	308.47164	67.60676	257.50011	100.97976	188.58364
21	35.26338	345.52797	75.25516	289.30691	111.40173	213.59568
22	39.84926	386.78749	83.31749	324.26216	122.33449	240.69268
23	44.30643	428.68575	91.75176	360.30263	133.77852	269.13239
24	49.51460	474.97851	100.63808	399.62210	145.73428	299.79254
25	54.59396	521.75370	109.93758	439.95065	158.20222	331.78828
26	60.51550	573.10130	119.69486	483.69276	171.18279	366.08271
27	66.24938	624.76262	129.87189	528.33515	184.67640	401.63546
28	72.92136	681.16274	140.51206	576.50187	198.68349	439.55934
29	79.29508	737.69721	151.54969	625.43059	213.20445	478.60275
30	85.67213	799.12700	162.42199	677.58471	228.23968	519.05001
31	91.50178	860.50266	173.59223	730.30610	243.78959	560.33114
32	98.22668	926.92173	185.09028	786.65016	259.85453	603.86782
33	104.28512	993.09036	196.86524	843.39626	276.43490	648.07570
34	111.30191	1064.44329	208.94711	903.83369	293.53104	694.55545
35	117.52558	1135.34283	221.28289	964.50806	311.14333	741.53010
36	124.77222	1211.56141	233.90297	1028.93762	329.27210	790.78893
37	131.09182	1287.11799	246.75193	1093.43296	347.91771	840.35398
38	138.50059	1368.12312	259.86095	1161.74341	367.08048	892.21241
39	144.60213	1448.25280	273.17093	1229.86659	386.76075	943.93778
40	151.58914	1533.95609	286.71418	1301.77511	406.95885	997.69185
41	157.33500	1618.56637	300.43012	1373.38246	427.67510	1051.31623
42	164.20284	1708.87153	314.35257	1448.88326	448.90980	1107.14147
43	169.71155	1797.86262	328.41666	1523.89601	470.66328	1162.65322
44	198.78839	1892.66659	356.15702	1611.75288	492.93583	1242.74479
45	207.29559	1985.93242	372.51621	1691.35618	515.72776	1303.24392
46	217.37567	2085.12638	389.26185	1775.07588	539.03936	1366.25803
47	226.28160	2182.55553	406.34784	1858.12575	562.87093	1429.00452
48	236.83578	2286.02563	423.82083	1945.34506	587.22275	1494.26969
49	246.14468	2387.50203	441.63326	2031.73343	612.09510	1559.12351
50	257.17774	2495.13010	459.83323	2122.33443	637.48828	1626.49846
51	266.89408	2600.53359	478.37170	2211.94250	663.40254	1693.31635
52	278.41098	2712.19762	497.29834	2305.80848	689.83818	1762.65677
53	288.33396	2821.40445	516.56159	2398.42017	716.79545	1831.08718
54	299.95086	2936.97902	536.21288	2495.24554	744.27462	1901.85705
55	307.32608	3018.58530	555.99019	2568.45548	772.27597	1968.99211
56	314.80830	3101.14966	576.12064	2642.61840	800.79974	2036.80205
57	322.39726	3184.63267	596.60377	2717.68891	829.84619	2105.24731
58	330.09269	3268.99461	617.43912	2793.62176	859.41558	2174.28808
59	337.89438	3354.19549	638.62621	2870.37185	889.50817	2243.88428
60	345.80210	3440.19504	660.16452	2947.89421	920.12419	2313.99558
61	353.81566	3526.95273	682.05351	3026.14400	951.26390	2384.58141
62	361.93487	3614.42779	704.29260	3105.07646	982.92754	2455.60093
63	370.15955	3702.57914	726.88119	3184.64694	1015.11535	2527.01305
64	378.48956	3791.36548	749.81867	3264.81326	1047.82756	2598.77643

Table E.5. (Continued)

dbh (cm)	Positive Correlation minimum	Positive Correlation maximum	Zero Correlation minimum	Zero Correlation maximum	Negative Correlation minimum	Negative Correlation maximum
65	386.92476	3880.74522	773.10436	3345.52822	1081.06442	2670.84949
66	395.46500	3970.67652	796.73755	3426.74732	1114.82616	2743.19037
67	404.11016	4061.11726	820.71750	3508.42609	1149.11301	2815.75697
68	412.86015	4152.02504	845.04344	3590.52003	1183.92520	2888.50690
69	421.71485	4243.35720	869.71457	3672.98466	1219.26296	2961.39753
70	430.67419	4335.07079	894.58991	3755.77361	1254.98460	3034.38593
71	439.73807	4427.12255	918.80876	3838.84367	1290.21898	3107.42890
72	448.90642	4519.46897	939.18454	3922.09457	1325.90885	3180.48295
73	458.17919	4612.06619	959.50772	4005.53158	1362.05330	3253.50430
74	467.55631	4706.21382	979.99586	4089.11073	1398.65145	3326.44885
75	477.03773	4834.51707	1000.64712	4172.78682	1435.70245	3399.27221
76	486.62342	4965.23063	1021.70077	4273.65711	1473.20546	3471.92967
77	496.31333	5098.36819	1043.19318	4394.11143	1511.15968	3544.37619
78	506.10744	5233.94347	1064.88234	4516.88434	1549.56432	3647.90045
79	516.00572	5371.96996	1086.76813	4641.98829	1588.41862	3759.90838
80	526.00815	5512.46114	1108.85053	4769.43588	1627.72182	3874.03866
81	536.11471	5655.43043	1131.12958	4899.23987	1667.47320	3990.30814
82	546.32540	5800.89116	1153.60541	5031.41312	1707.67205	4108.73373
83	556.64022	5948.85649	1176.27824	5165.96945	1748.31770	4229.33228
84	567.05915	6099.33960	1199.14830	5302.92083	1789.40946	4352.12076
85	577.58220	6252.35354	1222.21594	5442.28039	1830.94669	4477.11616
86	588.20938	6407.91121	1245.48151	5584.06118	1872.92875	4604.33539
87	598.94069	6566.02590	1268.94546	5728.27689	1915.35502	4733.79595
88	609.77616	6726.71020	1292.60824	5874.94059	1958.22491	4865.51466
89	620.71578	6889.97671	1316.47038	6024.06553	2001.53781	4999.50856
90	631.75958	7055.83806	1340.53174	6175.61096	2045.29317	5135.79474
91	642.90759	7224.30724	1364.79356	6329.64245	2089.49042	5274.39087
92	654.15981	7395.39688	1389.25653	6486.17942	2134.12903	5415.31428
93	665.51628	7569.11915	1413.92128	6645.23504	2179.20844	5558.58202
94	676.97702	7745.48624	1438.78845	6806.82259	2224.72816	5704.21124
95	688.54206	7924.51116	1463.85872	6970.95635	2270.68768	5852.22004
96	700.21143	8106.20608	1489.13280	7137.65100	2317.08649	6002.62580
97	711.98516	8290.58278	1514.61136	7306.91963	2363.92413	6155.44559
98	723.86328	8477.65343	1540.29511	7478.77585	2411.20011	6310.69701
99	735.84583	8667.43061	1566.18478	7653.23379	2458.91397	6468.39819
100	747.93284	8859.92650	1592.28107	7830.30731	2507.06528	6628.56695
101	760.12435	9055.15201	1618.58470	8010.00915	2555.65357	6791.21998
102	772.42038	9253.12015	1645.09639	8192.35419	2604.67844	6956.37614
103	784.82100	9453.84265	1671.81686	8377.35619	2654.13944	7124.05316
104	797.32622	9657.33087	1698.74684	8565.02862	2704.03617	7294.26849
105	809.93608	9863.59653	1725.88702	8755.38545	2754.36822	7467.04007
106	822.65064	10072.65180	1753.23812	8948.44114	2805.13521	7642.38638
107	835.46992	10284.50801	1780.80085	9144.20951	2856.33673	7820.32518
108	848.39398	10499.17689	1808.57589	9342.70473	2907.97240	8000.87474

Appendix F Height Prediction

Height Prediction

Tree volume and biomass are dependent upon tree height as well as diameter at breast height (dbh). Some biomass, and almost all volume, prediction equations incorporate this variation by requiring height as an input variable. An estimate of height at each dbh class for each species was therefore needed to produce biomass predictions to satisfy our methodology. We evaluated various methods of height prediction for ease of use and accuracy.

Several options for estimating heights were tested.

Option 1:use the mean measured height for each species and dbh class from the Forest Inventory and Analysis (FIA) Integrated Database (IDB) version 1.4 (Hiserote and Waddell 2004),
Option 2: regress height on dbh class using all measured heights for each species,
Option 3: regress height on dbh class using mean measured height for each dbh class,
Option 4: regress height on dbh class using all measured heights for each species, weighted by 1/dbh, and
Option 5: regress height on dbh class using mean height for each dbh class weighted by 1/dbh.

Option 1

Option 1 applied mean measured height for each species and 1-cm dbh class from the IDB for Northwest Oregon (NW OR). This was the simplest approach and probably accurately described the FIA data. Because FIA data were presumably representative of the trees in NW OR, using mean FIA measured heights would also provide unbiased data for the NW OR tree population.

However, because height measurements are more time-consuming to obtain than dbh, within the 12,537 trees inventoried in NW OR by the FIA only 7155 trees have measured heights. The remainder have heights estimated in the field or office. Recent work has indicated that equations used to estimate heights for a small number of trees where height had not been measured were found to be inaccurate,

and new equations are under development (T Barrett personal communication 25 September 2004). We believed that measured heights would give better accuracy, although some information might be lost by not incorporating field-estimated heights. Therefore, whenever no measured heights existed within a 1-cm dbh class for a species, there was no height available for use in a volume or biomass equation unless some interpolation or extrapolation method was employed. Limited data resulted in an apparent fluctuation of the mean height at large dbhs, as illustrated in Figure F.1. Option 1 was therefore rejected in favor of a method that could determine height for every dbh class, to facilitate working with all FIA data, data from other studies, or with theoretical dbh distributions.

Fluctuating mean heights can be smoothed by creating regression functions of height on dbh. There are several ways to create the regression relationship and many possible mathematical forms that equation could take. After reviewing height equation literature, we chose the equation form

$$h = 1.37 + \left(b_0 \left[1 - e^{(b_1 d)} \right]^{b_2} \right),$$

where

h = total tree height in m,
d = dbh outside bark in cm,
e = 2.71828…,
b_0 = maximum height,
b_1 = steepness parameter, and
b_2 = curvature parameter.
This is a Chapman-Richards function that allows direct comparison with the set of equations developed for many western Oregon species by Garman et al. (1995). They created separate equations for ecological zones, site classes, and in some cases, elevation ranges. This equation form is useful for its asymptotic behavior, which prohibits the unrealistic height estimates given by many other equation forms at large dbhs. We created only one equation for each NW OR species, but comparison
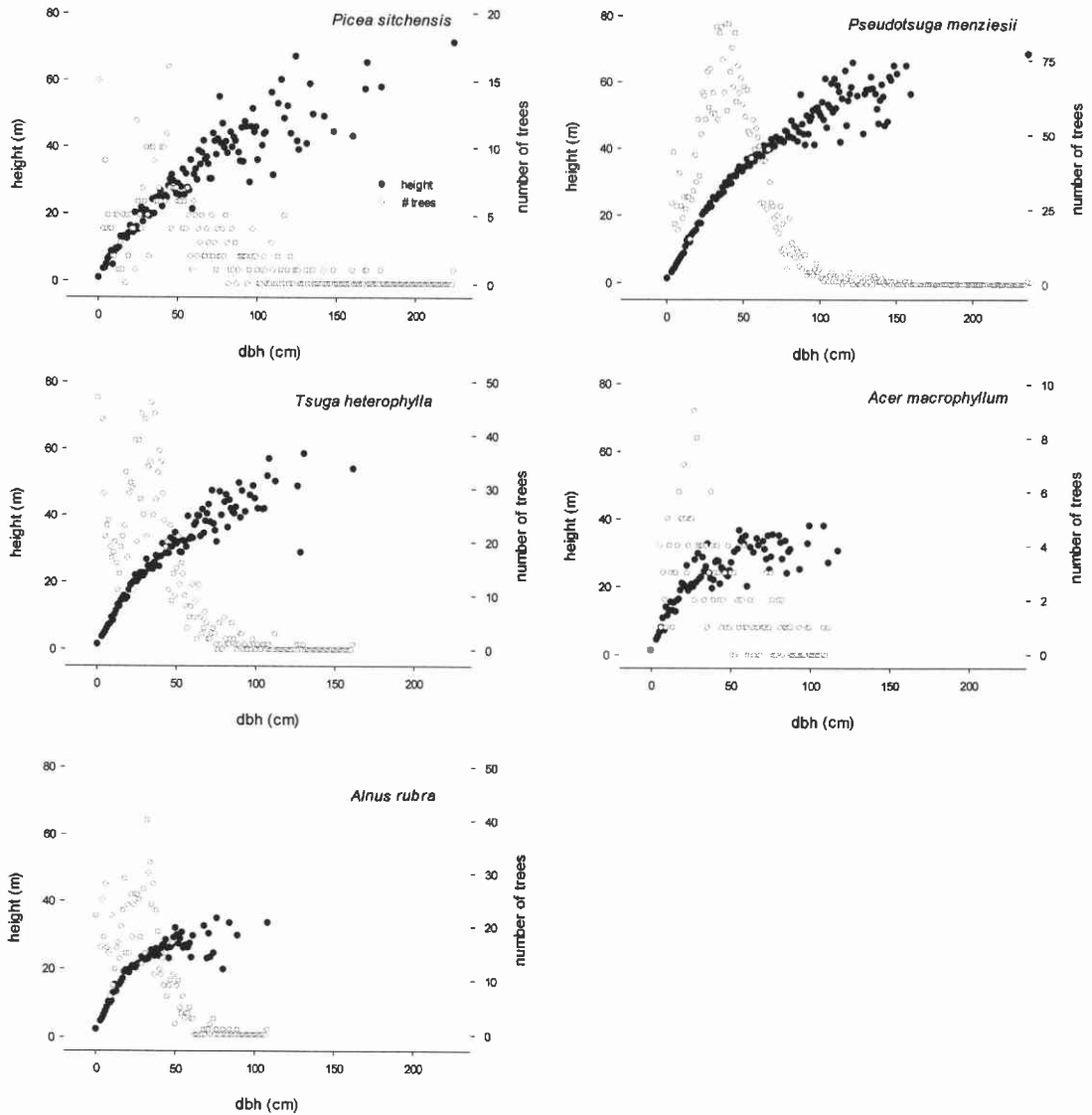
Figure F.1. Mean height and number of trees with measured heights by dbh class for target species in NW OR. At large dbhs mean height begins to fluctuate due to limited sample size. Dbh and height scales were kept constant for all species, the number of trees axis was allowed to vary.

with Garman equations might later prove instructive in determining likely sub-regional variations. The Chapman-Richards form was fit by nonlinear regression in SAS (SAS System 2000).

Option 2

The first possibility for creating regression equations was to use all measured heights in NW OR. This seemed an advantageous approach in that all relevant data would be incorporated, and abundant data might limit the number of times the program failed to converge. Residuals for this and the following possibilities are displayed in Figure F.2 for *Pseudotsuga menziesii*. An undesirable non-homogeneity of variance is clearly present.

Option 3

Regressions were created using only the mean measured height in each dbh class. This reduced processing time and data storage space. It also reduced the absolute amount of residual variation because the mean removed much of the variation before regression. There was a suggestion of bias at small dbhs that was absent, or at least not discernable, when all heights were used to create the prediction equation (Figure F.2).

Option 4

The third regression method weighted all measured heights with 1/dbh, as was done by Garman et al. (1995). This dramatically reduced magnitude of residuals. However, it seemed that the opposite pattern of heteroscedasticity was present, although that effect might be created by the limited observations at higher dbhs.

Option 5

The final regression method weighted mean measured height by 1/dbh. Residual magnitude was again much reduced over the unweighted regression, but a pattern of alternating negative and positive bias was apparent.
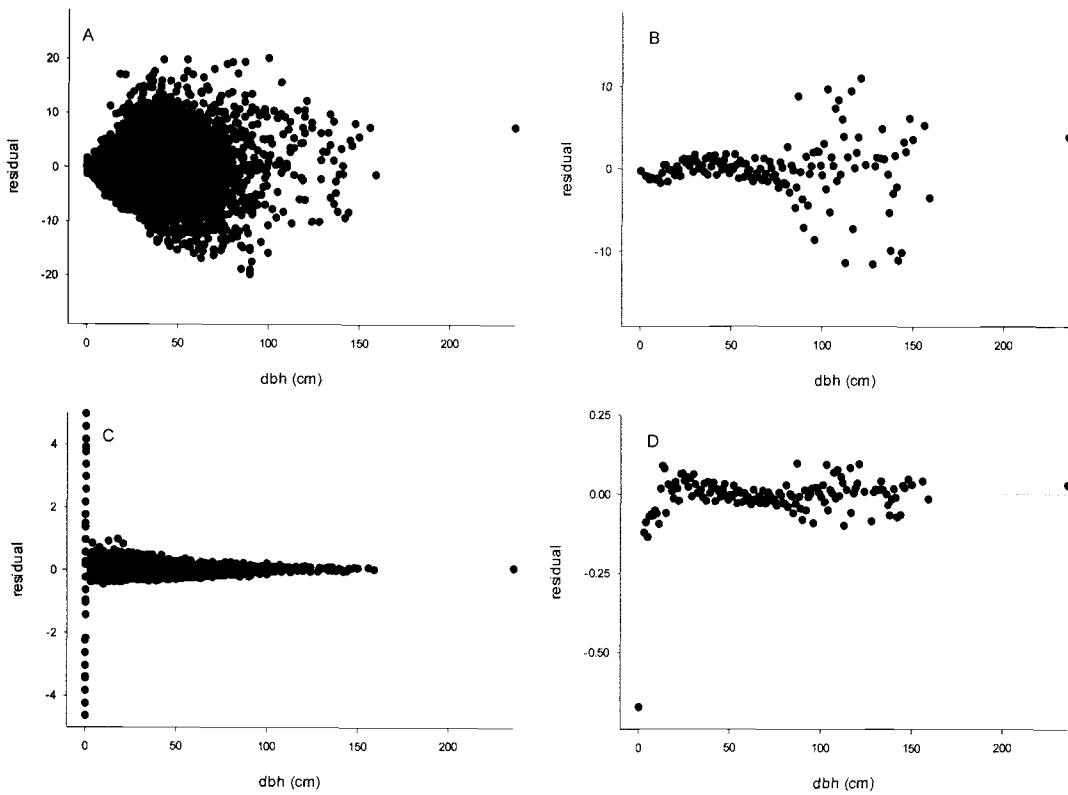
Figure F.2. Residuals from four height regression options from *Pseudotsuga menziesii* in NW OR. Residuals in: Figure A (option 2) represent unweighted regression of 3,950 trees with measured heights; B (option 3) are from unweighted regression of mean height on dbh; C (option 4) are from regression of all measured heights weighted by 1/dbh; and D (option 5) were produced by regressing mean height weighted by 1/dbh.

Option 3 (regression of means only) produced the equation with the highest asymptote, and option 4 (regression of all measured heights weighted by 1/dbh) the lowest (Figure F.3). To test bias introduced by these equations, we ran Shaw's (1979) *Pseudotsuga menziesii* stem wood biomass equation with all 5 height estimation options on all *Pseudotsuga menziesii* with measured heights in NW OR. Measured heights from the IDB were employed to provide the "true" estimate of biomass. Estimated total biomass in NW OR represented by trees was obtained by summing individual biomass predictions that had been expanded to NW OR using FIA expansion factors. Options 2 and 4 over-predicted by 0.26 and 0.37%, respectively, while Options 3 and 5 under-predicted by 0.28 and 0.16%.

There appeared to be a tradeoff between the main factors considered here for choosing a method for height prediction: homogeneity of variance, introduced bias, and speed of calculation. No option appeared entirely free from heteroscedasticity, though in Option 4 (C in Figure F.2) it might simply be an artifact of sample size. The second and fourth options (A and C in Figure F.2) slightly over-predict biomass, the third and fifth under-predict it, but none were dramatically different from biomass predicted with measured heights. Because options 2 and 4 used all measured heights, regressions take longer to perform. Despite its less than perfect residual plot, option 5 was chosen to produce height equations used for this study based on ease of calculation and lowest bias at the regional level. Parameters and standard errors for all regressions appear in Table F.1.
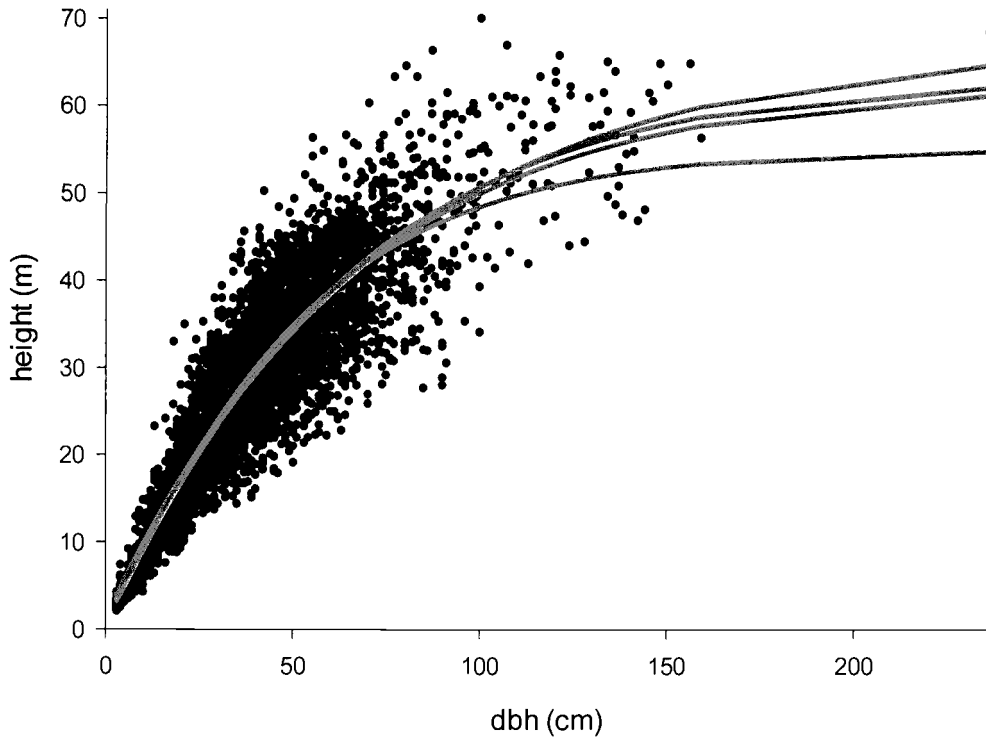
Figure F.3. *Pseudotsuga menziesii* predicted heights from regressions. Black dots represent 3,950 measured heights recorded in the FIA IDB for NW OR. Regressions in order from top to bottom are from options 3, 5, 2, and 4.

Table F.1. Parameters and standard errors (SE) for NW OR height equations derived from option 5. B_0 defines the asymptote, b_1 relates to the slope of the regression line, and b_2 to its curvature. The equation formula is given in the text. Equations are intended for use with dbh in cm and height in m.

Scientific Name	b_0 (SE)	b_1 (SE)	b_2 (SE)	n	MSE
Picea sitchensis	62.9868 (5.6187)	-0.0116 (0.00235)	0.9972 (0.0692)	117	22.17
Pseudotsuga menziesii	62.0553 (1.6823)	-0.017 (0.00129)	1.1268 (0.0427)	140	9.07
Tsuga heterophylla	51.8357 (2.5683)	-0.019 (0.00244)	1.0451 (0.0573)	100	8.96
Acer macrophyllum	30.0785 (1.1677)	-0.0493 (0.00764)	1.1177 (0.1205)	80	14.21
Alnus rubra	28.8684 (1.0323)	-0.0443 (0.00573)	0.9798 (0.0714)	69	4.97

Appendix G Acronyms and Unit Conversions

Table G.1. Acronyms used in the text.

Acronym or Abbreviation	Full Name
AK	Alaska
BLM	Bureau of Land Management
C	Carbon
CA	California
CO_2	Carbon Dioxide
dbh	diameter at breast height
DNR	Department of Natural Resources
FI	Forest Industry
FIA	Forest Inventory and Analysis
FPA	Forest Practices Act
FS	Forest Service
FSDB	Forest Science Databank
g	gram
GAP	Gap Analysis Project
GCM	General Circulation Model
ha	hectare
km	kilometer
m	meter
Mg	Megagram
MP	Miscellaneous Private
MSE	Mean Square Error
NF	National Forest
NFP	National Forest Plan
NP	National Park
NW OR	Northwest Oregon
OP	Other Public
OR	Oregon
OSU	Oregon State University
Pg	Petagram
PL	Private Lands (FI + MP)
PNW	Pacific North West
RMSE	Root Mean Square Error
Tg	Teragram
USDA	United States Department of Agriculture
US	United States
USDI	United States Department of the Interior
UW	University of Washington
WA	Washington
WOR	Western Oregon
WWA	Western Washington

Table G.2. Units and conversion factors.

Unit (Abbreviation)	Multiply By	Unit (Abbreviation)
centimeter (cm)	0.3937	inches (in)
meter (m)	3.281	feet (ft)
kilometer (km)	0.621	mile (mi)
gram (g)	0.03527	ounce (oz)
kilogram (kg)	2.2046	pound (lb)
Megagram (Mg)	1×10^6	grams (g)
Teragram (Tg)	1×10^{12}	grams (g)
Petagram (Pg)	1×10^{15}	grams (g)
hectares (ha)	2.47	acres (ac)