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ASSESSMENT OF PREDICTION BIAS IN CROWN BIOMASS EQUATIONS FOR IMPORTANT CONIFER SPECIES OF THE INLAND NORTHWEST

By

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Assessment of Prediction Bias in Crown Biomass Equations for Important Conifer Species of the Inland Northwest

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Prediction equations are used worldwide to estimate the amount of biomass at the tree, stand, and landscape level. These estimates provide valuable information to land managers for use in fire modeling, land tax assessments, carbon emission offsets, and timber sale contracting. To this end, several crown biomass equations have been developed for local, regional, and national scale biomass estimation across the United States. The prediction equations most commonly used in the inland northwest, USA, were developed by Brown (1978) and Jenkins et al. (2003). Because of the widespread application of these equations for managerial and scientific use, crown mass data for several important conifer species were collected and used to examine the direction and magnitude of bias associated with predictions made from the diameter-based equations of Brown and of Jenkins et al. A total of 140 trees of 4 different conifer species were sampled, providing 725 individual unbiased estimates of total crown mass. Regression analyses were run on differences between crown mass estimates and the Brown and Jenkins et al. equation predictions to determine whether any bias was present. Results of the regression analysis determined that bias was present in both equation sets. Brown's equations were found to over-predict the crown mass of ponderosa pine (*Pinus ponderosa*) and western larch (*Larix occidentalis*), and under-predict the crown mass of Douglas-fir (*Pseudotsuga menziesii*) and lodgepole pine (*Pinus contorta*). Further, it was found that the magnitude of the bias increased with diameter at breast height (DBH) for all species but western larch. The Jenkins et al. equations were found to over-predict the crown mass of Douglas-fir and western larch, while no significant bias existed for lodgepole pine or ponderosa pine. Again, the magnitude of bias was generally found to increase with DBH. Bias correction models are presented which, if used within the inland northwest, could potentially increase the accuracy of these equations.

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Glossary

BA. Basal Area. This is a measurement of the density of the forest around the sample trees. It is a ratio describing the aggregate area of wood at breast height (1.37 m) relative to total land area, and is expressed as m^2/ha (ft^2/acre).

BCM. Bias Correction Model. The bias correction model is a DBH-based regression fit to describe the trend in differences between equation predictions and RBS field estimates.

BLC. Height to the Base of the Live Crown. The base of the live crown is defined as the point on the stem where live branches extend into at least two quadrants of the tree's trunk. Height to the BLC may or may not be the same as the height of the lowest live branch.

CB. Crown Biomass. Total crown mass including all branches, live or dead, foliage, cones, and tree top from 5 cm stem diameter.

CR. Crown Ratio. A ratio of the amount of a tree's total length that is occupied by the live crown. This ratio can be ocularly estimated on standing trees, or computed by dividing crown length by the tree height.

CL. Crown Length. This is the distance from the base of the live crown to the top of the tree, calculated by subtracting the base of live crown from the down height.

DBH. Diameter at Breast Height. The girth of the tree stem measured at 1.37 meters (4.5 feet) above the base of the uphill side of the tree.

DBLC. Diameter of the tree stem measured at the height of the base of the live crown.

HT. The height of the tree, measured with a cloth tape, is the total length of the tree measured after the tree has been cut and is lying on the ground.

INW. Inland Northwest. The region referred to as the inland northwest stretches from the Cascade Mountains in Washington and Oregon, north from the Blue Mountains in Oregon and the Snake River in Idaho, and east to the continental divide in Montana and Idaho, south of the Canadian border.

LLB. Lowest Live Branch. This branch is the lowest live branch in the tree’s crown. Its height from the ground is measured; also, this is where RBS begins.

RBS. Randomized Branch Sampling. This is the general sampling strategy used to estimate the crown biomass of selected trees in this research project.

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Chapter 1

Introduction

Forests cover a vast area in the inland northwest (INW) region of the USA. These forests are used for timber production, recreation, ecosystem services (such as the provision of freshwater), and can potentially be used for bioenergy feedstock, or to offset carbon emissions through a cap and trade carbon credit system (Daniels, 2010). Because of the intensive use of forest resources for the support of human culture, adequate measures or estimates of forest biomass are necessary to determine growth and yield of a stand for long-term management objectives, or to accurately inventory what is on site to assign a fair value to the volume that is to be removed.

One facet of science is the continuing review of past studies in an effort to validate the assumptions used and conclusions reached. This review is very important for keeping the wealth of information active and up to date with new findings. More importantly, it allows us to discern which scientific articles and ideas are useful to the topic at hand, such as which biomass prediction equations are accurate and useful for use in any particular area. In an effort to measure the crown biomass of major tree species in the inland Rocky Mountain west, previously published prediction equations, both regional and local in scope, were researched. The most widely used of these equations were identified and a sampling strategy was implemented to evaluate the equations' biases and accuracies.

Many biomass prediction equations currently in use supply a tree-level estimate of crown, stem, or total tree mass. These predictions are then scaled up to the stand or landscape level to get a sense of how much biomass is resting on a given area. Often, the equations allow one to estimate the portion of a tree's overall mass found in different components such as foliage, branches, or stem bark. An alternative approach is to directly estimate stand level biomass, using measures of stand density, average tree height, and average diameter at breast height (DBH). Using a tree-level approach potentially offers more information to land managers for applications such as uneven-aged management or fire hazard reduction projects where tree distribution data are required and total stand biomass is of limited utility.

However, it is difficult for individual land managers to collect and create their own set of biomass prediction equations because of the destructive nature of the methods needed for measurements of mass, as well as the cost and time required for the processing and drying of plant materials. As a result, land managers may have to rely on published equations to estimate the biomass in their forests, with no ready means of verifying whether the prediction equation they are using is appropriate. Furthermore, many biomass equations produced were not intended for commercial use, were based on small or poorly-distributed samples, or were simply created in an area far removed from where they are being considered for application.

To address these issues, data collected for this study came from several different tree species over a wide range of diameter classes from a plethora of site types and locations throughout the region during two successive field seasons. Further, sample trees were collected from several different land ownerships, including corporate, federal, state, and tribal lands. By collecting a large and distributed sample in this way, the hope was that the bias of selected biomass prediction equations could be evaluated for the region as a whole, reducing the possible associations that may exist for different trees growing under isolated conditions, managerial or otherwise, and providing expansive results that can be used throughout the planning area. To put it another way, while it may be true that trees of a given species and a set DBH growing on moist sites have heavier crowns than trees with similar attributes growing on dry sites, an assessment of the average, across-site properties of a particular biomass equation can be made if trees are selected from across different site types.

The specific objectives of this research project were (1) to research the scope and limitations of previously developed crown biomass equations for commercial tree species of the INW, (2) to develop and implement a crown sampling protocol, and to describe crown biomass allometries for Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), and western larch (*Larix occidentalis*), and (3) to investigate the magnitude and sources of bias in the most widely used crown biomass equations in the INW.

Chapter 2

Literature Review

2.1 Overview

There is a considerable amount of research that has been conducted in the area of standing tree biomass at many different levels. Interest in describing relationships of tree crown biomass to several variables such as DBH, tree height, or stand density has waxed and waned since the late 1950s during periods of economic uncertainty and high energy costs. Since that time, it has been speculated that tree biomass may be useful for describing site productivity (Lefsky et al., 2005), sequestering carbon (Hoen and Solburg, 1994), deriving renewable energy (Buchholz et al., 2011), or modeling fire behavior and impact.

Worldwide, there are numerous studies that look at tree biomass for a range of study objectives over a variety of species and site conditions. Nationwide, much of the work has been done in specific regions, and mostly for management intensive, commercial rotation forestry where maximizing merchantable products is priority. Within the inland northwest (eastern Washington, northern Idaho, western Montana), there has been very little work done. Two major sets are most commonly used within the region, Brown (1978) and Jenkins et al. (2003), for large scale forest management. Because of the widespread use of these two major equation sets, as well as the lack of knowledge about other biomass equations available, the purpose of this literature review is to identify methods used to create biomass equations within the region, to review sampling design and sizes, to identify site characteristics and applicability in other areas, to determine inefficiencies and shortfalls, and to recognize interesting points that stand out within past studies.

2.2 Background Information

To prepare reliable estimates of biomass for the myriad of resource uses and management decisions to be made, we must first have accurate regression equations for each species of interest. Site specific equations have been found to have substantial errors when used outside the area where they were produced (Feller 1992). To provide reliable, accurate estimates at a large scale, regional equations must encompass a range of site, stand, and tree conditions for a land manager to be confident in the predictions; to some extent this has been done, as discussed below. However, the validity of many of the equations produced is questionable considering the generally small sample sizes and small range of sample sites for any given species due to the time required for destructive sampling, creating equations that may not be useful across a wide in other areas.

There are various literature reviews available that have compiled a great deal of the published biomass equations for the majority of commercial tree species in North America, as well as for the Pacific Northwest (Jenkins et al. 2004; TerMikaelian and Korzukhin 1997). One issue with these large reviews is their disregard for different sampling methods or techniques of equation development. Also, they fail to identify the particular regions that an equation may have been built for; often an equation is created for a specific stand type or management purpose, creating equations that are utterly site specific.

Probably the most well known compilations of biomass equations for North American tree species are Jenkins et al. (2004) and Ter-Mikaelian and Korzukhin (1997). Jenkins et al. (2004) is a US Forest Service technical report which explains certain transformations that were applied to produce some degree of conformity among the equations it lists. It lists various component equations which provide predictions for components such as live branches, foliage, stemwood and stembark (there are 37 component classes listed). Overall, it indexes 169 published biomass equations for Douglas-fir (*Psuedotsuga menziesii*), 41 for lodgepole pine (*Pinus contorta*), 29 for ponderosa pine (*Pinus ponderosa*), and 8 for western larch (*Larix occidentalis*). Ter-Mikaelian and Korzukhin describe similar equation transformations for conformity. Their database lists various biomass component equations: 29 for Douglas-fir, 6 for lodgepole pine, 9 for ponderosa pine, and 3 for western larch. These equations were developed from data collected in disparate locations all over North America, and not all may be suitable for use within the region.

2.3 National Scale Estimators

In developing potentially the most widely used national scale estimators, Jenkins et al. (2003) sought to smooth the estimation of biomass at the landscape scale. Destructively sampling a vast number of trees of every species and diameter over a range of site conditions throughout the country would be very expensive and time consuming. Instead the authors compiled a list of 2,456 biomass equations for 104 different tree species across the United States and, through a meta-analysis, produced a small set of biomass equations for various species groupings.

A modified meta-analysis approach based on a study by Pastor et al. (1984) was used by Jenkins et al. (2003) to accumulate the long list of biomass equations into a small set useful for large scale applications. Equations were built for species groupings, for example all pine species use a single equation. The biomass equations compiled were DBH-based, and any equations using other variables were not considered in the final analysis. If these compiled equations were log transformed, any bias correction factors available were not used. To ensure the resulting national-scale biomass estimators would be useful over a range of size classes, existing large diameter equations were included, and in some cases pseudo-data were created for large trees by extrapolating beyond the diameter limits of the original studies. Equations to estimate the fractions of total aboveground biomass were created for foliage, merchantable stem wood, stem bark, and coarse roots. Branch biomass equations were not produced because this component can be obtained by subtraction.

While the compiled list of biomass equations provided for the potential estimation of several tree components, there are some potential prediction errors that are difficult to quantify when compiling existing equations in this way. These include: (1) application of equation coefficients developed for one species (or group of species) to another species (or group of species); (2) the use of sample trees and wood density samples not representative of the target population because of factors such as size range of sample trees and stand conditions; (3) statistical errors associated with estimated coefficients and the forms of the selected equations; (4) inconsistent standards, definitions, and methodology; (5) use of indirect estimation methods that compound errors; and (6) inherited measurement and data processing errors.

Disregarding the errors in methodology used to create these prediction equations, consider the fact that these biomass estimators are created from equations built for a range of locations, site types, stand conditions, and study objectives. As a result, it was assumed that the final equations would be useful at the landscape scale. However, they may have large errors in local applications, and would likely yield poor estimates of an individual tree's biomass. Another potential limitation of Jenkins et al. (2003) biomass equations is that they were fitted on the logarithmic scale and no correction was made for the bias that accrues when predictions are made in arithmetic units (Beauchamp and Olson, 1973). Also, there is a lack of data, within this study and nationally, concerning the biomass of large trees. Furthermore, there has been no published account of any attempts to verify the accuracy of these equations. Considering the use of these equations as part of the Forest Inventory and Analysis (FIA) program (Woodall et al. 2011), and their resulting impact on management decisions, further inquiry is necessary.

2.4 Regional Scale Estimators

2.4.1 Inland Northwest

A widely used set of species-specific equations were produced by Brown (1978). The equations and methods were also presented in an earlier paper by Brown and Johnston (1976). The goal of Brown's project was to construct biomass equations for various standing tree components by filling in size and species gaps of the studies completed by Storey et al. (1955) and Fahnestock (1960), which contained some pioneering research about the relationships between crown weight and bole diameter. By combining data from these studies with new sample trees, Brown was able to increase the sample size used to build his equations, as well as cut down on time required for sampling.

Tree measurements were collected by Brown (1978) in 14 different locations across Idaho and Montana, over 3 successive field seasons (April to October). The sites were described as "poor-to-good sites and from low-to-high stand density conditions throughout western Montana and northern Idaho." The trees were picked randomly, but were not accepted if "they were (1) open-grown or wolf trees; (2) extremely lopsided in the crown; (3) deformed excessively by disease; (4) heavily defoliated; and (5) broken topped."

Brown (1978) visually divided the tree crowns into two or three sections, which were then clipped while the tree was standing by tree climbers and weighed (live and dead separate) entirely with a hanging sling scale. From each section a single live and dead branch was selected that appeared to be average in size. These branches were then divided into 1, 10, and 100 hour fuel size segments (0-0.6 cm, 0.6-2.5 cm, 2.5-7.5 cm), and foliage. Components were weighed separately, green and dried, to produce ratios and moisture contents for determining dry weight totals for the entire tree. Most of the trees sampled by Brown were of DBH 30 cm (12 inches) or less, with about half of those being less than 5 cm in DBH. All remaining tree data came from Storey et al. (1955) and Fahnestock (1960).

The study by Storey et al. (1955) looked at 13 different tree species in 4 states (CA, ID, NC, NV) over a range of site conditions. Data collected in Idaho was collected on the Priest River Experimental Forest in northern Idaho. Only crown data was collected (nothing of stem characteristics), as the primary goal of the study was to identify relationships among crown characteristics. Trees were selected that were healthy and not deformed or damaged. A selected tree was split into five sections based on total tree height, and any branches below the level of the top of the first section (below the top 80% of the crown) were removed (tree pruned to 4 sections). Each remaining crown section was then clipped and weighed, then eventually dried and moisture contents calculated. The authors found great variability in crown weights between different sites. The study produced some biomass equations, though these required measurements of the diameter at the base of the live crown, rendering them impractical.

Fahnestock (1960) sought to quantify the amount of logging slash that can be expected from a single tree to determine possible disposal methods and costs. All trees of nine different species were sampled on the Priest River Experimental Forest in northern Idaho. Individual trees were measured in the same fashion as the Storey et al. (1955) study; in fact the two studies were done in collaboration. Dry weight of green material was determined by assuming 100% moisture content. Limited data was published with the booklet; rather it was more of an informative or educational pamphlet on the dangers of logging slash.

A preliminary assessment of the accuracy of Brown's (1978) equations was made by Gray and Reinhardt (2003) for Douglas-fir, white fir (*Abies concolor*), lodgepole pine, ponderosa pine, subalpine fir (*Abies lasiocarpa*), and incense cedar (*Calocedrus decurrens*). The widespread use Brown's (1978) equations to generate canopy characteristics for many fuels models prompted this study. Gray and Reinhardt collected new crown biomass data from 5 different study locations, the Salmon-Challis National Forest (ID), Lolo National Forest (MT), Lewis and Clark National Forest (MT), Coconino National Forest (AZ), and the Blodgett Forest Research

Station (CA). Sites were chosen by local managers which were "to be prone to crown fire – dense, often multi-storied stands" (Gray and Reinhardt, 2003; p. 1). All trees were sampled inside a circular plot that was randomly placed within a stand. Every branch on every tree was weighed, and 10% of branches were selected to break down into components for ratio estimation. Predictions for each tree were made using Brown's (1978) DBH-based equations. Graphical analyses indicated that the equations for white fir and lodgepole pine made accurate predictions, while the predictions for incense cedar (made from Brown's equation for *Thuja plicata*) and Douglas-fir tended to under-estimate the actual crown biomass. With ponderosa pine the equations generally over-estimated the biomass, though the four trees with the largest DBH sampled were under-estimated by Brown's equation.

2.4.2 Biomass Estimators for Neighboring Regions

Some work has also been conducted in regions bordering the INW. For example, regional biomass equations were produced for 22 tree species in British Columbia by Standish et al. (1985). The objective of their study was to produce generalized equations in order to quantify the amount of forest biomass available in British Columbia in both old-growth and second-growth stands. A total of 1155 trees were sampled over the majority of British Columbia, excluding the far northern region and the Queen Charlotte Islands. Both coastal and interior trees were included to produce regional equations.

Sample trees were selected proportional to provincial volume inventory for tree species, but Standish et al. (1985) sampled a minimum of forty trees for each species over a wide range of stand, site, and geographic conditions. Also, they attempted to gather sample trees equally among DBH and height classes within each species, and to disperse those size classes over the range of areas where the species are found. Measurements of DBH and height were taken before felling. Once a tree was felled measurements were taken directly of height, crown length and width, age at 30 cm diameter, and DBH outside bark.

Standish et al. (1985) cut the bole into two meter sections and weighed these in the field, except for very large sections, which were measured in the field for volume to estimate a mass in the lab using mass-to-volume ratios created by the other sample sections. Live branches were sorted into three basal diameter classes and weighed in full. Two branches from each diameter class were then selected randomly and broken down into different components (dead, foliage, large and small diameter branch-wood). Portions were returned to the lab to obtain moisture contents and estimate dry weights of the total.

Standish et al. (1985) evaluated several different biomass prediction models, from a simple model using only DBH and height to models that also included tree volume, which was found to have significant effects on some of the model estimates. Overall, these equations may be useful for regional scale estimation in the inland Rocky Mountain West. However, the use of coastal tree data (for some species) to build the regression equations may produce biased estimates, though for Douglas-fir separate equations were produced for interior and coastal trees.

The Cascade mountain region of western Oregon and Washington was the focus of the research by Gholz et al. (1979). Producing regional biomass equations for several different species of trees, shrubs, and herbs was their primary goal. They attempted to include a range of site conditions and size classes for creation of the equations. However, study sites were limited, and data was mined from several other research papers and projects to produce the final biomass equations. Methods outlined in this paper are scattered and unclear, and it appears that sampling methods vary, which may have caused some discrepancies in final prediction equations. Sample sizes for equations range from 2 to 99 trees. In general, it appears that for the tree species sampled, methods were similar to that of Brown (1978), where the crown was divided into equal parts, each section weighed in full, and a single randomly selected branch was used to determine proportions of different components (foliage, small and large diameter branchwood).

Because the methodology of Gholz et al. (1979) is difficult to follow, these equations cannot be recommended for use. Also, because this region receives a greater amount of precipitation than the inland northwest, and considering differences in other factors such as growing season length, temperature, and nutrient availability, which may cause major variations within species, the equations produced by Gholz et al. (1979) may not be suitable for use east of the Cascades.

2.5 Localized Estimators

Regression models for predicting lodgepole pine biomass components were produced by Johnston (1977). The study produced equations for two separate sites of differing site indexes on the Lubrecht Experimental Forest. Both sites were high elevation and in the subalpine fir habitat series (Pfister, 1977). Sample trees were chosen using a pseudo-random scheme; transects were run across the selected sites, with random intervals between sample points. A single tree that was not deformed, damaged or forked was chosen at each point. Only live material and cones were collected. All branches were bagged and brought to the lab where they were dried and weighed. The bole was divided into four sections, diameters measured at each end of the section, and a 1 cm disk cut from the bottom of each. The models predicting crown components (leaf, cone, branch) for both locations are poor due to high standard errors of the model coefficients. However, a reliable model of total crown biomass was produced for one site, though it is obviously site specific and may not be suitable for use throughout the entire region.

Local, site- and stand-specific biomass equations were produced by Cochran et al. (1984). The study area was a pre-commercially thinned, even-aged, second-growth ponderosa pine stand in central Oregon. The sample size was 23 trees. This was a Forest Service study, with the goal to produce an equation that accurately estimated standing biomass of ponderosa pine to determine forest productivity and nutrient cycling in common second-growth forest stands that result from intensive clear-cut logging practices in Oregon.

Cochran sampled healthy intermediate to dominant trees over a range of DBH classes (5 to 38 cm) chosen from two study locations 18 km apart. Crowns were divided into 3 sections, and all foliage and branches were separated and weighed for each section. Samples were dried for moisture contents and to obtain dry weight estimates for entire trees. The volume of sample discs removed at various locations along the bole was determined by water displacement. Crown biomass equations were produced, but would likely not be suitable for use as a regional biomass estimator for the inland northwest due to the site specific nature of the study. Also, the management of the forest in the study area has created highly uniform conditions that are otherwise uncommon across the region. It should again be noted that any studies produced in coastal regions will likely produce equations ill-suited for use in the inland empire.

A study by Krumlik (1974) consisted of 24 sample trees taken in the south coastal region of British Columbia near Vancouver. Two plots were established and trees selected randomly within the plot boundaries. Measurements of DBH, height, crown ratio, base of live crown were taken while the tree was standing. Branches were divided into 100 hour (diameter > 2.5 cm) and 10 hour (0.6 cm < diameter < 2.5 cm) fuel classes as well as 1 hour fuels (diameter < 0.6 cm) with attached foliage. The whole crown was broken down and weighed, with the exception of twigs with foliage, which were subsampled to obtain a 10% sample of the total weight of this component. Fresh branch weights were taken; oven-dried measurements were also obtained. Overall, the methods are similar to those described in previous studies. Here, since the trees are from the coastal region, the equations would likely not be useful within the region.

2.5.1 Locally Interesting

Biomass regression models for various tree components (needles, stembark, stemwood, branchwood, stumpwood, and stumpbark), as well as for total above ground tree biomass were produced for Douglas-fir by Marshall and Wang (1995). Objectives of this study were not limited to the construction biomass equations for interior Douglas-fir, but also to the quantification of biomass in each of 6 permanent plots, and ultimately the assessment of whether stand density has an impact on the form of biomass equations. Sixty trees were sampled on the Alex Fraser Research Forest of the University of British Columbia. Ten trees were sampled near each of 6 permanent sample plots with the hope that conditions were equal to those which existed within the plot boundaries. It was found that there was a significant difference in the coefficients of the equations compiled for each plot density grouping (lowest, medium, and highest density groups with 2 plots in each group), suggesting that the input of stand density, or some factor affected by it, may improve the accuracy of a biomass equation.

Again extending the use of biomass research, in a study by Monserud and Marshall (1999), three northern Idaho conifer species (Douglas-fir, ponderosa pine, western white pine (*Pinus monticola*)) were sampled on the Priest River Experimental Forest to learn about crown characteristics. The objective of the study was to create allometric equations to estimate leaf area, leaf biomass, and branch biomass for use in creating process based models of forest productivity. Trees were selected using a fixed basal area factor, stand density was evaluated prior to felling, and standard height and DBH measurements were taken. Crown competition factors (CCF; Krajicek et al., 1961) were calculated for each tree. Selected trees were void of obvious defects, spanned a range of size classes within the stand, and grew in areas not populated by other tree species.

Once a tree was felled, the crown was divided into four quarters, and two branches were selected from each quarter. The first branch was chosen randomly, and was then paired with a second antithetical branch. That is, the second branch was on the opposite side of the bole and crown, and of approximately equal distance from the center of the crown. The intention of this strategy was to create a negative correlation between the weights of the two branches so as to reduce overall sampling variation. These branches were divided into foliage and branch components and weighed for ratio estimation of whole-crown component weights (each quarter was weighed in full to have a measure of total crown weight). Equations for branch- and tree-level estimates were produced, requiring several different variables, beyond DBH and height, which may be very difficult to obtain in practice. For tree-level estimates, two sets of equations were built, one set requiring DBH, stand density, and crown competition factor, the other requiring several other variables including basal area of sapwood at DBH, which again, is difficult to obtain.

2.6 Comparative Studies

A study by Feller (1992) compared site specific biomass equations to generalized regional equations. Using the regional equations produced by Standish et al. (1985) the objective was to compare estimates of high and low quality sites for Douglas-fir and western redcedar to site-specific and regional equations. Poor sites had trees that were described as having "poor" growth and low nitrogen contents, and good sites had trees with "good" growth and high nitrogen contents. Trees of each species were taken from two locations, one good site and one poor.

Feller's (1992) methods were similar to those of Brown (1978), where the crown was divided into three parts, each part weighed in full, though then three branches were randomly selected from each section and separated into foliage and remaining branch material to determine ratios for the whole tree. The branch segments were then oven-dried to determine moisture contents and dry weights for the whole tree. All dead branches were weighed together, with a single sample taken for moisture content. Discs were cut from the midpoint of each crown section in large trees, and at certain intervals on small trees, and measured for relative density and weight. Tree roots were also excavated and weighed.

Feller (1992) trimmed the large dataset that produced the regional equations by eliminating trees not sampled in the coastal region, extreme outlying points, as well as data they thought clearly “could not possibly have represented a real tree” (Feller, 1992, p. 11). Using their own data, they formed regression equations which they compared to the regional biomass equations. The equations were compared using methods described by Zar (1984), first addressing whether residual variances were equal, then whether slopes were equal, and finally whether vertical positions on the graph were equal. It was found that geographical and site quality differences significantly affected the biomass equations produced, with the biggest difference occurring on the poor quality site. Evidently, more extreme sites have a higher need for site specific equations. However, costs associated with creating site specific biomass equations may outweigh the benefits, making the case for regional biomass equations stronger.

The use of Brown’s (1978) equations in the Fire and Fuels Extension of the Forest Vegetation Simulator (FVS-FFE; Reinhardt and Crookston 2003) prompted Keyser and Smith (2010) to evaluate whether current estimators of canopy bulk density, mass, and height are suitable for predicting fire behavior in Black Hills ponderosa pine. As mentioned previously, the sample tree data used to create Brown’s (1978) equations were collected west of the continental divide, whereas Keyser and Smith gathered their data east of the continental divide. While there may be some bias related to using the Brown (1978) equation for ponderosa pine crown mass outside its intended range, it is useful to know how well this equation performs. Destructive sampling was completed on 80 trees in 16 different stand types throughout the Black Hills National Forest. In an effort to gain information about the vertical profile of the crown, sample trees were broken up into ten equal vertical segments on the tree stem.

Standing tree measurements were taken prior to felling. Within each segment biomass was separated into foliage and branches by fuel category, weighed green, and bagged to obtain dry weights. The data collected was then used to create localized biomass equations for ponderosa pine foliage and 1 hour fuels (<1/4") in the Black Hills. Results of the study pointed to large differences between localized biomass equation estimates and regional estimators. Compared to the localized equations produced, Brown's (1978) equations consistently underestimated crown foliage and 1 hour fuels and canopy bulk densities, three important variables for predicting fire behavior. The authors concluded that localized equations are necessary for proper approximation of biomass and fire behavior.

2.7 Conclusions

Much of the work completed in the area of biomass sampling and quantification was done in the late 1970s and early 1980s during a period of energy crises and higher than usual energy costs similar to current market conditions. It seems the interest in biomass waxes and wanes with the price of oil. It may be that the interest in quantifying biomass will again fall to the back burner. While the use of biomass as an energy source may not remain popular, biomass and crown allometric equations remain useful management and scientific tools.

The biggest issue associated with regional biomass equations currently used in the INW is the lack of sample coverage. More sites are necessary, over a range of stand densities and conditions, and geographic and elevation variations must be included for a fully comprehensive biomass equation. Also, a mix of land ownerships would be helpful to address potential effects of different management practices on the growth of trees. Overall, it may be best to set up a system of biomass data collection, where every timber sale adds a few trees that are destructively sampled and uploaded to a server which continuously updates biomass equations to enhance accuracy and precision over time.

Within the region described as the INW, only two sets of prediction equations are widely used in practice. These are the sets published by Brown (1978) and Jenkins et al. (2003). Because of their use across the region and their application in governmental and private management decisions, these equations will be the focus of this project. Figure 2.1 illustrates the form of selected crown biomass equations from these two publications. While all of the equations illustrated are DBH-based there are three peculiarities to point out. First, Brown's (1978) equation for Douglas-fir has a kink at DBH 42.5 cm (17") where a separate crown biomass equation was specified for large DBH trees. Second, Jenkins et al. (2003) provides only one crown biomass equation for all pine species, illustrated in both the lodgepole pine and ponderosa pine panels. A third interesting point to mention is that the Jenkins et al. (2003) equation for western larch is an equation for a group of species (the Cedar/larch group) that includes larch species (*Larix laricina* and *Larix occidentalis*) as well as cedar, juniper, and sequoia species (*Calocedrus decurrens, Chamaecyparis spp., Thuja spp., Juniperus virginiana, Sequoiadendron giganteum*).

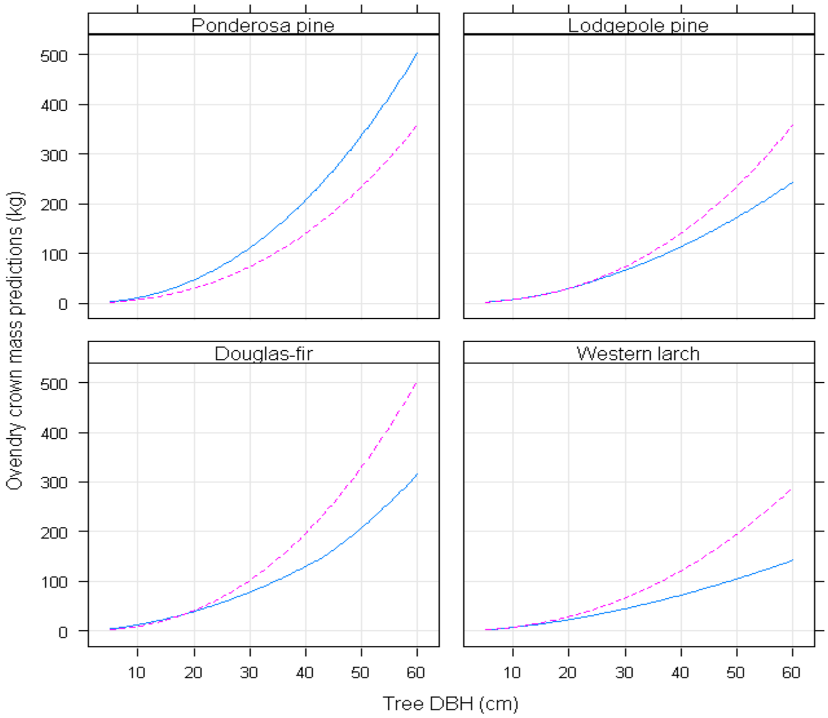

Figure 2.1. Crown biomass prediction equations for each of four species of interest in this project. Brown's (1978) equations are denoted by solid lines; Jenkins et al. (2003) equations are dashed.

Chapter 3

Methods

3.1 Stand and Tree Selection

Trees selected for sampling came from a number of stand locations across the INW. Results for this project are intended to be an indicator of the usefulness of Brown's (1978) and Jenkins et al. (2003) crown biomass equations for species within the region. Funding members of the project include federal, state, and tribal forest management agencies, as well as private forest companies. These members made their land available for biomass sampling. Yet owing to physical difficulties in accessing certain lands and to the destructive nature of the biomass measurements to be taken, it was not possible to draw a probability sample of forest stands across the region. Instead, efforts were made to ensure that stands were selected throughout the geographic extent of the region and across the ranges of elevations and habitat series (Pfister, 1977) present. Ultimately, stands were located with the assistance of local land managers according to the tree species and size classes desired. To minimize the financial loss associated with the destructive measurements some stands were part of active or planned logging sales, but others were in undesignated second growth forest. None of the stands had been treated (e.g., thinned or burned) in the previous 10 years.

Within a selected stand, potential sample points were established at 50 m intervals on the Universal Transverse Mercator (UTM) grid. Points within 25 m of the nearest road were dropped. At the remaining sample points, an angle gauge with a basal area factor of 2.3 m^2/ha (10 ft^2/ac) was used to identify candidate trees for biomass sampling. Candidate trees had to be live trees with a DBH of at least 5 cm. Also, trees were considered unacceptable for sampling if they had broken tops, forked tops, mechanical damage, marked defoliation, or significant mistletoe damage.

At each point up to 2 trees were selected uniformly at random from the set of identified candidate trees. If there was only 1 or 2 candidate trees identified at a sample point then one or both of the candidates were selected. After all trees were selected at a particular point, standing tree measurements of DBH, total height, and BLC were taken, and crown ratio was estimated. Once these measurements had been taken, the tree was felled in the best possible location, with the field crew first clearing the landing zone of other trees and debris to ensure that broken branches could be reconstructed. Data from several major commercial tree species was collected during the sampling season. Only four tree species, Douglas-fir, lodgepole pine, ponderosa pine, and western larch, are used throughout this research as data for these species was compiled first.

3.2 Randomized Branch Sampling

Having selected and felled the sample trees, a randomized branch sampling (RBS) protocol was then used to estimate foliage and branch wood biomass. Beginning at the lowest live branch on the stem, the bole was divided into 1 meter segments until the 5 cm top was reached (i.e., until the bole had tapered to a diameter of 5 cm). Along each 1 m segment, the diameter and height of each live branch was measured, as was the bole at the top of the segment. Once these diameters had been measured, the diameters were input into a program written on TI-84+ © calculator. The program calculated selection probabilities for each branch and for the stem at the top of the segment based on the diameters. Specifically, conditional selection probabilities were made proportional to branch or stem cross-sectional area (i.e., diameter^2):

$$P(\delta_{ij} = 1) = x_{ij}^2 \,/\, \sum_{j=0}^{n} x_{ij}^2 \tag{1}$$

where x_{ij} denotes the diameter at node *j* (*j* = 0 for the stem at the top of the segment and *j* = 1, 2, 3, …, *n* for branches along the segment) on segment *i*, and δ_{ij} is an indicator of node selection (1=selected; 0=else). A set of pseudo-random numbers was then generated by the calculator to select one or more nodes (branches or stem) on the segment under consideration using a list sampling procedure.

The probability of equation (1) is conditional on the RBS procedure extending up the stem and reaching segment (*i* – 1). The unconditional probability of selecting branch *j* on segment *i* is therefore

$$\Pi(\delta_{ij} = 1) = P(\delta_{1,0}) \times P(\delta_{2,0}) \times \ldots \times P(\delta_{i-1,0}) \times P(\delta_{ij}) \tag{2}$$

For example, the conditional probability of selecting branch 1 in segment 3 if there are exactly 4 branches in the segment (see Fig. 3.1) is

$$P(\delta_{3,1} = 1) = x_{3,1}^2/(x_{3,1}^2 + x_{3,2}^2 + x_{3,3}^2 + x_{3,4}^2 + x_{3,0}^2) \tag{3}$$

and the associated unconditional probability of selection is:

$$\Pi(\delta_{3,1} = 1) = P(\delta_{1,0}) \times P(\delta_{2,0}) \times P(\delta_{3,1}) \tag{4}$$

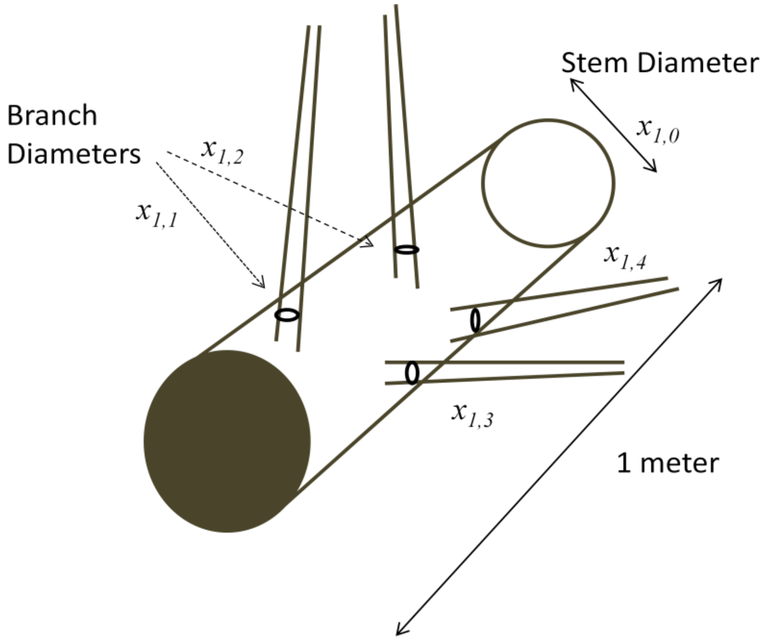

Figure 3.1. Schematic of the RBS protocol. Each branch diameter (x_{ij}; j>0) is measured, as is the stem diameter (x_{i0}) at the top of the one meter segment. Any branches selected are removed; if the stem is selected then sampling proceeds to the next segment.

The RBS protocol used is an unequal probability, with replacement design. Since multiple branches were selected independently on each tree, any given branch on those trees had the possibility of being selected multiple times. However, given the probability-proportional-to-size design, branches with larger cross-sectional areas were more likely to be selected, an important design consideration given that larger branches carry a larger fraction of total crown mass.

A minimum of 5 branches were selected on each tree, with the number of branches selected increasing to as many as 8 branches depending on tree DBH. Specifically, all trees below 25 cm DBH had 5 branches selected. An additional branch was then selected for each 10 cm increase in DBH so that trees up to 35 cm had 6 branches selected, trees with DBH up to 45 cm DBH had 7 selected, and any larger trees had 8 branches selected. Once a branch was selected, it was removed from the tree and divided into different components. Branch wood was divided into segments of different diameter classes based on fire time lag classes (i.e., into 1, 10, and 100 hour fuels) and foliage was separated. All materials were stored in paper bags until they could be oven dried at 105°C to a constant weight.

3.3 Data Analysis

3.3.1 Crown Biomass Estimation

Using the unconditional selection probabilities determined in the course of sampling, branch weights were expanded to estimate the total weight of the tree crown. For each tree sampled, 5 to 8 independent branch-level estimates of crown biomass were produced. In the case of tree *i*, for branch *j*, the branch weight, b_{ij}, can provide an unbiased estimate of crown mass, $m_{R,i}$, such that:

$$\widehat{m}_{R,ij} = \frac{b_{ij}}{\Pi(\delta_{ij} = 1)} \tag{5}$$

Combining these using a Hansen-Hurwitz estimator (Hansen & Hurwitz, 1943), an averaged crown mass estimate for each tree can be calculated, where *n* is the number of branches sampled on any given tree:

$$\overline{m}_{R,i} = \frac{1}{n}\sum_{j=1}^{n} \widehat{m}_{R,ij} \tag{6}$$

Each branch-level estimate (and of course the average of all branch-level estimates for each tree) approximates the amount of live and dead biomass in the crown, including the mass of the stem above a 5 cm diameter. Each branch-level estimate can be considered independently; alternatively, the average of these estimates, supplemented with an estimated standard error, can be used. In the data analysis below, individual branch-level estimates were not combined. Yet for simplicity, some of the figures show the averaged crown weight estimate (equation 6) for each tree.

3.3.2 Preliminary Data Analysis

Using the standing and down tree measurements recorded for each tree, relationships among different tree variables were assessed. For each species a graphical analysis of DBH, total height (HT), height at the base of the live crown (BLC), height of the lowest live branch (LLB), diameter at the base of the live crown (DBLC), height of the 5 cm top, and average estimated crown biomass ($\bar{m}_i$) was completed for each species to determine if any relationships among the different tree variables were present. An assessment of which of these variables were highly correlated was needed for subsequent regression analyses. Where deviations occurred from the normal array of points, trees were identified for further analysis.

Across all species, and for the entire sampling region, DBH and HT were strongly positively related, an association commonly known among foresters. It is also important to note that DBH has a strong positive relationship to most measurements of tree dimension, with a few exceptions. Lodgepole pine, for instance, does not vary too widely in crown length over the full range of DBHs sampled. It was during this initial assessment of tree and crown characteristics that an increasing variability in crown mass as a function of tree size became evident.

3.3.3 Analysis of Differences Between Equation Predictions and Field Estimates

Since the purpose of this study is to determine whether the crown predictions produced by the equations of Brown (1978) and Jenkins et al. (2003) are unbiased, the analysis directly examined the differences between field estimates and equation predictions. Only DBH based equations were considered (Table 3.1), although only Brown (1978) produced separate crown biomass equations that included other covariates. Brown (1978) formed separate equations for live crown mass and dead branch mass; also, for some species, these equations were size-class dependent (i.e., one equation was developed for trees larger than a certain DBH and another equation for smaller trees). The equations in Jenkins et al. (2003) predict total aboveground tree biomass, from which stemwood and stembark fractions must be removed to compute crown mass.

Table 3.1. Brown (1978) prediction equations evaluated for bias as part of this study. Equations were added so that each tree had a total predicted crown biomass including live and dead crown weight. DBH in inches; biomass in pounds.

Species	Equation
Douglas-fir	
Live Crown < 17”	$\exp(1.1368 + 1.5819 \times \ln(DBH))$
Live Crown > 17”	$1.0237 \times DBH^2 - 20.74$
Dead Branches	$0.01094 \times DBH^3$
Lodgepole pine	
Live Crown (LC)	$\exp(0.1224 + 1.8820 \times \ln(DBH))$
Dead Branches > 10”	$1.235 \times LC$
Dead Branches < 10”	$0.026 \times DBH - 0.025$
Ponderosa pine	
Live Crown	$\exp(0.268 + 2.074 \times \ln(DBH))$
Dead Branches	$\exp(2.8376 \times \ln(DBH)) - 3.7398$
Western larch	
Live Crown	$\exp(0.4373 + 1.6786 \times \ln(DBH))$
Dead Branches > 4”	$1.1 \times LC$

Table 3.2. Jenkins et al. (2003) prediction equations evaluated for bias as part of this study. Equations were added so that each tree had a total predicted crown biomass including live and dead crown weight. DBH in centimeters; biomass in kilograms.

Species	Equation
All Species	
Stem Wood Ratio (SWR)	Exp(-0.3737 - 1.8055/DBH)
Stem Bark Ratio (SBR)	Exp(-2.098 - 1.1432/DBH)
Douglas-fir	
Total Tree (TT)	Exp(2.2304 + 2.4435 × ln(DBH))
Crown	TT × (1 - SWR - SBR)
Lodgepole pine	
Total Tree	Exp(-2.5356 + 2.4349 × ln(DBH))
Crown	TT × (1 - SWR - SBR)
Ponderosa pine	
Total Tree	Exp(-2.5356 + 2.4349 × ln(DBH))
Crown	TT × (1 - SWR - SBR)
Western larch	
Total Tree	Exp(-2.0336 + 2.2592 × ln(DBH))
Crown	TT × (1 - SWR - SBR)

None of the equations shown in Table 3.1 or 3.2 were used independently. Rather, they were used together for each species to predict total crown mass for any given tree. The compilation of components provided predictions of total crown mass:

$\hat{m}_{B,i}$ = Brown's (1978) predicted total crown mass for tree *i*

$\hat{m}_{J,i}$ = Jenkins' et al. (2003) predicted total crown mass for tree *i*

Recognizing the variability in crown mass between trees, as well as the variability between RBS estimates of crown mass within a tree, differences were computed at the branch-level such that:

$$d_{B,ij} = \hat{m}_{R,ij} - \hat{m}_{B,i} \tag{7}$$

$$d_{J,ij} = \hat{m}_{R,ij} - \hat{m}_{J,i} \tag{8}$$

Since $\hat{m}_{ij}$ is unbiased for the true crown mass of tree *i (m$_i$)*, these differences are unbiased estimators of the bias of the crown prediction equations applied to individual sample trees. That is, for any tree *i*

$$E(d_{B,ij}) = E(\hat{m}_{R,ij}) - \hat{m}_{B,i} = m_i - \hat{m}_{B,i} \tag{9}$$

The result is that if the $d_{B,ij}$ are on average positive, there is an indication that Brown's (1978) equation is under-predicting crown mass. Conversely if the $d_{B,ij}$ are negative, there is an indication that Brown's (1978) equation is over-predicting crown mass. Since the RBS field estimates are subject to sampling error it cannot be observed whether the crown mass of any individual tree is either over-predicted or under-predicted. But, looking at the overall trends in $d_{B,ij}$ and $d_{J,ij}$ for each species as a function of various tree dimension it is possible to produce a model that describes the magnitude of the bias in any given prediction equation. Following this logic, the goal is to look at trends in $d_{B,ij}$ and $d_{J,ij}$ as a function of (1) all measured tree dimensions and (2) DBH alone. The latter set of trends define bias correction models (BCM) that could be used to increase the accuracy of predictions computed by the equations of Brown (1978) and Jenkins et al. (2003) when applied in the region of interest.

3.3.4 Regression Analyses

Using the differences calculated for each sample tree, two types of regression analyses were undertaken. The first thing to note is that variation in crown mass was not constant throughout the data, so homoskedasticity could not be assumed. As a result, all models utilized a power function to model crown mass variance as a function of DBH, regardless of whether

DBH was included as a predictor of mean crown biomass. All analyses were done with R, using the nlme package (Pinheiro et al., 2011) which allows for mixed-effects modeling strategies and non-constant error variance. Regression models were produced which attempted to characterize the differences between observed levels of crown biomass and predicted levels using either Brown's (1978) or Jenkins et al (2003) equations.

The first type of regression analysis undertaken for each species was the exploratory correction model (ECM), which began with common measured tree dimensions as covariates. Also included were tree-level random effects and a power function parameterizing increasing residual variation with increasing DBH. Starting with a model which contained DBH, DBH^2, HT, DBLC, and CR as covariates, all 20 possible model combinations which include these variables were examined. Lowest corrected Akaike information criterion (AICc) was used to select the best three models. Interactions between different variables were not considered, and multicollinearity was ignored. The purpose of this type of regression was to determine whether any variables were as or more valuable than DBH in describing variability among the $d_{B,ij}$ and $d_{J,ij}$. Another goal of these regressions was to take note of any across-species trends associated with any particular tree attributes that might be important in describing crown mass and creating more accurate prediction equations.

The second type of regression carried out examined only DBH effects. Because the Brown (1978) and Jenkins et al. (2003) equations under scrutiny are DBH-based, it was ultimately decided that the BCM describing $d_{B,ij}$ and $d_{J,ij}$ only contain DBH. Further, DBH is strongly related to nearly any other tree measurement. Again, these regressions included tree-level random effects and in all cases it was found that a non-constant DBH-based variance power function was needed to accommodate the dispersion patterns of the data. Again, the model selection criterion used was the lowest AICc method. The resulting BCMs had the general polynomial form:

$$d_{B,ij} = b_0 + b_1 DBH_i + b_2 DBH_i^2 + \cdots + b_p DBH_i^p + T_{B,i} + e_{B,ij} \quad (10)$$

$$d_{J,ij} = b_0 + b_1 DBH_i + b_2 DBH_i^2 + \cdots + b_p DBH_i^p + T_{J,i} + e_{J,ij} \quad (11)$$

where:

$$T_{B,i} \sim N\left(0,\ \sigma_{T_B}^2\right) \quad (12)$$

$$T_{J,i} \sim N\left(0,\ \sigma_{T_J}^2\right) \quad (13)$$

$$e_{B,ij} \sim N(0,\ \sigma_e^2 DBH^{\alpha}) \quad (14)$$

$$e_{J,ij} \sim N(0,\ \sigma_e^2 DBH^{\alpha}) \quad (15)$$

and these random terms are presumed mutually independent.

For DBH-based regressions, the BCM was selected using a backward selection procedure where higher polynomial terms were removed if AICc was lower and residual plots showed no lack of fit.

Chapter 4

Results and Discussion

4.1 Distribution of Sample Data

Sample trees were collected from 16 stands in western Montana, northern Idaho, and eastern Washington (Fig. 4.1). Effort was made to sample trees from a range of stand types, habitat series, aspects, and elevations (Tables 1 and 2). Trees were sampled in 6 different habitat series (obtained from digital raster data; US Forest Service, 2002), elevations ranging from 744 to 1911 m, on all four major aspects.

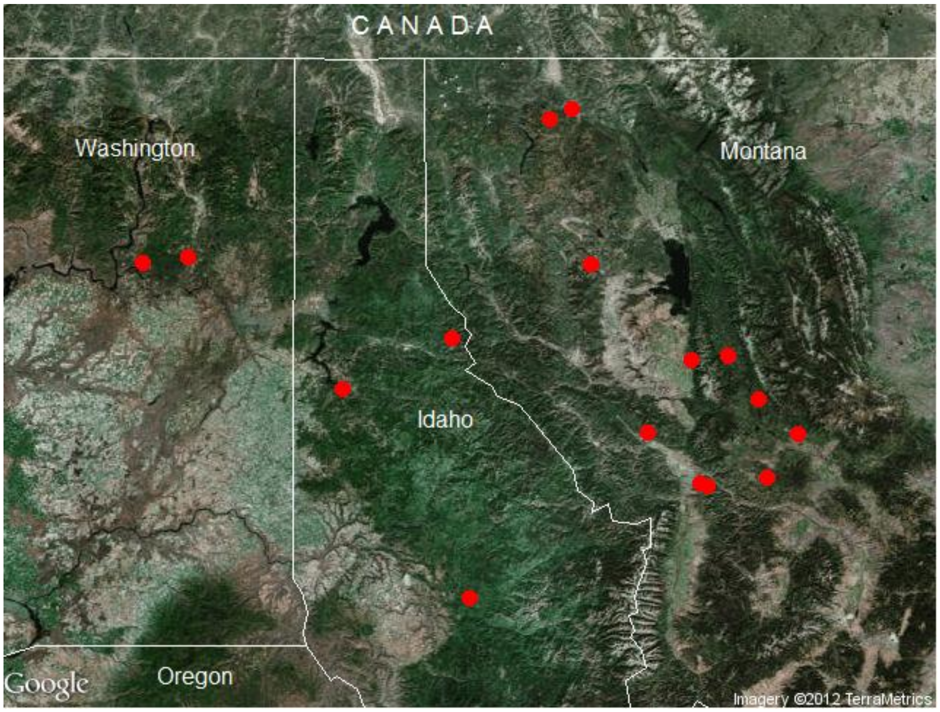

Figure 4.1. Locations of selected stands across the inland northwest.

Table 4.1. Habitat series distribution of selected trees.

Habitat Series	Species			
	Douglas-fir	Lodgepole pine	Ponderosa pine	Western larch
Douglas-fir	24	10	39	21
Grand fir	5	9		
Redcedar	2	1		2
Spruce	2			6
Subalpine fir	4	6	1	5
Western hemlock	3			
Total	40	26	40	34

Table 4.2. Elevation and aspect distribution of selected trees.

Elevation	Aspect				
	North	East	South	West	Total
600			17	6	23
800		2	10	6	18
1000	1	6	2	2	11
1200	7	15	27	14	63
1400	4	4	4	1	13
1600		6	2		8
1800	2			2	4
Total	14	33	62	31	140

After two successive field seasons of data collection, a total of 140 sample trees with 725 branch-level estimates of crown biomass were obtained for this analysis. The sample trees range from 5.0 to 61.5 cm in DBH (Table 4.3) and from 4.63 to 35.99 m in height. Of the 140 trees, 40 were Douglas-fir, 40 ponderosa pine, 26 lodgepole pine, and 34 western larch. For Douglas-fir there were 221 individual branch-level estimates of crown biomass; for ponderosa pine, 200; for lodgepole pine, 129; for western larch, 175.

Table 4.3. Species and DBH distribution of selected trees.

DBH (cm)	Species			
	Douglas-fir	Ponderosa pine	Lodgepole pine	Western larch
5-9.9	5	4	3	3
10-14.9	4	4	3	5
15-19.9	4	6	5	6
20-24.9	6	5	5	6
25-29.9	5	4	2	3
30-34.9	3	4	4	3
35-39.9	5	4	1	3
40-44.9	2	2	2	1
45-49.9	3	3	1	3
50-54.9	1	2		1
55-59.9	1	2		
60-64.9	1			
Total	40	40	26	34

By selecting trees from across a large geographic area and over a range of site variables, the idea was to test the validity of the Brown (1978) and Jenkins et al. (2003) equations, shown in Tables 3.1 and 3.2, for a range of site conditions found within the region. Then, if any of these equations are found to be biased or inaccurate for the region, more effort can be put into further data collection and warrant the creation of new prediction equations for publication and use.

4.2 Estimation of Crown Biomass in Douglas-fir

Douglas-fir is a major commercial timber species in the inland northwest. It is a relatively shade-tolerant species in this region and a large portion of the region falls within the Douglas-fir habitat series (Pfister et al., 1977). Further, many stands found throughout the region have seen an increase in Douglas-fir composition due to substantial fire suppression activities since the turn of the century (Arno, 1980). Thinning activities and fuels reduction projects in ponderosa pine/Douglas-fir forest often aim to remove Douglas-fir from the overstory and understory, either to reduce ladder fuels or to favor the growth of other species. Overall, Douglas-fir is a focal management species for timber production, is common throughout the INW, and requires the use of accurate prediction equations.

Among the selected trees there is a strong positive relationship between height and DBH (r=0.93), as well as between crown length and DBH (Fig 4.2, r=0.84). However, some of the trees (shown in red in Fig. 4.2) deviate markedly from the overall allometric relationships. For example, the 50.9 cm DBH tree has a height that would be expected, though it has a very short crown length, as well as a low average estimate of crown mass, suggesting that trees with short crowns have less crown mass. In another example, the 58.5 cm DBH tree which has a shorter crown length, possibly due the fact that it is shorter than expected, has an average estimated crown mass that is not unusual for its DBH. This suggests that height and crown length have no impact on crown mass. Further, the 46.5 cm DBH tree that has both an expectable height and crown length, but has a very high average estimate of total crown mass.

These deviations from trends may be due to factors which are difficult to ascertain. The 46.5 cm and 58.5 cm trees were both sampled on Lubrecht Experimental Forest (MT) in Douglas-fir habitat, while the 50.9 cm tree was sampled near Garnet, not far from Lubrecht in subalpine fir habitat (a higher site which may be why the crown mass estimate is low). The point is that there are many variables, often not measureable, that may affect the total crown mass of any given tree.

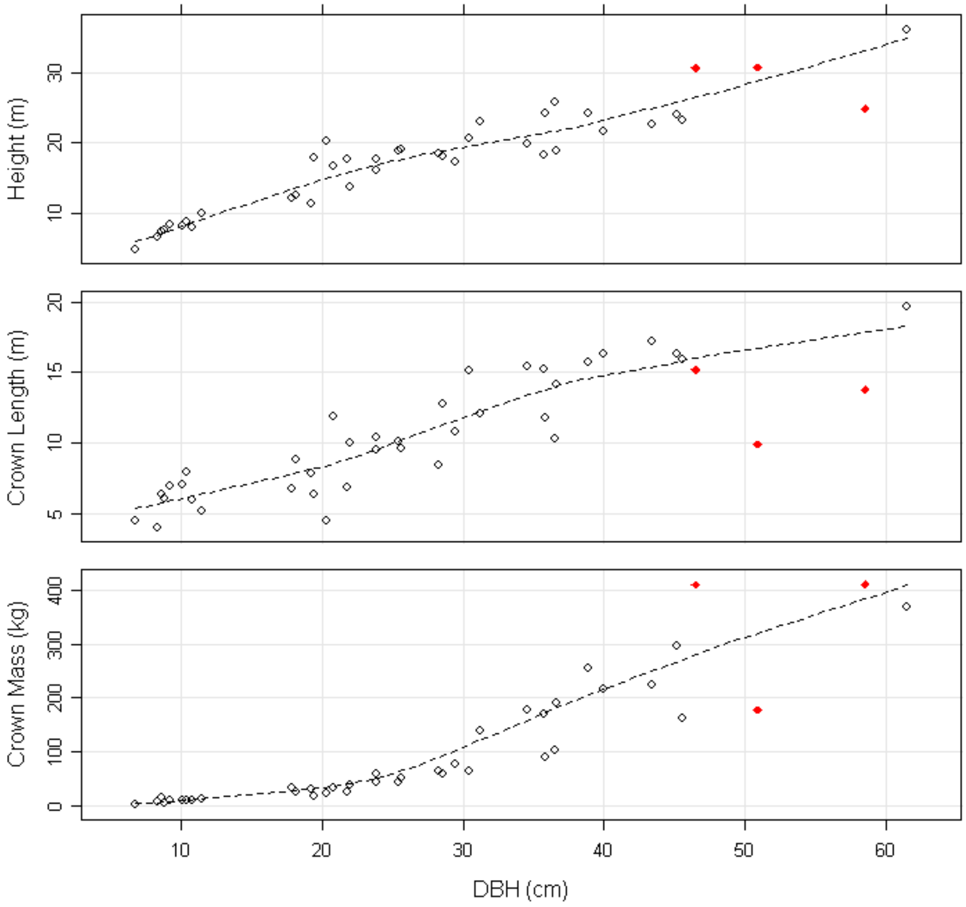

Figure 4.2. Tree and crown characteristics of Douglas-fir sample trees; trees outlying in at least one dimension are shown in red. Average-tree estimates of crown mass are shown in the lower panel.

Further review of Douglas-fir data shows that crown biomass estimates are quite variable within a tree. As mentioned previously, every tree has between 5 and 8 individual branch-based estimates of crown biomass, so for any given tree there is a range of estimates. Figure 4.3 highlights the variability within and among trees, with both branch-level (blue) and average-tree (red) estimates shown. It is clear that branch-based estimates vary widely and that their variability increases with tree DBH.

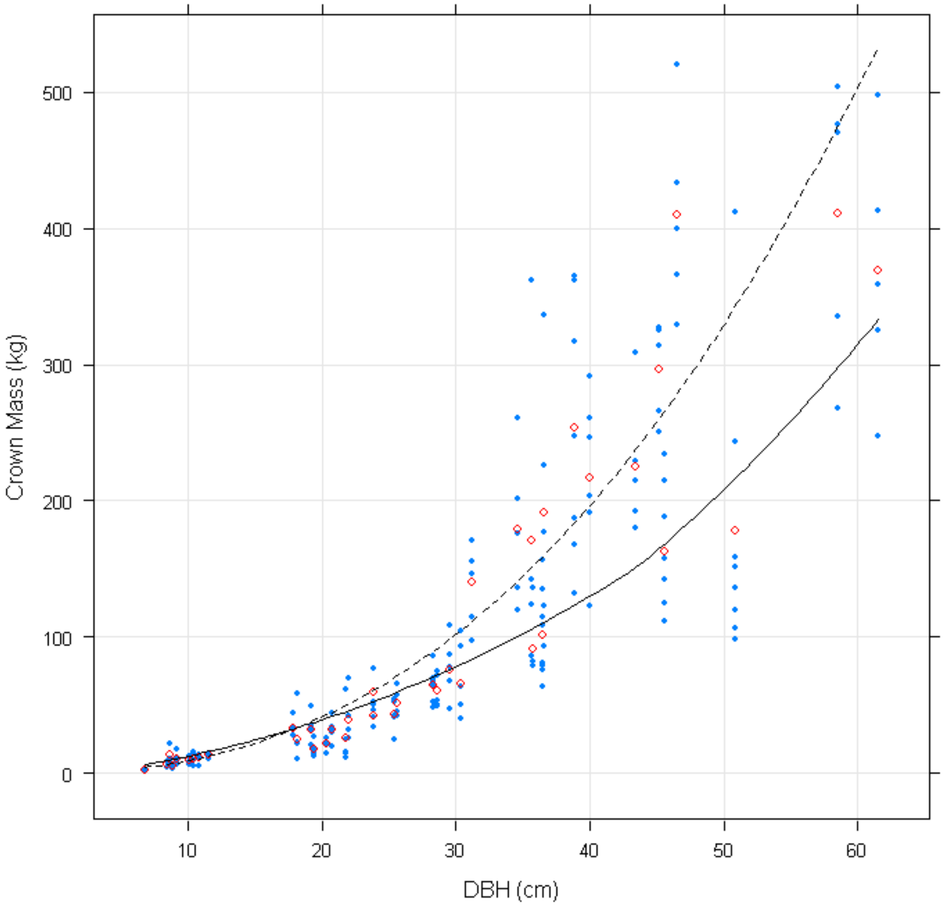

Figure 4.3. Douglas-fir crown mass estimates from field sampling (blue points are branch-level estimates, red points are average-tree estimates), Brown's (1978) equation (solid line), and Jenkins et al. (2003) equation (dashed line).

The prediction equations from both Brown (1978) and Jenkins et al. (2003) are also traced in Fig. 4.3. These predictive equations supply similar estimates up to a DBH of approximately 20 cm but deviate considerably for larger trees. Regression analysis of the differences between field estimates and each of these two prediction equations began by running regressions on all combinations of variables and finding the models with the lowest three AICc. Focusing first on Brown's (1978) equation, a model containing DBH, DBH^2, and DBLC terms was found to be most powerful in terms of explaining differences between field estimates of crown biomass and predictions from that equation. The best DBH-based model for describing the expected difference, or bias, as it will be called from here on, contained linear and quadratic DBH terms. This model, listed in Table 4.4 and plotted in Fig. 4.4, showed the lowest AICc for DBH-based models. The Pearson residuals from the model fit were also well-behaved, displaying no marked trends in location or dispersion (Fig. 4.5).

A point-wise 95% confidence envelope drawn in Fig. 4.4 around the fitted bias correction model (BCM) for Brown's (1978) equation indicates a slight negative bias for trees in the 12-18 cm DBH range but a positive and increasing bias for trees above 30 cm. That said, there appears to be some lack of fit in the quadratic bias correction model in trees above 50 cm, and this is likely due to the high variance of crown biomass estimates in that region. However, no pronounced lack of fit is evident in the standardized residual plot (Fig. 4.5).

Regarding the crown biomass equation of Jenkins et al. (2003), it was found that both DBH and DBLC terms were significant in modeling the differences of this equation relative to field estimates. The best DBH-based model contained only a linear DBH effect (Table 4.4; Fig. 4.4). Standardized residuals for the latter model are shown in Fig. 4.5, and again show no marked trends in mean or variance. A 95% confidence envelope around the fitted bias correction model indicates that there is appreciable negative bias in the crown biomass equation of Jenkins et al. (2003) for trees exceeding approximately 15 cm DBH.

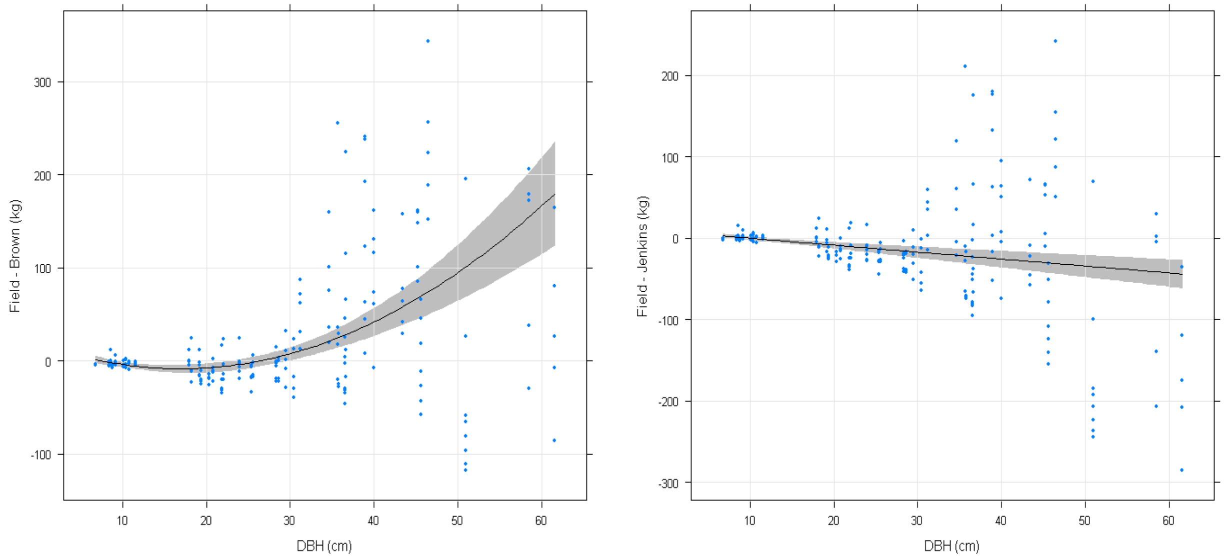

Figure 4.4. Differences between field estimates and equation-based predictions of crown biomass from Brown (1978; left) and Jenkins et al. (2003; right) for Douglas-fir. The fitted bias correction model (solid line) and 95% point-wise confidence envelope (grey) are also shown.

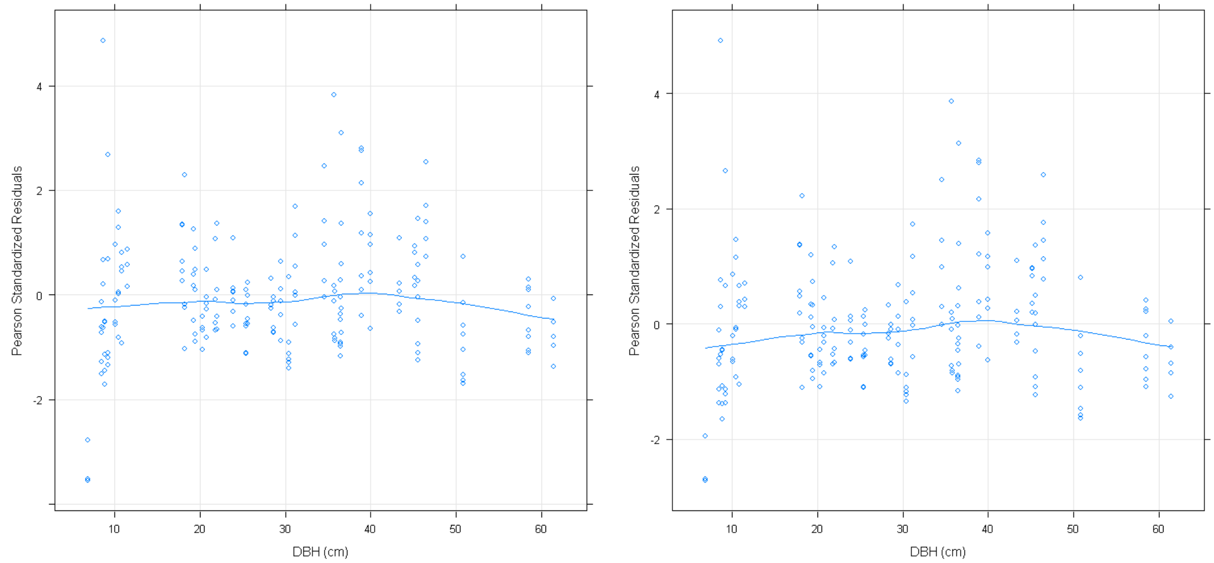

Figure 4.5. Pearson residual plots for the Douglas-fir bias correction models created for the crown biomass equations of Brown (1978; at left) and Jenkins et al. (2003; at right).

In Fig. 4.2, a tendency for large DBH trees with relatively short crowns to have smaller than average estimates of crown mass is illustrated. This tendency suggests that a measure of crown ratio or crown length should be included in any prediction equation for crown biomass.

In Fig. 4.6 a positive relationship between crown ratio and equation bias emerges for large DBH trees (each panel contains an equal number of trees, grouped by small, medium, and large DBH trees). That is, differences between field estimates of crown biomass and the equations of both Brown (1978) and Jenkins et al. (2003) appear to be insensitive to crown ratio for small DBH trees, but for large DBH trees large positive (negative) differences are associated with larger (smaller) crown ratios. Thus both equations overestimate the crown biomass of large DBH trees with small crowns.

Table 4.4. Bias correction models for Douglas-fir and associated model selection statistics. Bold models were the selected BCMs and are illustrated in Fig. 4.4.

Prediction Equation	Model	Differences Function	AICc
Brown (1978)			
	ECM	$7.80 - 4.15\times DBH + 0.08\times DBH^2 + 2.38\times DBLC$	2050
		$15.30 - 4.84\times DBH + 0.08\times DBH^2 - 0.13\times CR + 3.36\times DBLC$	2051
		$9.17 - 3.64\times DBH + 0.08\times DBH^2 + 2.18\times DBLC - 0.52\times HT$	2052
	BCM	-2.47	2113
		$-34.78 + 1.94\times DBH$	2102
		$18.84 - 3.21\times DBH + 0.09\times DBH^2$	2089
		$40.85 - 7.04\times DBH + 0.27\times DBH^2 - 0.002\times DBH^3$	2101
Jenkins et al. (2003)			
	ECM	$1.17 - 2.25\times DBH + 2.29\times DBLC$	2046
		$8.78 - 2.95\times DBH - 0.13\times CR + 3.23\times DBLC$	2047
		$-0.11 - 2.13\times DBH - 0.004\times DBH^2 + 2.34\times DBLC$	2048
	BCM	-6.57	2093
		$8.29 - 0.85\times DBH$	2078
		$10.81 - 1.20\times DBH + 0.01\times DBH^2$	2086
		$30.27 - 4.61\times DBH + 0.17\times DBH^2 - 0.002\times DBH^3$	2099

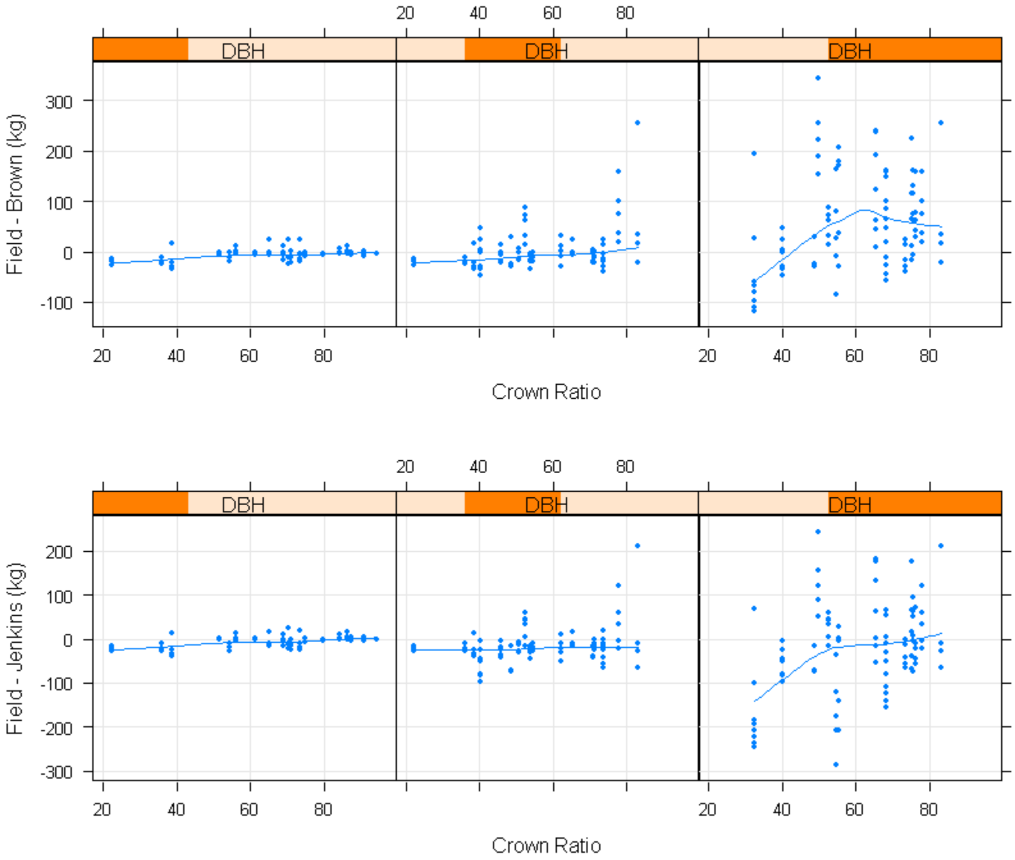

Figure 4.6. DBH conditioning plots of Douglas-fir crown ratio against difference between field estimates and equation-based predictions of crown biomass from Brown (1978; top) and Jenkins et al. (2003; bottom). Rightmost panels show data from trees with DBH > 29.5 cm.

4.3 Estimation of Crown Biomass in Lodgepole Pine

Lodgepole pine is generally a higher elevation species which tends to grow in large, dense, even-aged stands. A fire adapted species, lodgepole pine often grows in stands that experience large, stand replacing fires with between fire intervals ranging from 1 to 300 years depending on site and stand conditions (Arno, 1980). Lodgepole pine maintains a niche in drier areas of poor, rocky soils, in near sub-alpine zones. However it can be found in many other sites, as well as included in mixed species, uneven-aged stands. For the most part, according to the sample trees selected for this study, lodgepole pine have short crowns (i.e. small crown ratios), are not very tall relative to other species for the same DBH, and tend to be diameter limited (it is difficult to find lodgepole pine much larger than 50 cm DBH).

Among the lodgepole pine sampled, there are strong relationships between DBH and HT (r=0.91), DBLC (r=0.89), and crown mass (r=0.88). Figure 4.7 illustrates the major characteristics for these sample trees. No tree really stands out as being relatively tall given its DBH. There is only a slight trend between DBH and crown length, but for the most part lodgepole pine sampled in this study seem to have a crown length of 5 to 12 meters regardless of DBH or height. Only one tree, colored in red, really stands out due to its extremely long crown, while in other regards it seems to be a normal mid-sized tree. This tree was the only lodgepole pine sampled in the Swan Valley, northwest of Missoula, MT, on moist grand fir habitat. This may again suggest the variability among trees due to site differences which are difficult to measure.

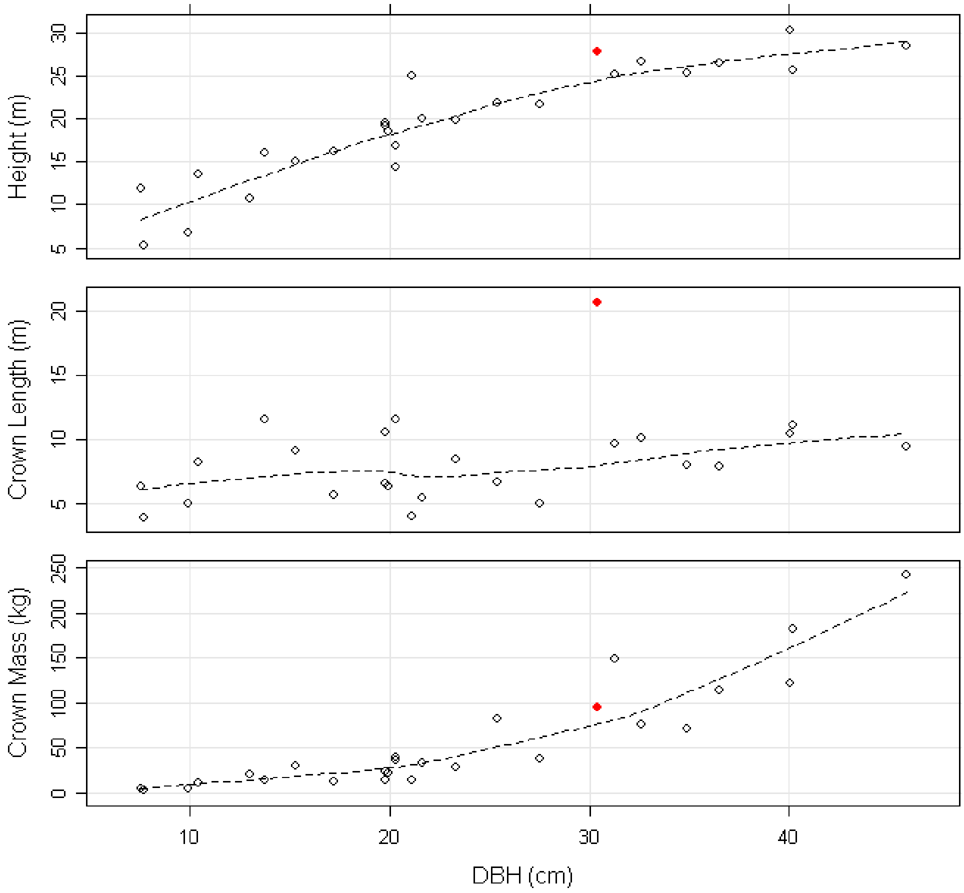

Figure 4.7. Tree and crown characteristics of lodgepole pine sample trees; trees outlying in at least one dimension are shown in red. The lower panel describes a relationship between DBH and average crown mass estimates for each tree.

As with Douglas-fir, the range of crown mass estimates produced by each branch had a wide degree of variability (Fig. 4.8). However, with lodgepole pine, the variability among estimates is fairly high even in smaller DBH trees and increases with size. The great degree of variability among individual branch estimates selected from a given tree could be associated with the crown structure of lodgepole pine. In this species, it seems that some branches tend to be very large and overgrown, compared to other branches of a similar diameter on the same tree. Though there is increasing variability with increasing DBH, there remains a strong positive trend between DBH and individual branch-based estimates of crown mass.

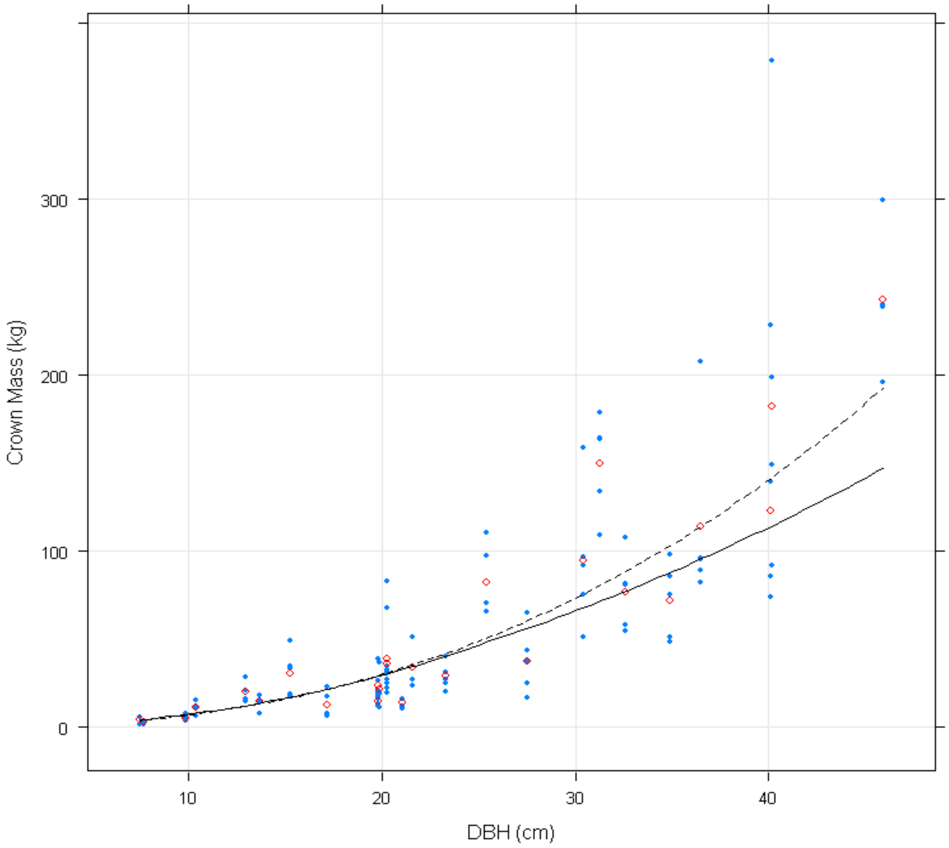

Figure 4.8. Lodgepole pine crown mass estimates from field sampling (blue points are branch-level estimates, red points are average-tree estimates), Brown's (1978) equation (solid line), and Jenkins et al. (2003) equation (dashed line).

Models fit for lodgepole pine are listed in Table 4.5. For regressions of the differences between RBS field estimates and Brown's (1978) equation prediction, the ECM was found to include DBH, DBH^2 and DBLC. For the best DBH-based model, a linear mixed effects model with a DBH-based power function to model variance was fit which incorporated both linear and quadratic DBH terms. While this model does not have the lowest AICc (though it is close), this model was favored because its residual plot (Fig. 4.10) showed no trend or lack of fit. Both the intercept model and linear DBH model shown in Table 4.5 had residual plots which showed trends which suggested a lack of fit for the smallest and largest DBH trees. Where AICc provides information about global model fit, residual plots do a better job of describing local fit. Because it is important to have a BCM that has good global and local fit, and therefore works for any DBH, the quadratic DBH model was selected.

Figure 4.9 illustrates the best DBH-based model, including a 95% point-wise confidence interval around the estimated bias. For trees smaller than 30 cm DBH, the estimated bias is not significantly different from zero, which would suggest that no bias is present in predictions produced by Brown's (1978) equation at these sizes. Beyond 30 cm DBH, the bias is significant and increasing rapidly, although the variance of the differences as well as the estimated bias is also large, causing the confidence interval to be wide. Again, a residual plot for this model fit (Fig. 4.10) does not show any marked trend.

For differences from Jenkins et al. (2003) equation predictions, the ECM included only DBLC. The best DBH-based model (Fig. 4.9) incorporated linear and quadratic DBH terms. As with the BCM for Brown's (1978) equation, this model does not have the lowest AICc, but rather has a residual plot which shows no marked trend or lack of fit. Also, the intercept and linear DBH models have residual plots which show a strong trend, and local lack of fit for small and large DBH trees. However, looking closely at the BCM (Fig 4.9), there is a failure to adequately explain a trend in the differences between equation predictions and individual crown estimates as a function of DBH. The grey 95% confidence envelope illustrated overlaps zero, suggesting that the Jenkins et al. (2003) equation for lodgepole pine is unbiased.

Table 4.5. Bias correction models for lodgepole pine and associated model selection statistics. Bold models were the selected BCMs and are illustrated in Fig. 4.9.

Prediction Equation	Model	Differences Function	AICc
Brown (1978)			
	ECM	$10.68 - 3.24\times DBH + 0.08\times DBH^2 + 1.57\times DBLC$	983
		$-20.28 + 1.83\times DBLC$	984
		$-14.45 - 1.32\times DBH + 0.07\times DBH^2 - 0.50\times DBLC - 0.39\times CR$	985
	BCM	1.61	1102
		$-11.79 + 0.79\times DBH$	1101
		$17.99 - 2.53\times DBH + 0.08\times DBH^2$	1103
		$2.22 + 0.26\times DBH - 0.06\times DBH^2 + 0.002\times DBH^3$	1114
Jenkins et al. (2003)			
	ECM	$-10.99 + 0.90\times DBLC$	981
		$-9.94 - 0.58\times DBH + 1.67\times DBLC$	983
		$4.01 - 2.10\times DBH + 0.04\times DBH^2 + 1.56\times DBLC$	984
	BCM	0.49	1094
		$-2.61 + 0.18\times DBH$	1097
		$10.95 - 1.37\times DBH + 0.04\times DBH^2$	1102
		$3.56 - 0.07\times DBH - 0.03\times DBH^2 + 0.001\times DBH^3$	1114

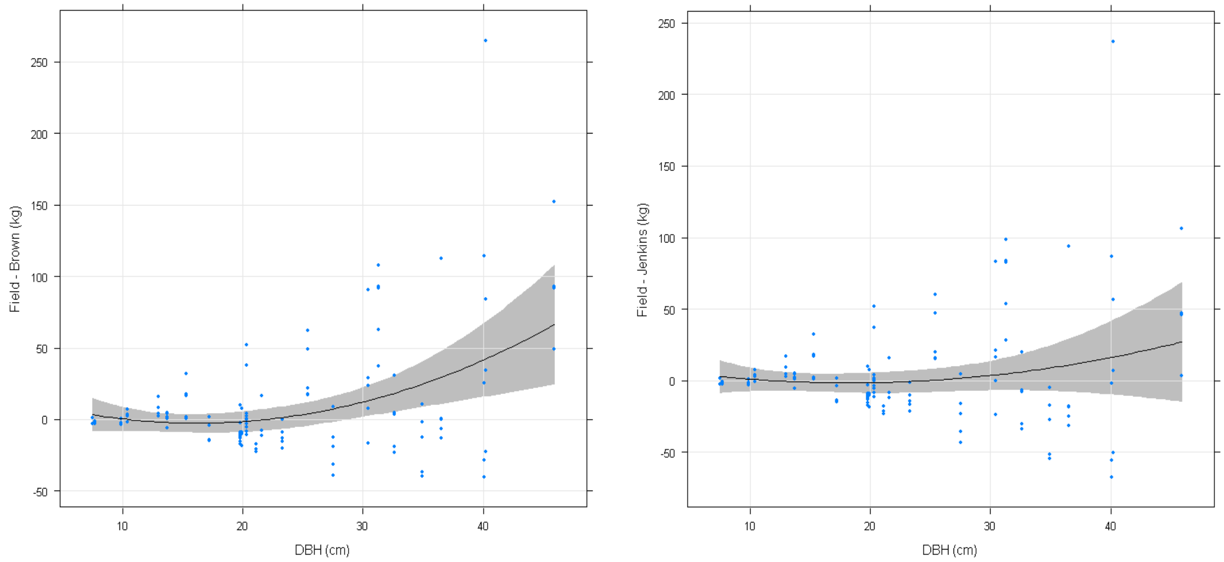

Figure 4.9. Differences between field estimates and equation-based predictions of crown biomass from Brown (1978; left) and Jenkins et al. (2003; right) for lodgepole pine. The fitted bias correction model (solid line) and 95% point-wise confidence envelope (grey) are also shown.

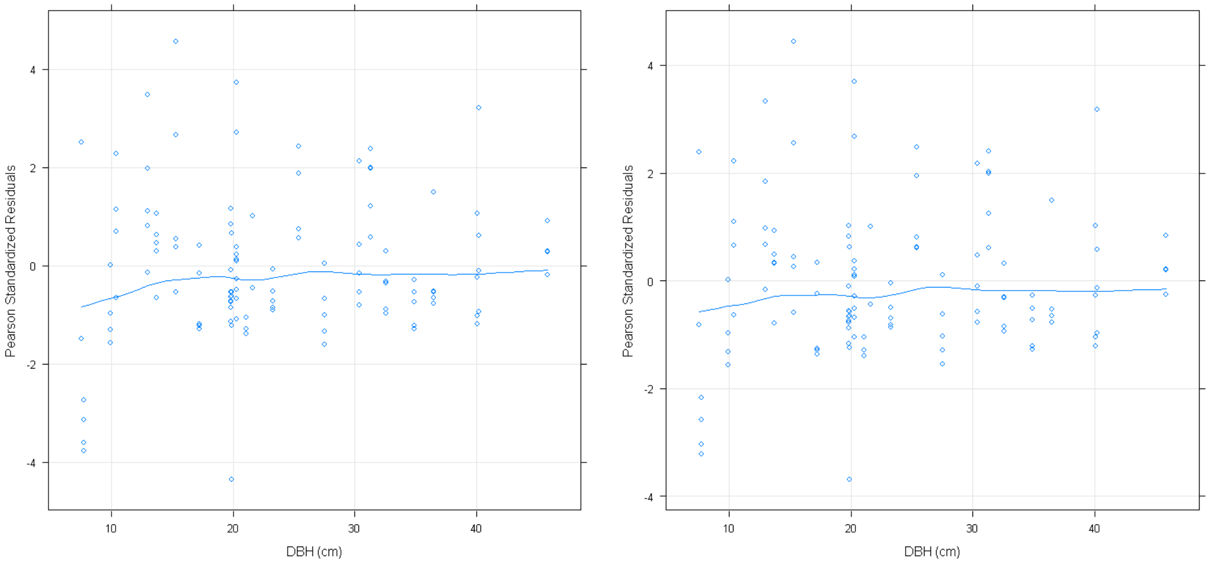

Figure 4.10. Pearson residual plots for the lodgepole pine bias correction models created for the crown biomass equations of Brown (1978; at left) and Jenkins et al. (2003; at right).

The notion that the Jenkins et al. (2003) equation for all pine species (including, but not limited to, loblolly pine (*Pinus taeda*), whitebark pine (*Pinus albicaulis*), and ponderosa pine) is unbiased for lodgepole pine is quite interesting. What it suggests is that all pine species have on average an equal crown weight for any given DBH, or at least that lodgepole pine is the average of pine species. Most people would not look at a lodgepole pine and a ponderosa pine side by side and make that assumption. Another intriguing note is that Brown (1978) sampled only three trees to build the equation for lodgepole pine. The remainder of his lodgepole pine data came from Storey et al. (1955) and Fahnestock (1960), which contained sample trees collected from the Priest River Experimental Forest in northern Idaho, Mt. Shasta in California, and various locations in Nevada. The lack of coverage for this species, the collection of only three sample trees, and the potential error related to the use of multiple sampling schemes may be an indication of the source of bias associated with the prediction equation produced.

4.4 Estimation of Crown Biomass in Ponderosa Pine

Ponderosa pine are most productive and remain the dominate species on lower elevation, dry sites. Typically forming open, uneven-aged stands, the ponderosa pine is also a fire adapted species, though it historically maintained a shorter average fire-free interval of between 5 and 20 years, with only rare stand replacing fire events (Arno, 1980). Due to its mostly open grown stand characteristics, ponderosa pine have wide, long crowns, large outstretched branches with long needles and low amounts of 1 hour fuels (branches don’t taper, rather they just foliate) indicated by the data collected for this study. As elevation and moisture increase, ponderosa pine begins to compete with Douglas-fir for nutrients and water, where Douglas-fir tends to replace ponderosa pine as the climax species (Arno, 1980). Ponderosa pines have very thick ablative bark, which flakes off during fires to protect the tree cambium (Butler et al., 2005), and often grows to very large diameters.

Characteristics of ponderosa pine sampled for this study are shown in Fig. 4.11. Strong relationships are seen between DBH and HT (r=0.92), crown length (r=0.86), and crown mass (r=0.82). For the relationship between DBH and HT, there is more variability among trees of similar DBHs than what is seen in the other species, possibly due to site, stand, or growing conditions. For crown mass, there is a great degree of variation at larger DBHs, but similar levels of variation are not seen in the other dimensions. Some trees have high estimates of crown mass compared to others of similar DBH. Very interesting are the two trees marked in red. One tree has a DBH of 51.4 cm, is 32.4 m tall, and has a crown length of 16.6 m; the other tree has a DBH of 51.7 cm, stands 33.5 m tall, and has a crown length that spans 16.5 m. These two trees were located in the same stand near Ronan, MT, and are nearly identical in all respects, except that they have widely different estimates of crown mass. The larger of the two trees has the highest estimate of crown mass among the ponderosa pine sampled and, as seen in Fig. 4.12, has the highest amount of variability among individual branch estimates of any ponderosa pine sampled.

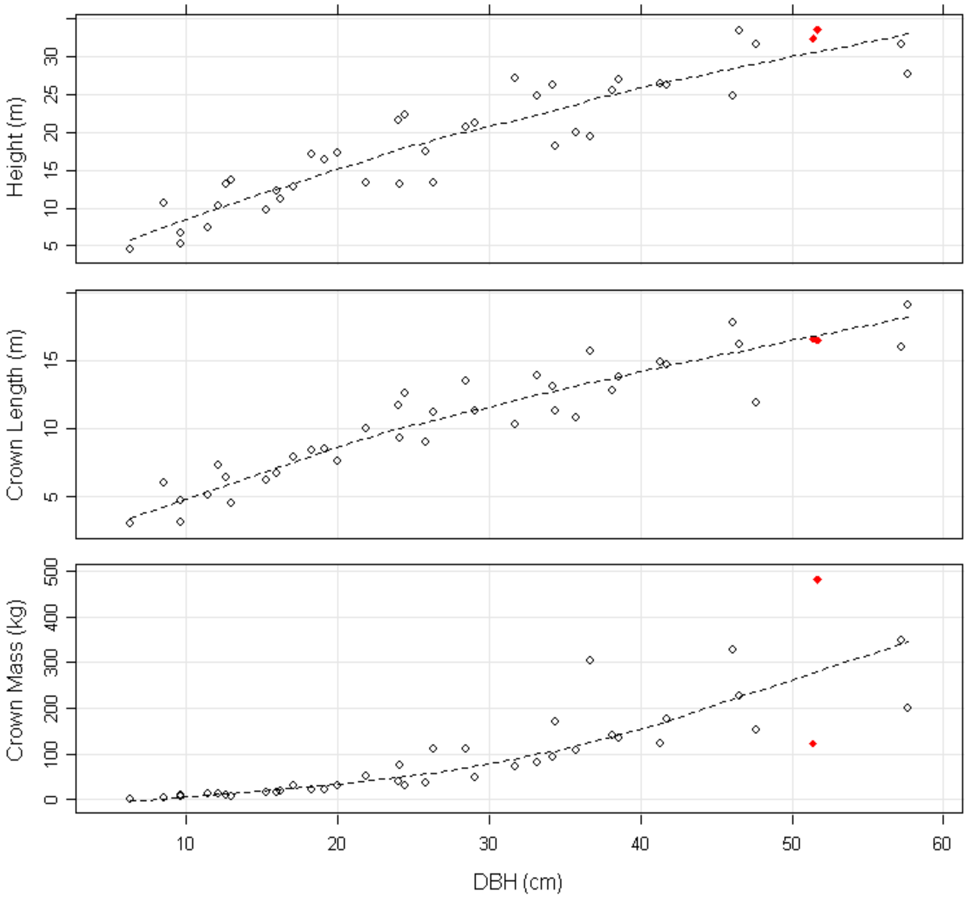

Figure 4.11. Tree and crown characteristics of ponderosa pine sample trees; trees outlying in at least one dimension are shown in red. Average-tree estimates of crown mass are shown in the lower panel.

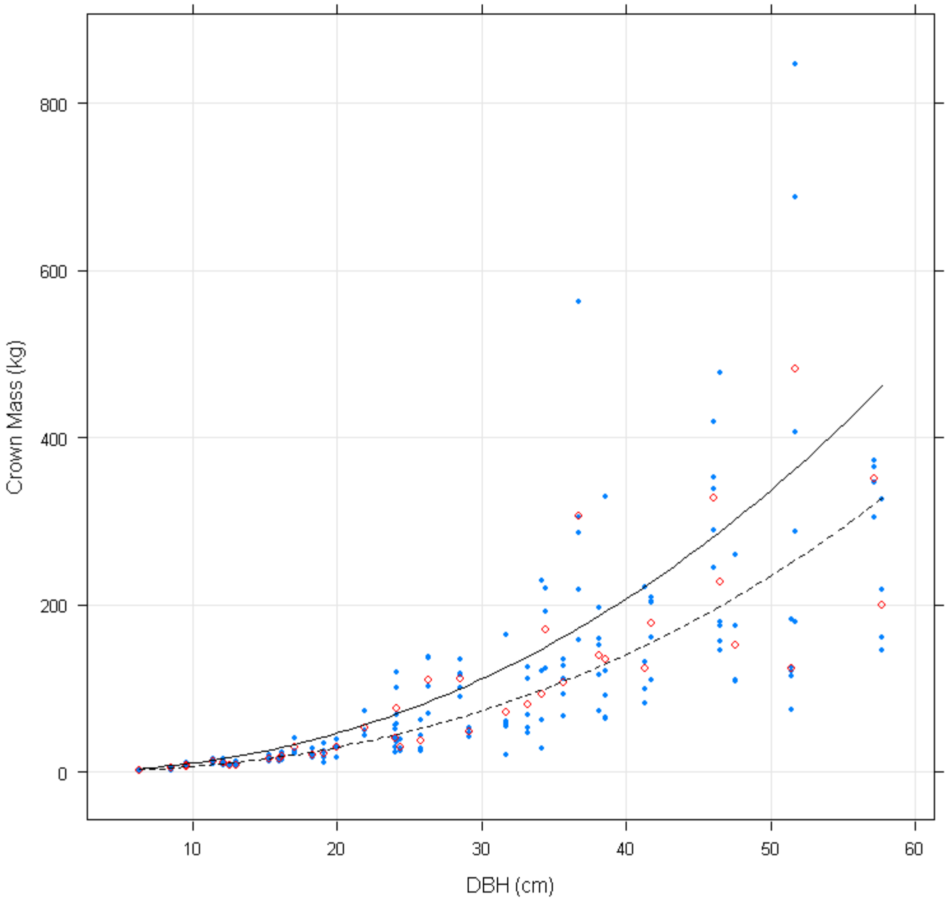

Figure 4.12. Ponderosa pine crown mass estimates from field sampling (blue points are branch-level estimates, red points are average-tree estimates), Brown's (1978) equation (solid line), and Jenkins et al. (2003) equation (dashed line).

For individual branch estimates of crown mass there is again a great degree of variability (Fig. 4.12). While there is relatively little variation among estimates for small DBH trees compared to large DBH trees, the amount of variation among estimates increases with DBH, and seems to hit a point at around 25 cm where the variability starts to explode. Looking again at the two trees with diameters of about 52 cm, the ranges of estimates differ considerably and only barely overlap. This extreme example points out the potential variability in crown mass estimates that can be produced by the RBS sampling scheme used, as well as the potential degree of difference in crown structure from one tree to another. What this means is that while any equation cannot accurately predict the crown mass of any given tree, it can hopefully impart some sense of how much mass, on average, trees of a given size have across a large area, and thereby provide a reliable estimate of the total mass in a particular stand or region.

Table 4.6. Bias correction models for ponderosa pine and associated model selection statistics. Bold models were the selected BCMs and are illustrated in Fig. 4.13.

Prediction Equation	Model	Differences Function	AICc
Brown (1978)			
	ECM	$4.64 - 2.48\times DBH - 0.03\times DBH^2 - 0.54\times HT + 4.09\times DBLC - 0.17\times CR$	1827
		$-5.75 - 1.76\times DBH - 0.03\times DBH^2 - 0.29\times HT + 3.00\times DBLC$	1831
		$-5.44 - 2.31\times DBH - 0.03\times DBH^2 + 3.26\times DBLC$	1833
	BCM		
		-10.27	1916
		$6.35 - 1.04\times DBH$	1898
		$-0.51 - 0.04\times DBH - 0.03\times DBH^2$	1911
		$-2.93 + 0.57\times DBH - 0.07\times DBH^2 + 0.001\times DBH^3$	1925
Jenkins et al. (2003)			
	ECM	$2.41 - 2.06\times DBH - 0.57\times HT - 0.16\times CR + 3.95\times DBLC$	1827
		$4.24 - 2.45\times DBH + 0.01\times DBH^2 - 0.54\times HT + 3.23\times DBLC - 0.13\times CR$	1828
		$-6.04 - 1.74\times DBH + 0.01\times DBH^2 + 2.98\times DBLC - 0.29\times HT$	1831
	BCM		
		0.47	1901
		$-2.46 + 0.29\times DBH$	1904
		$-0.85 - 0.04\times DBH + 0.01\times DBH^2$	1911
		$-2.83 + 0.47\times DBH - 0.02\times DBH^2 - 0.001\times DBH^3$	1925

Regressions for differences from RBS field estimates and Brown's (1978) equation predictions were produced and are shown in Table 4.6. The best ECM contained DBH, DBH^2, HT, DBLC and CR. The BCM contained only a linear DBH term (Fig. 4.13). The estimated bias trend immediately departs from zero, and increases with DBH. The 95% point-wise confidence interval for the estimated bias does not include zero beyond 10 cm DBH. The Pearson standardized residual plot for the model (Fig. 4.14) shows no defined trend.

For differences between field estimates and Jenkins et al. (2003) equation predictions, the best ECM included DBH, HT, CR, and DBLC. However, the BCM contained only an intercept (Fig. 4.13). The estimated bias is small, only 0.45 kg, and remains constant for all sizes of DBH. As with other species, variability is large and increases with DBH, but the differences appear to be centered about zero. Figure 4.13 illustrates the bias correction model and a 95% point-wise confidence interval. While it is difficult to see, the confidence interval does contain zero. A residual plot for the regression describes no strong trend or lack of fit (Fig. 4.14).

In the plots presented in Fig. 4.13, it is difficult to see the bias associated with either equation. Where Brown's (1978) equation has an increasing overestimation, hitting a maximum bias of -53.7 kg within the data range, Jenkins et al. (2003) equation has constant underestimation of only 0.47 kg. Remarkable is the fact that Jenkins et al. (2003) equation is only found to be biased by this small amount, and the confidence envelope also includes zero. For the largest ponderosa pine sampled, a 57.7 cm tree (expected to have a crown mass of 327 kg) the bias corresponds to a 0.14% error. It seems that the slight amount of bias here, when paired with the lack of bias associated with the pine equation for lodgepole pine, basically states that for the most part, the two species have equivalent crown mass for a given DBH.

Using the BCM fit for the Jenkins et al (2003) equation, the crown mass of a 35 cm pine tree, which on average weighs 104 kg, would be underestimated by 0.47 kg, or a 0.45% error for the ponderosa pine; and an underestimation of 8.7 kg, or an 8% error for the lodgepole pine. Given that the direction of bias is the same for both species, as well as the fact that the

BCM for each species is not large for a given tree DBH, and remembering that the confidence interval for these BCMs includes zero, it again seems reasonable to have only one equation to predict pine crown mass, at least in the case of these two species growing in the INW.

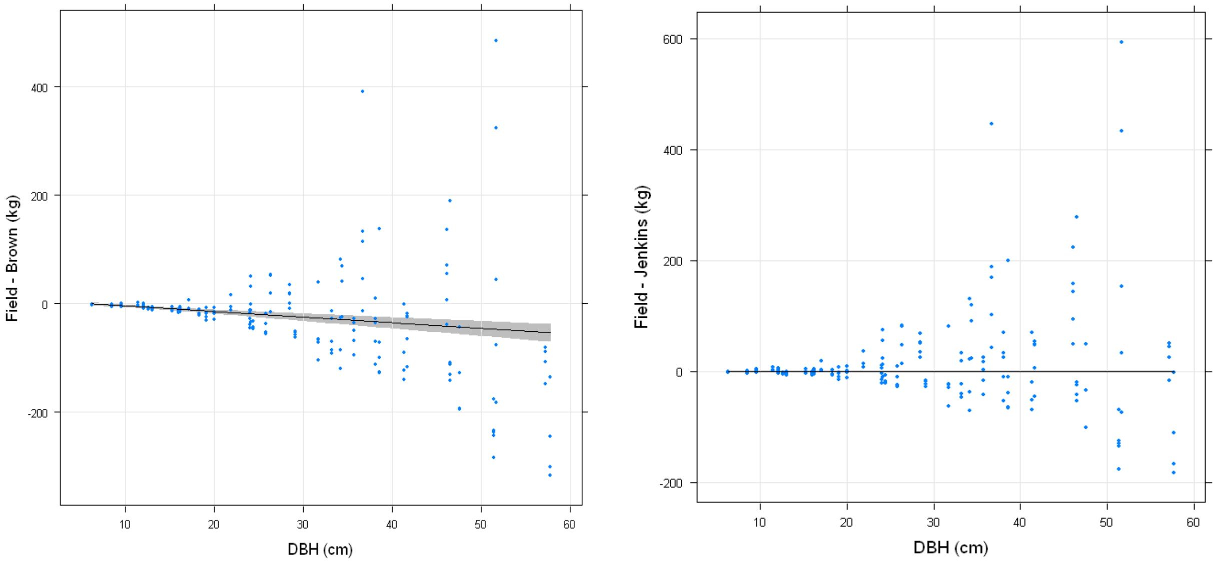

Figure 4.13. Differences between field estimates and equation-based predictions of crown biomass from Brown (1978; left) and Jenkins et al. (2003; right) for ponderosa pine. The fitted bias correction model (solid line) and 95% point-wise confidence envelope (grey) are also shown.

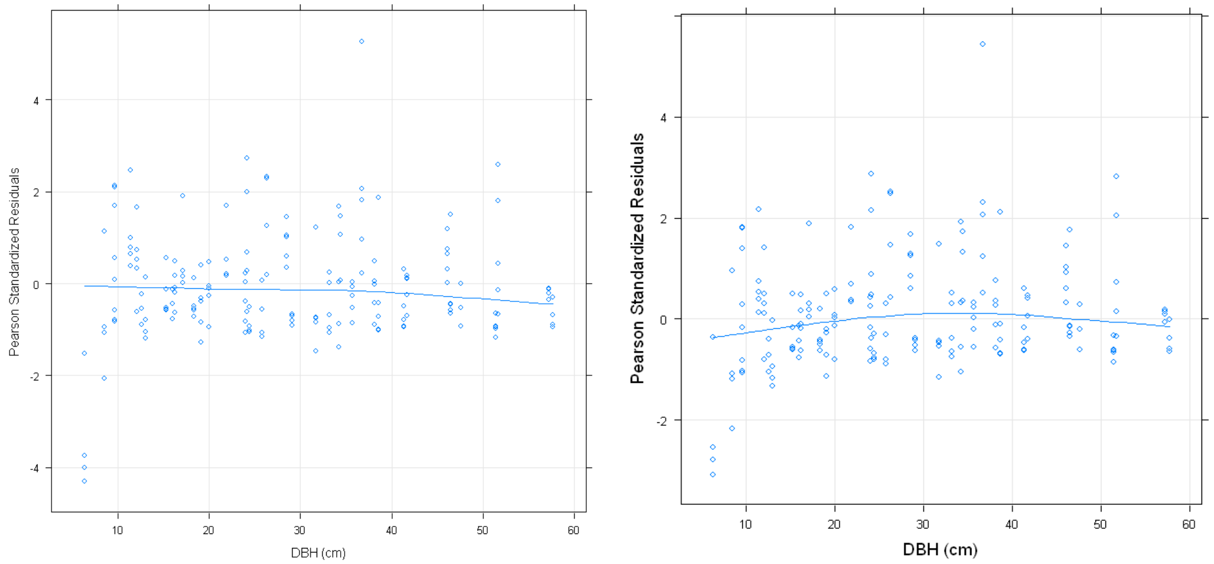

Figure 4.14. Pearson residual plots for the ponderosa pine bias correction models created for the crown biomass equations of Brown (1978; at left) and Jenkins et al. (2003; at right).

To further illustrate the notion of using only one equation for both ponderosa pine and lodgepole pine, it is helpful to look at a graph which contains both species (Fig 4.15). The plot shows the general trend in crown mass estimates for each species to be fairly consistent, and it is only where lodgepole pine tend to be DBH limited that the trend ends.

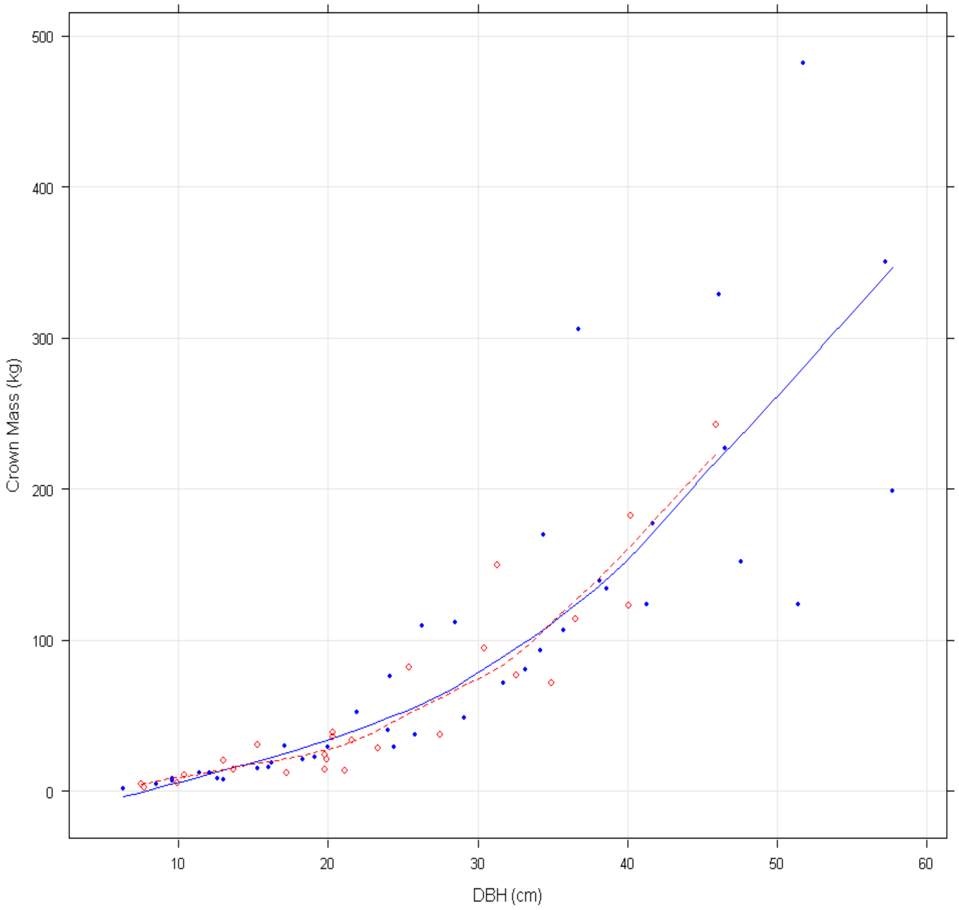

Figure 4.15. Plot of average crown mass estimates for ponderosa pine (blue points) and lodgepole pine (red circles). A smoother trend is drawn through each species, where the solid line is ponderosa pine and lodgepole pine is represented by the dashed line.

For ponderosa pine there is again some association in the differences between RBS field estimates and equation predictions in relation to crown ratio conditioned upon DBH. Figure

4.16 illustrates a trend in the differences against crown ratio in the group of trees with the largest DBHs, where the crown masses of trees with lower crown ratios are apparently being over-estimated and the masses of trees with higher crown ratios are being under-estimated. Noting that the regression fits shown in Table 4.6, one including only crown ratio, and another including both DBH and crown ratio, were found to be significant predictors of the differences between field estimates and equation predictions, it is possible that an equation used to describe ponderosa pine crown mass should also utilize some factor associated with crown ratio or crown length.

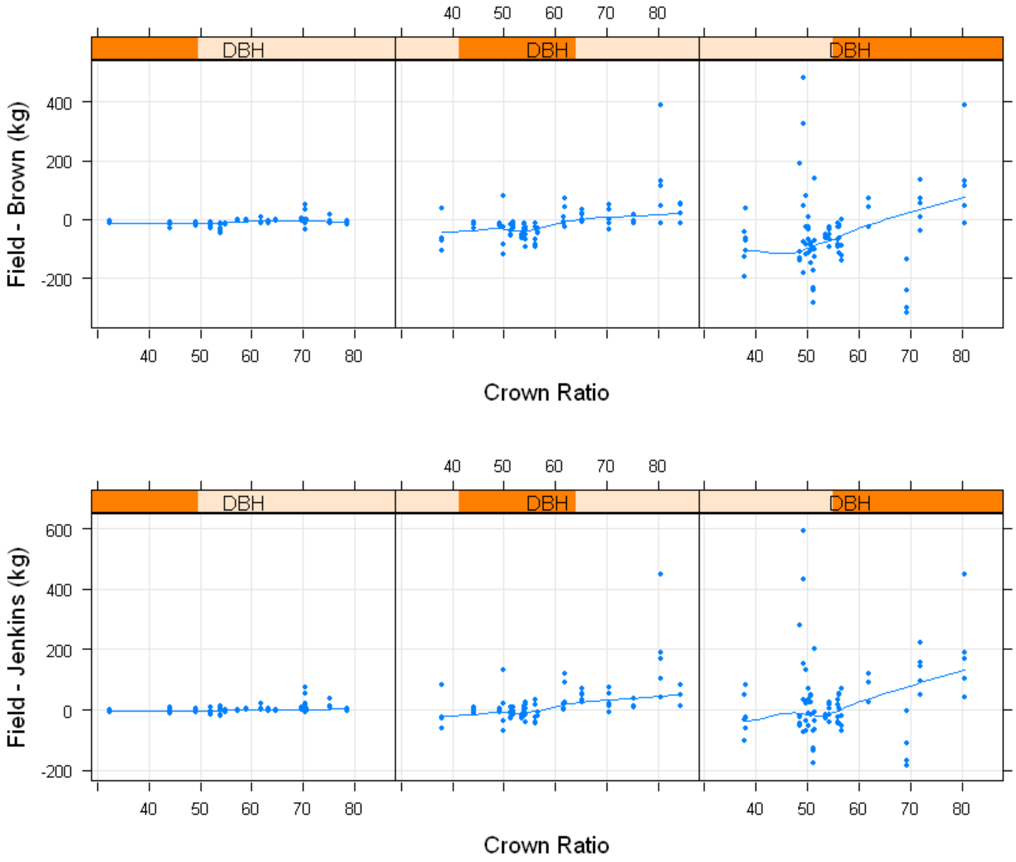

Figure 4.16. DBH conditioning plots of ponderosa pine crown ratio against difference between field estimates and equation-based predictions of crown biomass from Brown (1978; top) and Jenkins et al. (2003; bottom). Right panels show data from trees with DBH > 31.7 cm.

4.5 Estimation of Crown Biomass in Western Larch

Western larch is a shade intolerant species growing on moister sites throughout the region. It is a deciduous conifer species that loses its small, light leaves in the early to mid fall. Western larch is also a fire adapted species, having fire resistant ablative bark similar to ponderosa pine; it grows in stands with a historic average fire-free interval of between 25 and 50 years (Barrett et al., 1991). Western larch grows best in open, uneven aged stand structures, in either single species or multi-species stands. Western larch can often be found growing among other moisture loving tree species such as Douglas-fir. It can be a very long-lived species, and dominates moist, north- and east-facing slopes in mid-range elevations across the landscape.

Western larch sampled for this study came from several different locations in Montana, with the vast majority coming from Lubrecht Experimental Forest and the Flathead, Kootenai, and Lolo National Forests. There is a strong positive relationship between DBH and HT (r=0.89), crown length (r=0.76), and crown mass (r=0.86, Fig. 4.17). Western larch had a wide amount of variability in crown lengths for any given DBH, but had a positive, and seeming asymptotic relationship between crown length and mass. Western larch does have the lowest crown mass for any given DBH in relation to all other tree species sampled for this study, which is likely related to the fact that it is a deciduous species, producing small light leaves that it loses every fall, and also the fact that it is a very efficient self-pruner with very small amounts of dead branch wood found within the crowns of sample trees.

Again there are two trees in particular, colored in red (Fig. 4.17), one with a DBH of 46.7 cm, HT of 21.48 m, and crown length of 19.8 m, and the other with a DBH of 46.6 cm, HT of

29.0 m, and crown length of 11.1 m. The tree with the larger DBH has an average estimated crown mass of 157 kg, while the smaller has an average estimated crown mass of 54 kg.

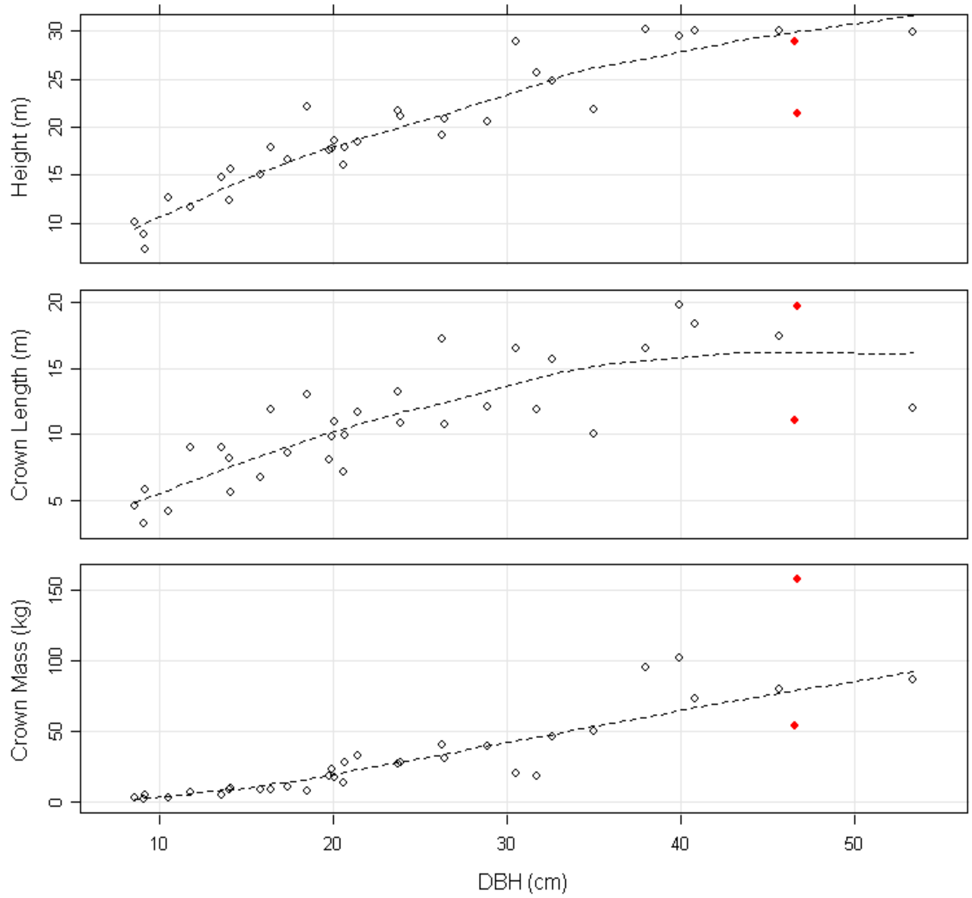

Figure 4.17. Tree and crown characteristics of western larch sample trees; trees outlying in at least one dimension are shown in red. Average-tree estimates of crown mass are shown in the lower panel.

As with all other tree species, the within-tree variability among branch estimates of total crown mass is large, especially as DBH increases (Fig. 4.18). However, variability seems to be much less with western larch than any other species, possibly because average crown mass tends to be much lower. With the exception of 2 outlying estimates of crown mass which are greater than 200 kg, the majority of points lie in a group of between 50 and 150 kg for large

DBH trees. In Fig. 4.18, the Jenkins et al. (2003) equation lies above the majority of crown mass estimates at all levels of DBH, while Brown's (1978) equation seems to cut through the scatter.

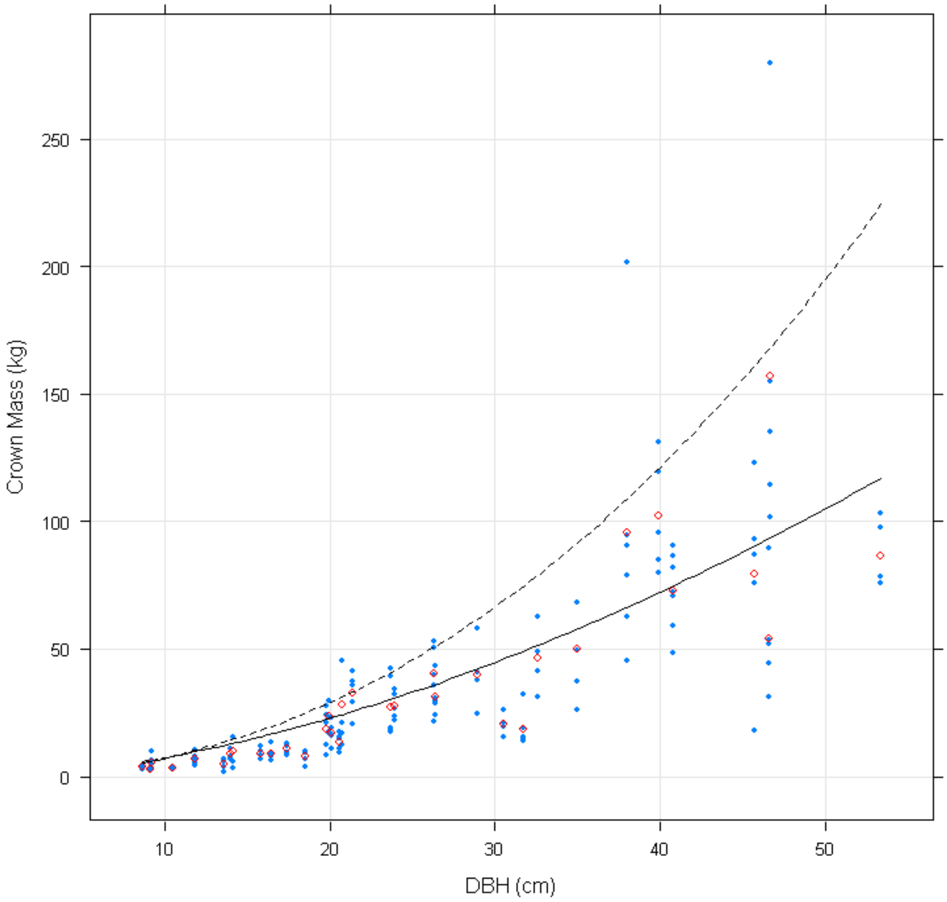

Figure 4.18. Western larch crown mass estimates from field sampling (blue points are branch-level estimates, red points are average-tree estimates), Brown's (1978) equation (solid line), and Jenkins et al. (2003) equation (dashed line).

As with the previous three species, regressions fit for differences between RBS field estimates and the two equation predictions utilized a mixed-effects, heterskedastic modeling scheme. Models fitted are described be found in Table 4.7. In describing departures from Brown's (1978) equation, a regression containing DBH, DBH^2, CR, and DBLC was found to be the best ECM. However, the best DBH-based model contained only an intercept, which is not technically DBH-based, except for variability, which was still modeled as a function of DBH. Figure 4.19 illustrates the model fit, enclosed in a 95% point-wise confidence interval which does not contain zero at any DBH. This result implies that the Brown (1978) equation has an equal bias across the DBH range of the sample trees, which is different from any other results found, where bias tends to increase with DBH. A residual plot shows no general trend associated with lack of model fit (Fig. 4.20).

Table 4.7. Bias correction models explored for western larch and associated model selection statistics. Bold models were selected BCMs and are illustrated in Fig. 4.19.

Prediction Equation	Model	Differences Function	AICc
Brown (1978)			
	ECM	11.05 - 0.67×DBH - 0.93×DBH^2 - 0.18CR + 1.70×DBLC	1312
		11.13 - 0.76×DBH + 0.003×DBH^2 - 0.89×HT - 0.17×CR + 1.64×DBLC	1314
		7.43 - 1.10×DBH - 0.11×CR + 1.01×DBLC	1315
	BCM		
		-3.95	1327
		-4.02 - 0.004×DBH	1332
		1.64 - 0.64×DBH + 0.02×DBH^2	1339
		10.32 - 2.09×DBH + 0.09×DBH^2 - 0.001×DBH^3	1352
Jenkins et al. (2003)			
	ECM	6.59 + 0.18×DBH - 0.05×DBH^2 - 0.87×HT + 2.29×DBLC - 0.18×CR	1315
		-0.14 + 0.14×DBH - 0.03×DBH^2 + 0.42×DBLC - 0.37×HT	1322
		0.45 - 0.45×DBH - 0.03×DBH^2 + 0.55×DBLC	1323
	BCM		
		-15.73	1388
		9.98 - 1.16×DBH	1342
		-3.81 + 0.41×DBH - 0.04×DBH^2	1340
		7.64 - 1.50×DBH + 0.05×DBH^2 - 0.001×DBH^3	1352

To describe differences between RBS field estimates and Jenkins et al. (2003) equation predictions, the best ECM contained DBH, DBH^2, HT, CR, and DBLC. The best DBH-based model contained linear and quadratic DBH terms. This model is represented visually in Fig. 4.19, and shows negative bias increasing with DBH, indicating a tendency for the equation to overpredict crown mass. The model immediately departs from zero, and a 95% confidence interval does not contain zero throughout the range of DBHs. The residual plot (Fig. 4.19) shows no trend, and indicates no local lack of fit.

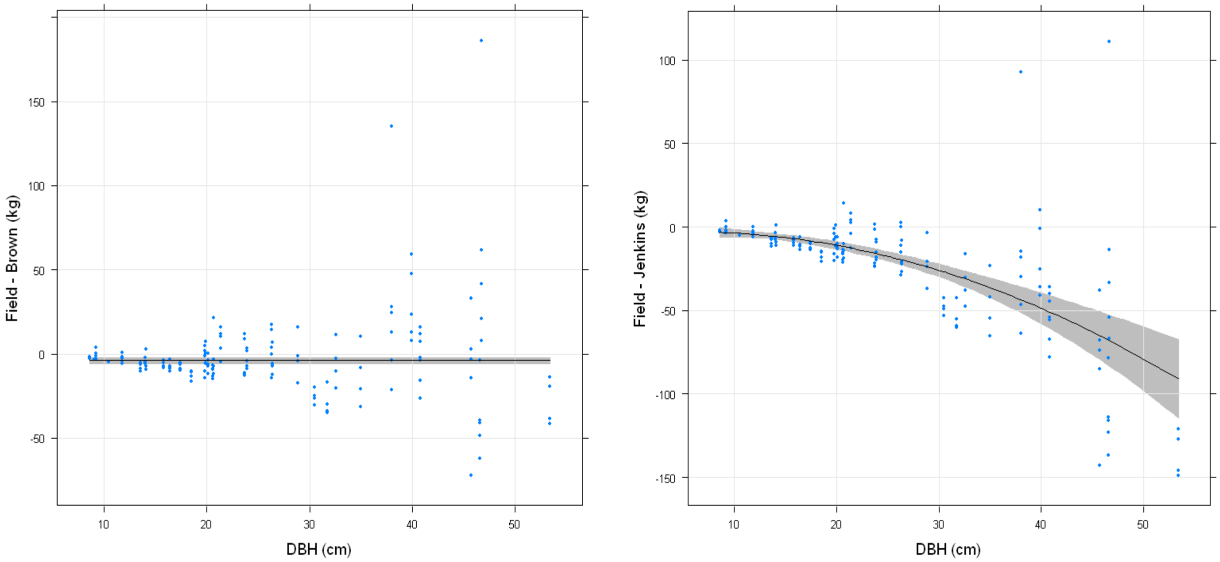

Figure 4.19. Differences between field estimates and equation-based predictions of crown biomass from Brown (1978; left) and Jenkins et al. (2003; right) for western larch. The fitted bias correction model (solid line) and 95% point-wise confidence envelope (grey) are also shown.

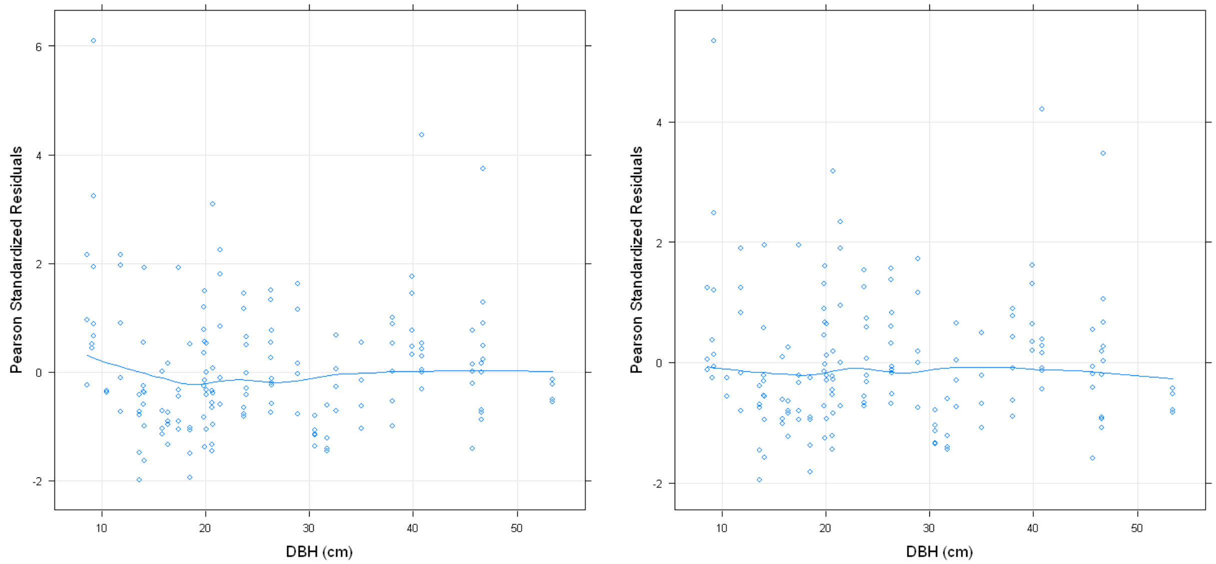

Figure 4.20. Pearson residual plots for the western larch bias correction models created for the crown biomass equations of Brown (1978; at left) and Jenkins et al. (2003; at right).

Some of the errors associated with predicting tree crown mass in western larch may be attributed to differences in crown ratio (Fig. 4.21). Large DBH trees with small crown ratios appear to be overestimated by both equation predictions, especially with the Jenkins et al. (2003) equation. For large DBH trees with long crowns, Brown's (1978) equation seems to underestimate crown mass, while the equation of Jenkins et al. (2003) is still overestimating these trees, though to a lesser extent than for trees with shorter crowns.

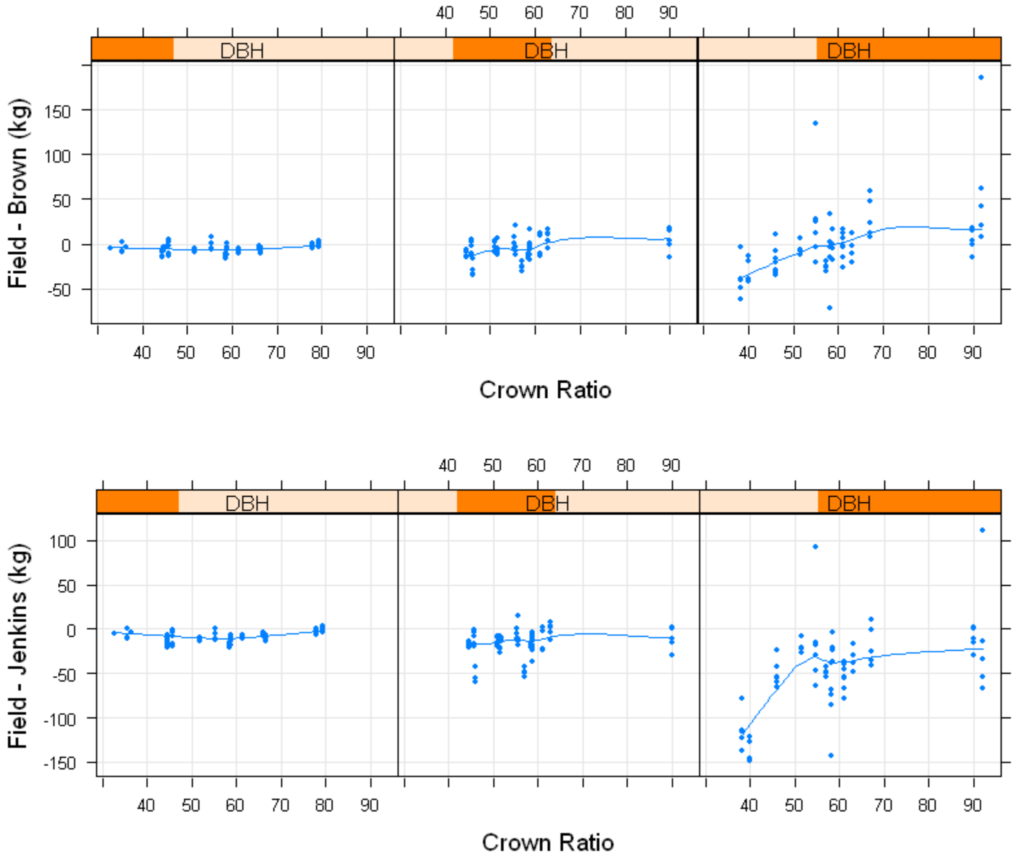

Figure 4.21. DBH conditioning plots of crown ratio against difference between field estimates and equation-based predictions of crown biomass from Brown (1978; top) and Jenkins et al. (2003; bottom) for western larch. Right panels show data from trees with DBH > 23.9 cm.

4.6 Across-Species Trends

4.6.1 Bias

For Douglas-fir and lodgepole pine, Brown's (1978) equation has an increasing bias in response to DBH. It was found that for these two species, the Brown (1978) equations under-estimate crown mass to a larger and larger degree with increases in DBH. For ponderosa pine, Brown's (1978) equation has an increasing bias with DBH which is associated with over-estimation of crown mass. With western larch the over-estimation of crown mass was found to be the same at all DBHs. The Jenkins et al. (2003) equations were found to increasingly overestimate crown mass for Douglas-fir and western larch, while no bias was found to be present for their lodgepole pine or ponderosa pine equation.

As mentioned in Chapter 2, Gray and Reinhardt (2003) graphically evaluated the accuracy of Brown's (1978) equations for Douglas-fir, lodgepole pine, and ponderosa pine. In the case of Douglas-fir, Grey and Reinhardt (2003) found that Brown's (1978) equation under-predicted the majority of their sample trees, especially the larger DBH trees, which is consistent with the results of this study. In lodgepole pine Gray and Reinhardt (2003) found that Brown's (1978) equation predicted quite well, whereas the results of this study show the 95% confidence envelope does not include zero beyond 30 cm DBH. For ponderosa pine, Gray and Reinhardt found the Brown (1978) equation to over-predict crown mass for most of their sample trees, which is also consistent with the results of this study.

Another study which evaluated the accuracy of Brown's (1978) crown biomass equation for ponderosa pine was produced by Keyser and Smith (2010). Because the purpose of that study was to evaluate the effectiveness of biomass predictions for the use of fire modeling in the FVS-FFE simulator, they limited their analysis to an evaluation of only foliage and 1 hour fuels. While their study used sample trees collected from the Black Hills of South Dakota, east of the continental divide, they found that Brown's (1978) equations consistently under-predicted these crown mass components. Though the present research aims at evaluating the accuracy of Brown's (1978) prediction equation for total crown mass, the similar conclusions reached by Keyser and Smith for different crown mass components is notable.

4.6.2 Variability

As mentioned throughout the results and discussion of each species, there was substantial variability among individual branch-based estimates of total crown mass for a given tree, as well as among all estimates for trees of a given species. One important thing to note is that there are two kinds of variability associated with the RBS estimates reported. Natural variability between trees is expected, even with all other factors (such as DBH, HT, crown length, and site) being equal. There is also within-tree sampling error in crown estimates created by the RBS sampling scheme used. Individual branch-based estimates from any given tree can vary considerably, with differences caused by any number of factors including, but not limited to, the diameters, heights, weights, and form of the selected branches. Though it is impossible to determine where all of the between-tree variability comes from, the major sources of this variability can be credited to a couple of tree attributes, as discussed below.

For all species, it appears that differences in DBH account for a substantial portion of the variability in crown mass. Also evident are trends associated with crown ratio, or crown length, in large diameter trees (for Douglas-fir, ponderosa pine, and western larch). These trends are not recognized by purely DBH-based models. Aggregated to the stand or landscape level, the overestimations and underestimations of individual crown biomass due to differing crown ratios would conceivably average out for small and moderate DBH trees. But, overall it seems the inclusion of crown ratio, or some interaction between crown ratio and DBH, in crown biomass prediction equations is required to account for more of the variability that occurs among tree crowns for large DBH trees.

The importance of including a measure of crown length for the possible estimation of tree-level crown mass may carry more weight in stands with less acreage. Crown length, or crown ratio, is an indirect measure of local stand density. Stands that are more dense, or those having a higher number of trees per acre relative to the size of trees in the stand, would be expected to have trees with lower crown ratios due to shading and self-pruning of lower branches on the trees. Inversely, in more open-grown stands, it would be expected that trees would have a longer crown length as they have more growing space, and lower branches would not be as often shaded (Bickford, 1957). This idea becomes important in respect to smaller stand scales. If a unit is targeted for fuels reduction, and there is some purpose to knowing the amount of biomass being removed, it can be important to have a more accurate measure of this. This small stand may be dense, and considering the potential for trees with low crown ratios to be overestimated by existing DBH-based biomass equations, there is a possibility of expecting much more biomass to be removed than actual. Management implications of this oversight may be slight, but if there is a targeted amount of removal, and after the project is completed an inventory finds that less was removed than required, a second (costly) stand entry may be necessary.

4.6.3 Differences in Crown Definitions

In the forest industry, a defined merchantable top is used to describe a suitable minimum upper-stem diameter for saw log products. This merchantable top diameter is often anywhere between 5 and 15 cm (2 and 6 inches). Beyond this upper-stem diameter, the wood is usually considered worthless for solid wood products. That being said, the question of how Brown (1978) and Jenkins et al. (2003) defined the boundary between stem and crown may be important, and could account for some of the apparent bias. Brown's sampling protocol appears to include all primary branches to the tree tip but no portion of the main stem, though it is a bit unclear. Jenkins et al. set a clearer boundary, and defined the crown mass for the entire tree to include all branches plus the tree top above a 10 cm (4 inch) diameter. Both these protocols differ from the definition used as part of the RBS sampling scheme applied in this study, where (only) the tree top above a 5 cm (or 2 inch top) diameter was considered as part of the crown (along with all primary branches connected to that top; see Fig. 4.22). This difference in the treatment of tree tops is measureable, and would result in the Jenkins et al. (2003) equations yielding inherently higher estimates than those collected through RBS, due to the addition of some stem material. Conversely, Brown's (1978) equations would yield inherently lower estimates than those collected by RBS due to his exclusion of any stemwood.

Calculating tree top weights using volume equations for cones and wood density measurements published by Hoadley (1990), some approximate weights can be obtained. For a

30 cm DBH Douglas-fir, the weight of the stem from the 10 cm to the 5 cm top is expected to be approximately 5.5 kg (or 5% of the predicted crown mass of 102 kg). That is, it would be expected that the Jenkins et al. (2003) equation for Douglas-fir would exceed the RBS estimate of a 30 cm DBH tree by 5.5 kg. For the same tree, the weight of the stem above the 5 cm top is about 1 kg (or 1.5% of the predicted crown mass of 78 kg), so it would be expected that the Brown (1978) equation for Douglas-fir would fall short of the RBS estimate by 1 kg. In fact, both prediction equations for Douglas-fir over-predicted the crown mass of a 30 cm tree to a large degree (the 30 cm tree sampled in this study had an estimated crown mass of only 65 kg).

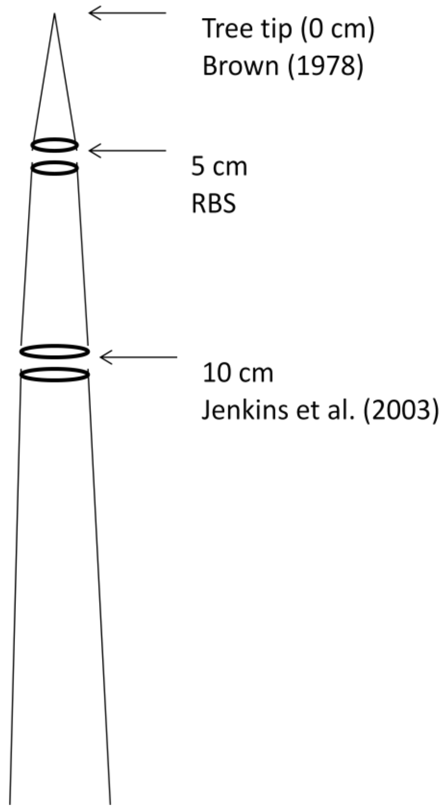

Figure 4.22. Diagram illustrating the different portions of the upper main stem classified as crown material by Brown (1978; no stemwood), the sampling protocol used for this study (RBS; stemwood above a 5 cm diameter), and Jenkins et al. (2003; stemwood above a 10 cm diameter).

Another potential cause of bias associated with Brown's (1978) equations may be due to discrepancies in crown definition. Recalling from Chapter 2, much of Brown's data came from studies by Storey et al. (1955) and Fahnestock (1960). Data collected for the purposes of these studies utilized a trimmed crown. Dividing the stem of the tree into five equal parts, the crown was trimmed to the nearest 20% mark on the tree (Fig. 4.23). The explanation for this procedure is not evident in the research paper. Further, Brown (1978) makes no note of this discrepancy in his work. The result of this difference in crown definition would be an expectation for Brown's equations to consistently underestimate crown mass by a degree which is impossible to estimate.

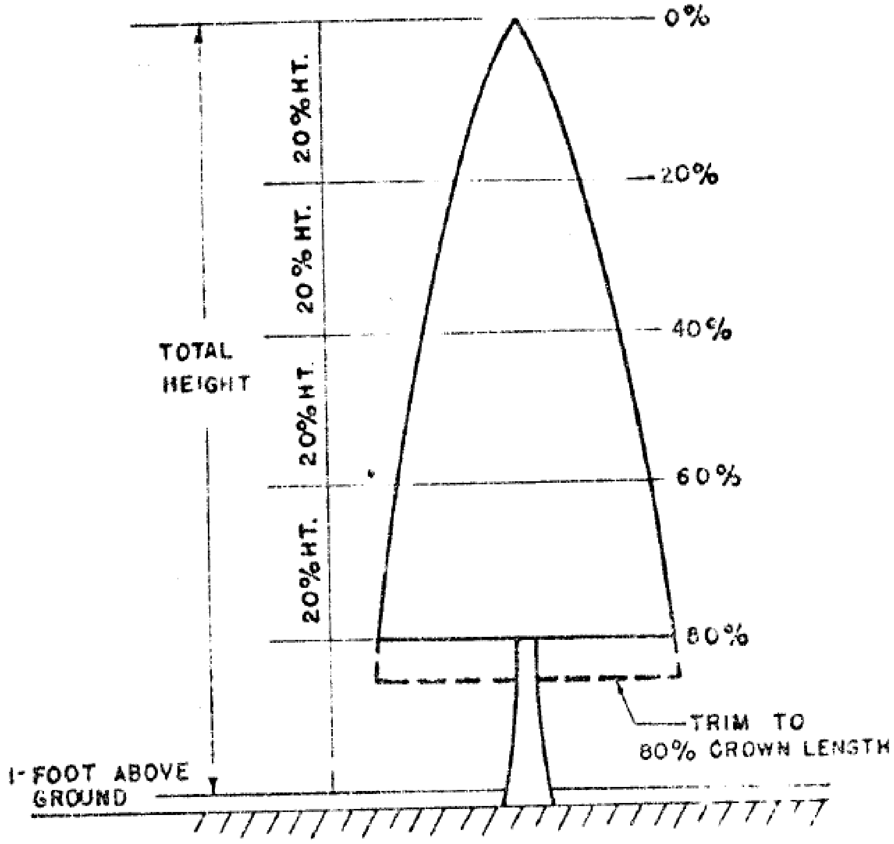

Figure 4.23. Illustration of trimmed crown as presented by Storey et al. (1955, pg. 9).

4.6.4 Differences in Sample Data

An interesting consideration of the crown biomass prediction equations evaluated above is how they were calibrated, and what could be the cause of the bias identified in the present study. The Jenkins et al. (2003) equations were built from pseudo-data generated from a nearly exhaustive list of biomass prediction equations from all over the continent. Jenkins et al. (2003) simply used several equations to predict the crown mass for a tree species over a range of DBH, and then fit a regression through the scatter of points. Brown's (1978) equations, however, were built from actual trees sampled from a number of locations in the Rocky Mountains, most notably the Priest River Experimental Forest (ID).

Brown (1978) presented tree data he collected. Some of the data, and for some species most of the sample trees, came from Storey et al. (1955) and Fahnestock (1960) which is not presented (see Chapter 2, pp. 8-10). Without those data, it is difficult to have a full understanding of the trees used to fit his equations, and whether those trees are much different from the trees sampled as part of this study. This is especially true in the case of lodgepole pine, where only 3 trees were sampled by Brown, with the remaining data coming from the other two studies. Although the data generated by the Storey et al. (1955) and Fahnestock (1960) studies were not published, it is possible to compare some of the trees used in Brown's study against the tree data collected in the field in this project.

Figure 4.24 superimposes the Douglas-fir sample trees selected by Brown (1978) over those selected in this study. While Brown sampled some trees that were much larger in DBH than the biggest tree selected for this study, the trees he sampled follow the same general trends associated with DBH, HT, crown length, and crown mass as those used in this study.

There is quite a bit of variability between trees for all attributes, which is expected. For lodgepole pine (Fig. 4.25), there were only three trees selected and sampled by Brown. Since these three trees are small in size, it is difficult to say much more about the trees used to build that prediction equation. However it does call into question the methods used to collect the sample trees used, and whether it is appropriate to utilize tree data collected by other studies that may not have used the same sampling strategy (or the same definitions of crown materials). Figures 4.26 and 4.27 show the ponderosa pine and western larch data collected by Brown, respectively. These plots again show that trees sampled by Brown are very similar to those selected by this study, follow the same general allometric trends in tree measurements, and exhibit similar levels of variability.

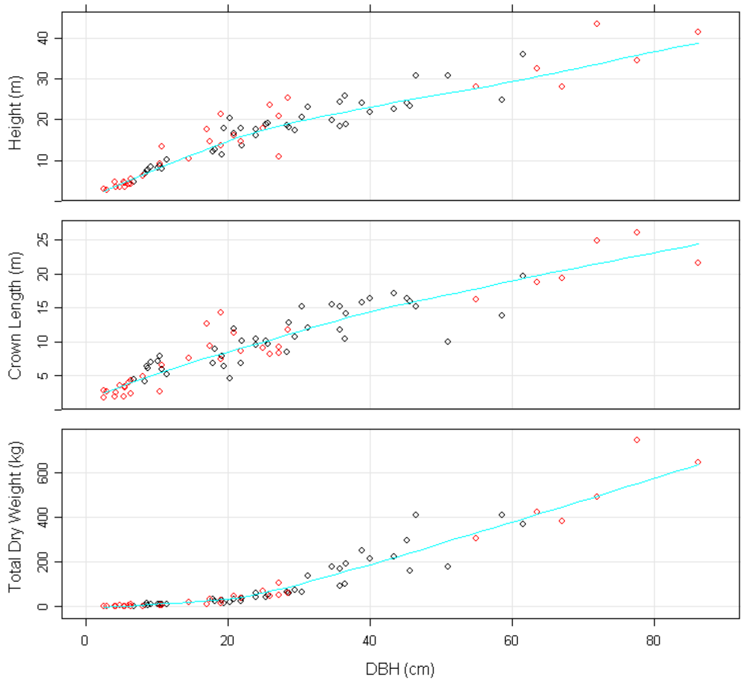

Figure 4.24. Sizes and allometric relationships among Douglas-fir sample trees collected for this study (black) and by Brown (1978; red).

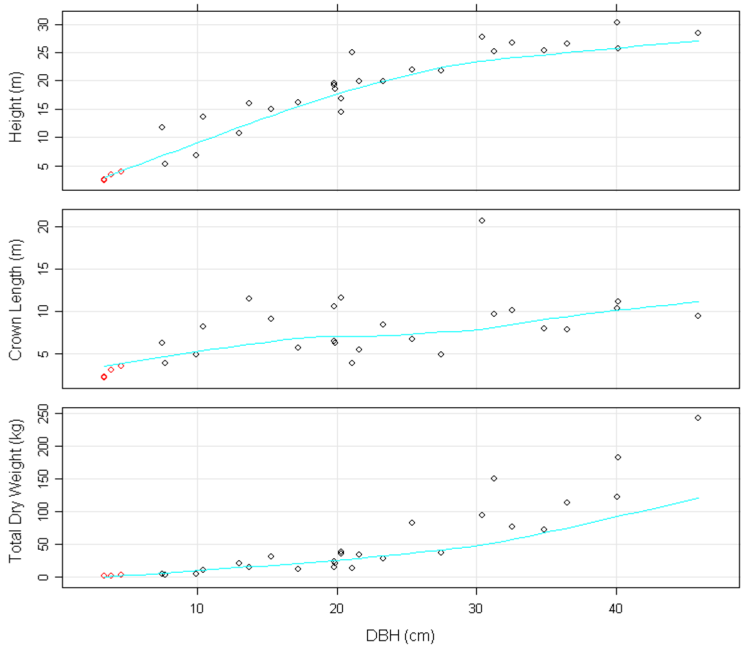

Figure 4.25. Sizes and allometric relationships among lodgepole pine sample trees collected for this study (black) and by Brown (1978; red).

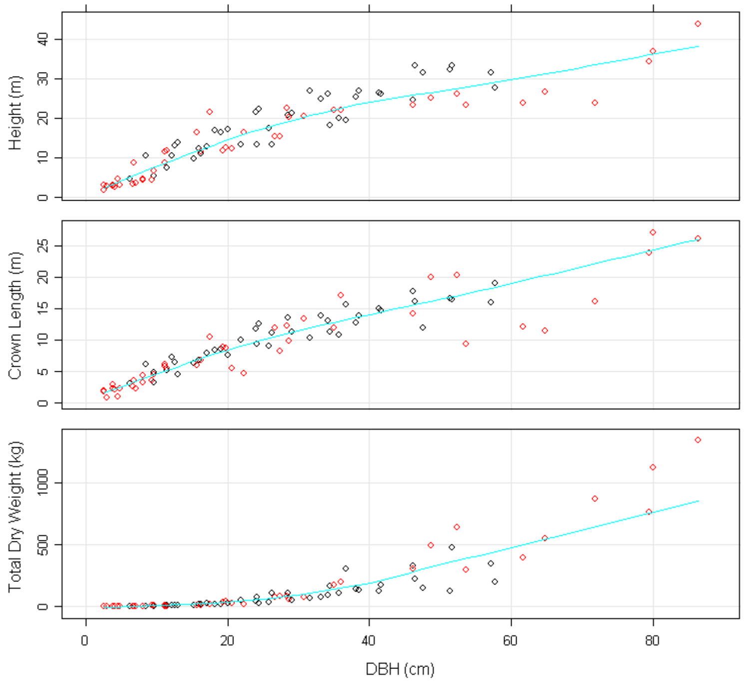

Figure 4.26. Sizes and allometric relationships among ponderosa pine sample trees collected for this study (black) and by Brown (1978; red).

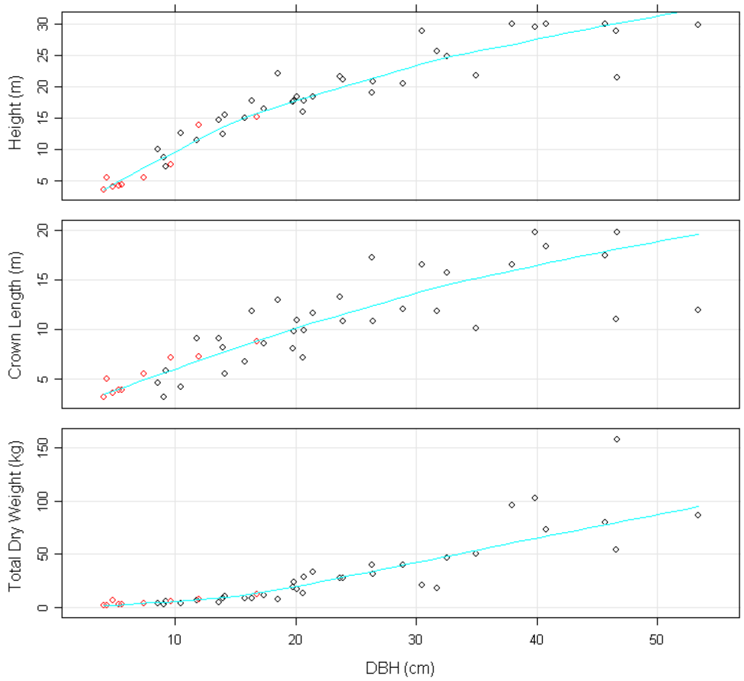

Figure 4.27. Sizes and allometric relationships among western larch sample trees collected for this study (black) and by Brown (1978; red).

Chapter 5

Conclusions

While many equations have been developed to predict crown mass, crown mass components, or total aboveground tree mass, the majority of these tend to be local in scope. For more wide scale use, it seems reasonable to develop and apply regional or national estimators. However, considering the results of this research project, regional equations may not necessarily be appropriate for use in any specific stand, or at all. For the species examined, all the DBH-based crown biomass prediction equations developed by Brown (1978) and Jenkins et al. (2003) exhibit some bias. In some cases the bias is worse than others. Brown's (1978) equations tend to under-estimate crown mass for Douglas-fir and lodgepole pine, while they tend to over-estimate crown mass for ponderosa pine and western larch. The equations of Jenkins et al. (2003) tend to over-estimate Douglas-fir and western larch crown mass, but show no significant bias in the prediction of lodgepole pine and ponderosa pine crown mass. While it is possible to use these equations to predict forest biomass across the inland northwest, it may be better to use them in conjunction with one of the BCMs published in this paper.

It is important to know if crown or overall biomass prediction equations are applicable to trees growing on land a manager is responsible for. Further, for regional equations to be unbiased, they should be produced from a large dataset, with many sample trees covering the range of all possible site types, elevations, slopes, etc. This is an expensive endeavor. The use of RBS for tree sampling can certainly reduce much of the cost associated with a more traditional approach to crown biomass sampling. Yet there can be large inherent variability among trees, and as seen above, there can be considerable sampling error incurred by an RBS (or other) sampling scheme. However, a crown sampling strategy will rarely include a sample of only one branch for a given tree, just as a stand sampling strategy should never be structured to comprise a sample of only one tree. To deal with the exceptional amount of variability associated with crown biomass sampling, increasing the number of branches sampled per tree, using a sampling design that defines branch selection probabilities directly in proportion to branch weight, or using a ratio estimator to more accurately estimate crown mass may be useful.

Modeling anything in the field of natural resources can be a difficult task. Bias associated with the prediction equations presented in this work (or any prediction equation) can be caused by many sources. The inclusion of crown ratio or crown length in addition to tree DBH may increase the precision and accuracy of crown mass predictions, and may be useful in future crown mass equation development. For some species, such as lodgepole pine, the inclusion of DBLC might be a better variable to improve the quality of predictions, but it is a difficult variable to measure precisely on a standing tree. It is important to look at these things on a species by species basis. It could be that isolating important tree measures to predict crown mass will allow for a better understanding of the species of interest. Knowing which factors contribute the most information for crown mass is especially important for large trees. For the majority of bias correction models produced, bias was found to increase with DBH. Though these bias corrections cannot be extrapolated beyond the range of DBHs observed, it seems probable that prediction bias continues to grow as tree DBH gets larger. Further research needs to be done for large diameter trees. For trees less than 60 cm DBH, the bias correction models presented in this work may be useful for obtaining more accurate predictions of crown mass for Douglas-fir, ponderosa pine, lodgepole pine, and western larch in the inland northwest.

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