ASSESSING THE ACCURACY OF CROWN BIOMASS EQUATIONS FOR THE MAJOR COMMERCIAL SPECIES OF THE INTERIOR NORTHWEST: STUDY PLAN AND PRELIMINARY RESULTS

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ABSTRACT

Fueled by the insistencies of wildfire mitigation, bioenergy development, and carbon sequestration, there is growing demand for reliable characterizations of crown and stem biomass stocks in conifer forests of the Interior Northwest, United States (western Montana, northern Idaho, and eastern Washington). Predictive equations for crown biomass have been developed for this region but they have limited empirical support and supply markedly different predictions. This paper provides a methodological overview and preliminary results from an on-going study aimed in part at describing the accuracy of existing tree biomass equations for the Interior Northwest. Crown biomass estimates obtained from destructive sampling of 81 trees exhibited considerable variation around predictions from commonly used crown biomass equations based on DBH (diameter at breast height, 1.37 m). Some of this variation is attributable to within-tree sampling error, but initial results suggest that an appreciable proportion is due to variation in crown dimensions within DBH classes. Continuing data collection efforts will permit statistical descriptions of the accuracy of existing equations, as well as a basis for developing more integrative and precise tree biomass equations.

INTRODUCTION

The management of western North American conifer forests is increasingly attentive to the quantity and distribution of non-merchantable biomass in tree crowns and small-diameter trees. The aggregate mass and distribution of foliage have long been recognized as important determinants of tree and stand growth (see Long and Smith 1990). Likewise, in intensively managed systems, considerable research has focused on stand tending practices to control conifer crown architecture and thus wood quality (e.g., Waring and O'Hara 2005). However, it is the potential of conifer foliage and non-merchantable branch wood in processes other than stem development that have become central to the management of public and private forests across the inter-mountain western USA. Specifically, these forests are increasingly being managed to mitigate wildfire risk, to provide bio-energy stocks, or to sequester atmospheric carbon. Foliage and branch wood distributions strongly affect wildfire behavior and, by the same token, form the primary constituents of bioenergy feedstocks. Thus, multiple emerging management goals have generated converging demands for accurate characterizations of conifer crown biomass, its distribution by component and branch size, and even its vertical distribution on the bole (see e.g., Dymond and others 2010, Keyser and Smith 2010, Reinhardt and others 2006).

BACKGROUND

Numerous studies undertaken across western North America have reported conifer biomass relationships and developed allometric equations (see reviews by Jenkins and others 2004, Ter-Mikaelian and Korzukhin 1997). Yet many of these studies have been confined to individual stands or have drawn data only from a particular subset of forest conditions, rendering the results unsuitable for widespread application. In practice, the biomass equations used in decision support for forest and fuels management in the Interior Northwest (i.e., from eastern Washington to western Montana) come primarily from a pair of studies carried out by Brown (1978; see also Brown and Johnston 1976) and by Jenkins and others (2003).

In 1978, Brown published a set of species-specific crown biomass equations for Rocky Mountain conifers. The equations were developed largely from dominant and codominant tree data collected in Idaho and Montana, but additional data from separate studies undertaken in Nevada and California were also incorporated. Brown developed predictive equations for multiple crown biomass components (foliage, dead branches, live branches of various size classes) but not for stem wood or stem bark. Separate equations were developed for 11 conifer species, including interior Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), ponderosa pine (*Pinus ponderosa*), and lodgepole pine (*P. contorta*). Brown developed log-linear predictive equations based solely on

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tree DBH (i.e., diameter at breast height, 1.37 m) as well as equations based on DBH, height, and dominance. His crown biomass equations have been integrated into the Forest Vegetation Simulator's Fire and Fuels Extension (Crookston and Dixon 2005, Reinhardt and Crookston 2003) and thus are now widely used in stand development simulations and fire behavior modeling.

The biomass equations of Jenkins and others (2003) were developed to provide a consistent basis for estimating tree biomass at large scales (e.g., at the regional or national level). Their DBH-based biomass equations were derived through meta-analysis of published biomass allometries (including the equations of Brown 1978) rather than from direct measurement of tree biomass. Based on similarities in equation form, Jenkins and others developed broad-based total aboveground biomass equations for species groups (e.g., all *Pinus* species; *Cupressaceae* plus *Larix* species) or, in the case of Douglas-fir, for both coastal and interior variants. Furthermore, since the study's primary emphasis was on total aboveground tree biomass, Jenkins and others (2003) developed a single set of component ratio equations to fractionate the total for any species into foliage, branch wood, and other tree biomass components. These component ratio equations are now used for tree biomass reporting in the Forest Inventory and Analysis (FIA) program (U.S.D.A. Forest Service 2010) and therefore find widespread application across the West.

The behavior of predictions from Brown's (1978) DBH-based equations and of those from Jenkins and others' (2003) crown biomass ratio equations are illustrated in Fig. 1. Both sets of equations were fit in log-linear form and while Brown's published equations incorporate a correction factor for logarithmic transformation, the equations from Jenkins and others do not. Within each of the 4 species shown, the predictions from these equations follow a similar exponential form but differ in magnitude. This is not surprising given the differences in the equations' derivations, intended spatial scales of application, and biological supports. As noted, the equations of Jenkins and others (2003) were intended for application across the continent and provide identical predictions for ponderosa and lodgepole pine; Brown (1978) focused exclusively on interior tree populations and estimated distinct allometric relationships for the two pine species in Fig. 1.

Figure 2 illustrates the magnitude of the differences between the predictive equations across a range of tree DBHs. The differences are appreciable, particularly for larger trees and for ponderosa pine, where crown biomass predictions from Brown's equations are consistently about 40 percent larger than those from the equations of Jenkins and others.

OBJECTIVES

The research presented here is part of a more extensive, on-going study of conifer biomass distributions in the Interior Northwest. The discrepancies evident in Fig. 2 between biomass equations applied in this region are large and consequential for applications involving fuels management, bioenergy feedstock estimation, and carbon sequestration. There is a clear need for assessments of the validity and scope of these equations. To date, there has been little work to validate Brown's (1978) equations (but see Gray and Reinhardt 2003, Keyser and Smith 2010) and no evaluation of the bias or accuracy of the equations developed by Jenkins and others (2003) when applied to the major commercial conifer species of the Interior Northwest. The objectives of this study are therefore to:

1. formulate and implement efficient tree biomass data collection strategies for the major commercial conifer species in the Interior Northwest;

2. describe the bias and accuracy of existing tree biomass equations by species, across stem and crown components, and as a function of whole-tree dimensions; and,

3. develop and evaluate new equations for tree biomass as well as its distribution across components and over the vertical profile of the stem.

This paper provides an overview of the data collection strategies that were developed and presents preliminary results regarding the accuracy of the crown biomass equations described above.

SAMPLING METHODS

Biomass equation validation and development efforts require sizable samples for individual species, preferably distributed across the region of interest and its forest habitat types. This is complicated by the high cost and destructive nature of tree biomass assessment. Stem biomass determination necessitates bole weight or wood density measurements. Biomass assessment of crown components demands defoliation of individual branches and the separation of branch wood into various size classes. Green tree materials also need to be oven-dried to obtain dry weights. To mitigate the high cost of tree-level biomass assessment and collect a large sample of trees, this study implemented a three-phase biomass sampling strategy to select stands, trees, and finally individual branches or stem discs along the boles of selected trees.

STAND AND TREE SELECTION

Second-growth stands across the Interior Northwest were selected to ensure broad geographic support (Fig. 3). Spatial coverage and dispersion across forest habitat types (Pfister and Arno 1980) were the primary factors in stand selection, but no formal systematic or random mechanism was applied. Only stands with no treatment history over the previous decade were candidates for sampling. Stand selection was also conditioned by the availability of permits for destructive sampling. Stands selected in 2009 and 2010 were located on federal, State, tribal, and private forest lands.

Within selected stands, sample points were located systematically at 100 m intervals on the Universal Transverse Mercator (UTM) grid. At each sample point a narrow angle gauge (2.3-4.6 m^2/ha basal area factor) was used to identify candidate sample trees. Candidate trees were then barred if they were not among the species of interest or had damaged or missing crowns. Up to two of the remaining candidate trees at a sample point were then selected uniformly at random for destructive sampling.

TREE BIOMASS ASSESSMENT

Individual trees were sub-sampled to estimate stem, branch wood, and foliage biomass. Trees were felled and then randomized branch sampling (RBS; Gregoire and Valentine 2008) was employed to select 5 live branches with probability proportional to branch cross-sectional area. For selection purposes, the branches making up the live crown were artificially clustered into 1-m intervals. That is, beginning at the lowest live branch, all branches found within successive 1-m segments on the bole were treated as distinct whorls so that in addition to branch basal diameters only a single stem diameter (at the top of a 1-m segment) was needed. RBS focuses sampling efforts on the larger diameter branches that account for the majority of the crown biomass. The corresponding estimators capitalize on the strong allometric relationships between branch mass and branch basal area (Fig. 4) to provide precise and unbiased estimates of whole-crown biomass.

The selected branches were separated into size-class components so that separate biomass estimates could be obtained for foliage and for branch wood within the 0-0.64 cm, 0.64-2.5 cm, and 2.5+ cm diameter classes (corresponding to 1-hour, 10-hour, and 100-hour time lag fuel classes). Dead and epicormic branches encountered along the live-branch selection paths were also cut and weighed. All live branch material as well as selected bolts of dead branch wood were oven-dried at 105°C. Drying times varied by component and were determined by evaluating the time needed to achieve a constant weight.

Though not discussed below, data were also collected to estimate the stem biomass of selected trees. Discs were cut from the downed tree at a systematically selected set of heights or, in some stands, at heights determined by merchantability criteria (e.g., at the tops and bottoms of the first two logs). Cross-sectional area and wood density were measured on the discs and calibration estimators (see Gregoire and Valentine 2008) based on regional tree taper equations were then used to obtain whole-stem biomass estimates. A more thorough description of the stem and crown sampling procedures can be obtained from the authors.

RESULTS AND DISCUSSION

In 2009, biomass data were collected from 81 trees in 11 stands in western Montana and eastern Washington (Fig. 3). Data from Engelmann spruce (*Picea engelmannii*) and grand fir (*Abies grandis*) were collected but the bulk of the data were from ponderosa pine, Douglas-fir, western larch, and lodgepole pine. The size-class distribution of the 2009 sample trees of these four species is shown in Fig. 5. Within each of the species, the sample trees spanned a wide range of DBH. The ponderosa pine sample was also well distributed across crown ratio classes but in other species high crown ratios were rarely observed at larger DBHs. This is broadly consistent with the growing conditions of these species. However, data spanning the DBH, height, and crown ratio domains are needed to characterize variation in crown biomass across these dimensions and to assess the utility of the DBH-based equations from Brown (1978) and Jenkins and others (2003).

Figure 6 shows the relationship between tree DBH and estimated total crown mass for the 4 most commonly selected species in the 2009 sample. Total crown mass includes the mass of foliage, live and dead branch wood, and the stem above a 5 cm top. The crown mass estimates are based on subsamples (drawn by RBS) from the crowns of individual sample trees and are thus subject to sampling error. In Fig. 6, this tree-level sampling error is conflated with among-tree differences in crown biomass potentially attributable to variations in tree height, tree crown length (or crown ratio), stand stocking, stand species composition, and site productivity, in addition to intrinsic heterogeneity. Only the conditioning effect of tree DBH is shown in Fig. 6 with the result that considerable variation in crown mass is evident. This is particularly true for larger trees and for ponderosa pine, where crown biomass estimates for trees above 40 cm DBH range from 123-482 kg.

Predictions from the DBH-based equations of Brown (1978) and Jenkins and others (2003) are superimposed on the data in Fig. 6, as are smoothed loess regression curves. Though little data are presently available for lodgepole pine, the pine and Douglas-fir predictions from Jenkins and others' equations appear to track the empirical trends more closely than those from Brown's equations. The opposite is true for the limited western larch dataset. In all cases, however, there exists substantial variation around the crown mass predictions for large-DBH (i.e., above 30 cm) trees.

As more data are made available for these and other species, more exacting assessments of the overall bias and conditional bias (see e.g., Reynolds and Chung 1986) of Brown's (1978) and Jenkins and others' (2003) prediction equations will be undertaken. At this preliminary stage, our interest is primarily in describing the sources and magnitudes of variation in crown biomass estimates around predictions. Figure 7 focuses on the performance of the predictive equations of Jenkins and others (2003) for Douglas-fir and ponderosa pine. The trend lines in Fig. 7 are smoothed loess regressions. In the case of Douglas-fir, the trend line identifies a DBH-class (approximately 15-35 cm DBH) for which the predictions exceed the observed crown mass estimates. On ponderosa pine, the empirical trend is more consistent but runs strictly above 0 percent, reflecting the tendency for this equation to consistently understate crown biomass relative to the levels observed. For both species the sample trees' crown biomass estimates diverge on the order of -100 to +50 percent from predictions.

Individual trees are drawn as solid or open circles in Fig. 7 according to whether their destructive sampling estimates respectively exceed or fall short of the DBH-based predictions from Jenkins and others' equations. This symbology is carried through to Fig. 8 where the sample trees' crown ratios are plotted against DBH. By this means, Fig. 8 shows that crown biomass estimates falling short of predictions are predominantly observed on trees with lower crown ratios within their respective DBH classes, and vice versa. This result accords with both dimensional and ecological considerations. After tree DBH, dimensions related to crown length should have the greatest impact on total crown mass. Likewise, in untreated stands, crown length and ratio reflect the past growing conditions of the tree and thus integrate the influences of stand density and species composition.

Future analyses will focus on the importance of crown ratio, tree height, and stand density in modifying foliage, branch wood, and total crown mass. In doing so, these analyses will provide information on the bias and accuracy of biomass predictions based only on tree DBH as well as on the potential need for predictive biomass equations integrating other tree and stand characteristics.

SUMMARY AND FUTURE RESEARCH

Management of conifer forests in the Interior Northwest for wildfire fuels reduction, bioenergy extraction, or carbon sequestration requires reliable estimates of tree and crown biomass. The bias and accuracy of the predictive equations currently applied in the region have not been evaluated and in many cases these equations supply markedly different predictions (Fig. 2). Based on a preliminary dataset of 81 trees selected from across the region in 2009, existing DBH-based biomass equations broadly follow the empirical trends in crown biomass but fail to account for considerable variation in individual-tree estimates. Some of this variation is attributable to within-tree sampling error. However, it is anticipated that a substantial portion of this variation is due to among-tree differences in crown length, tree height, and stand conditions. In particular, exploratory analyses of the 2009 data point to crown ratio as an important modifier of crown biomass in Douglas-fir and ponderosa pine (Fig. 8).

The present study is on-going and as more data become available for these and other species it will be feasible to statistically assess the presence of trends in the bias and accuracy of existing crown biomass equations as a function of tree DBH, tree height, crown ratio, and stand density. To do so, sampling procedures should ensure that trees selected for destructive biomass sampling span a broad range of tree sizes, crown lengths, and stand conditions. Future analyses will also examine variations in stem biomass for the commercial species of the region and the accuracy of existing stem biomass prediction algorithms, including those used in FIA reporting.

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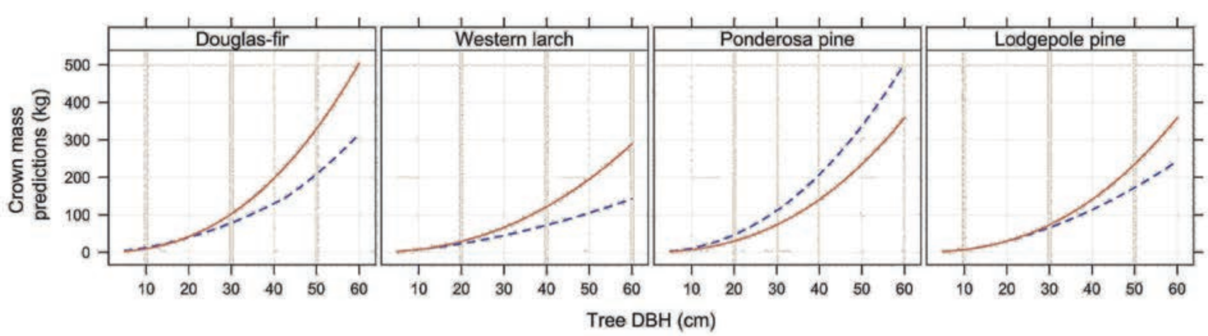

Figure 1—Diameter-based crown biomass equations from Jenkins and others (2003; solid lines) and Brown (1978; dashed line); predictions are of oven-dry mass.

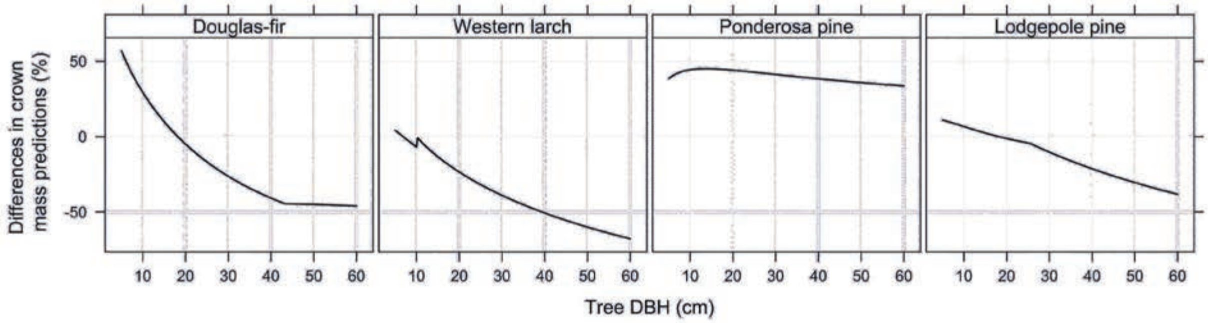

Figure 2—Percent difference in the diameter-based crown biomass equations from Jenkins and others (2003) and Brown (1978) as a function of tree diameter.

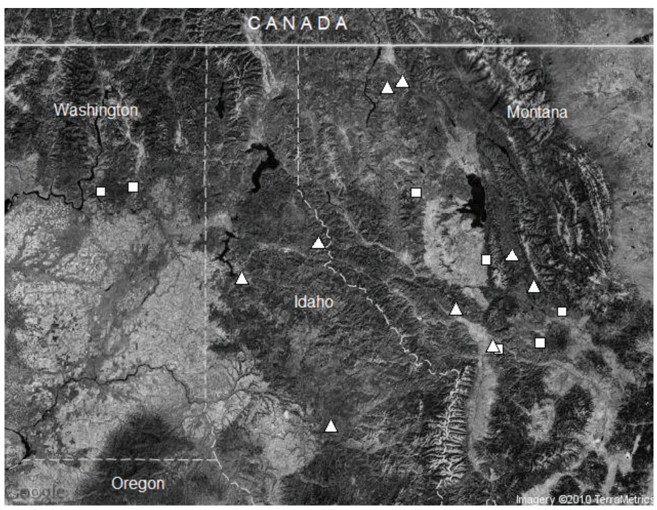

Figure 3—Geographic distribution of 2009 (squares) and 2010 (triangles) sample stands; satellite imagery from Google Maps.

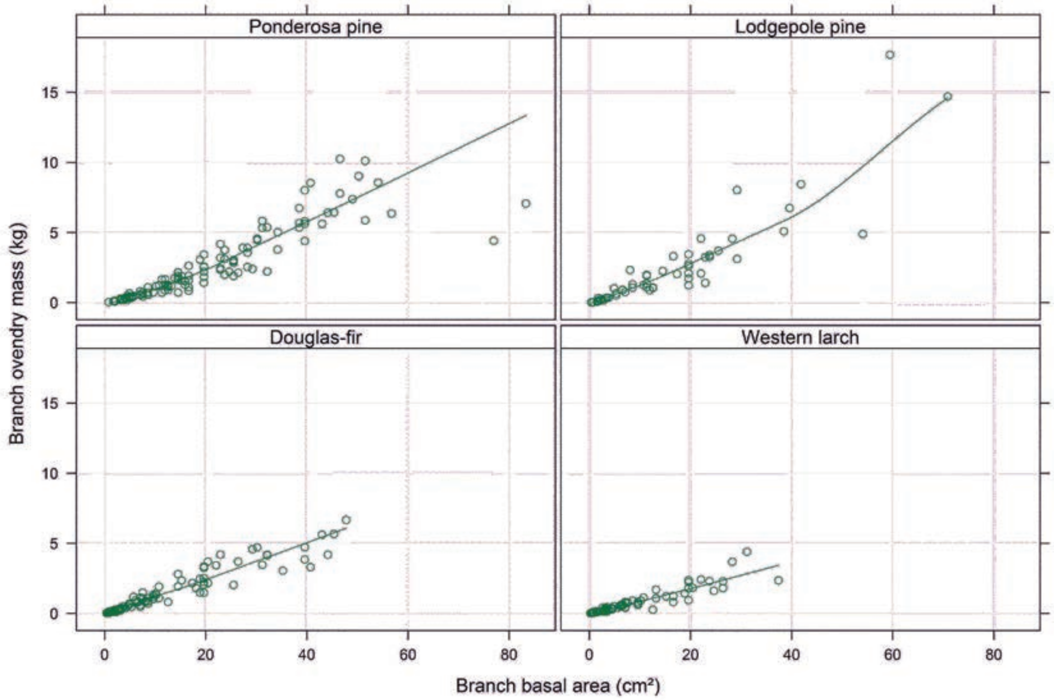

Figure 4—Allometric relationships for 352 live branches selected by randomized branch sampling (one ponderosa pine branch with basal area 170 cm^2 not shown); Pearson correlations were at or above 0.90 for all four species.

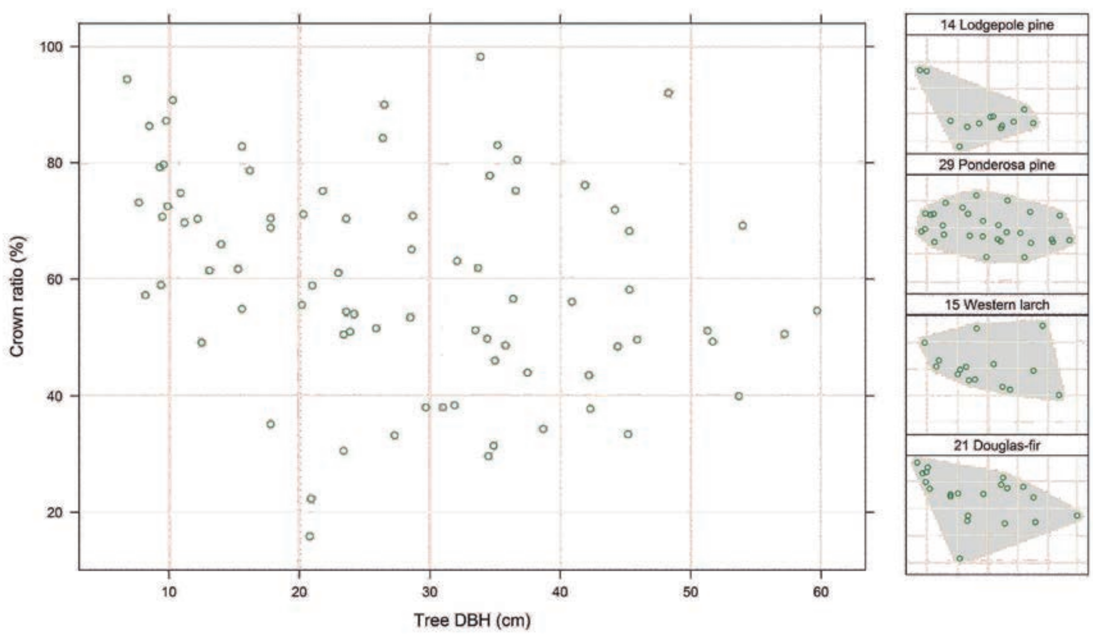

Figure 5—Overall and species-specific size distributions of sample trees selected in 2009.

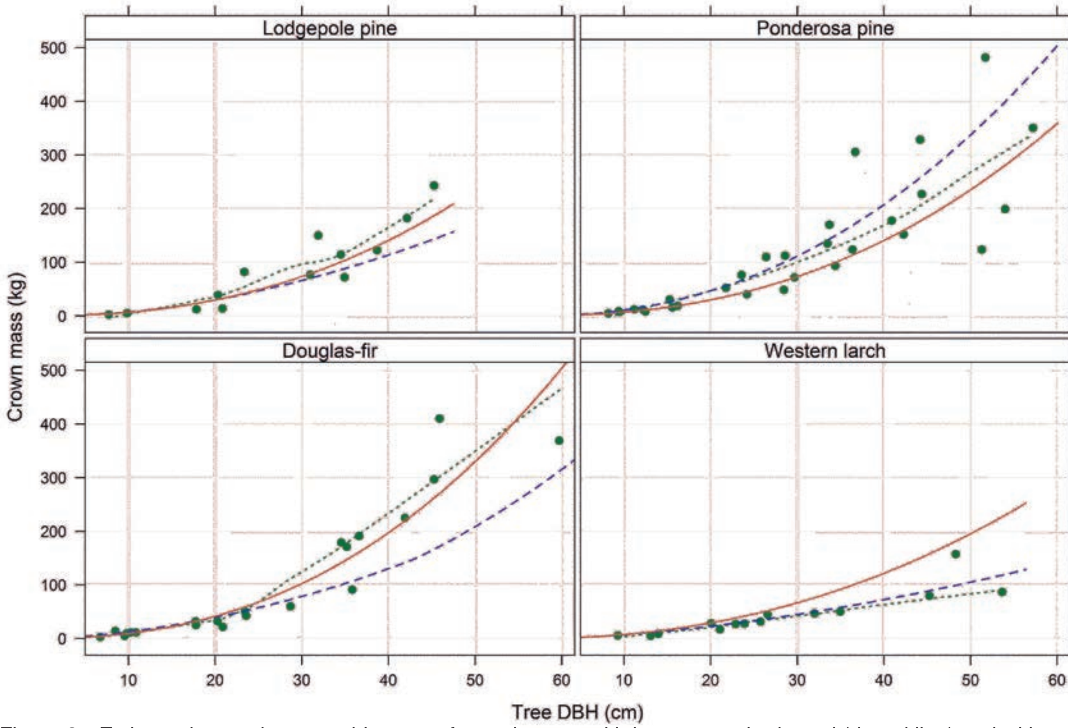

Figure 6—Estimated oven-dry crown biomass of sample trees with loess smoothed trend (dotted line) and with diameter-based crown biomass equations from Jenkins and others (2003; solid lines) and Brown (1978; dashed line).

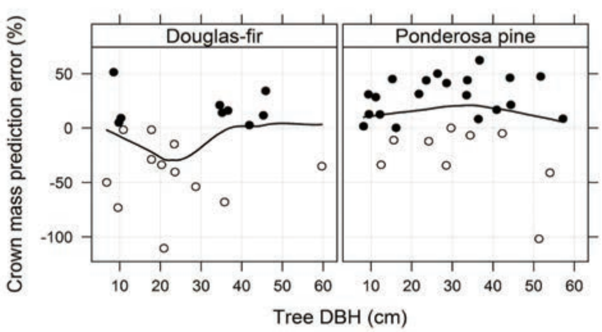

Figure 7—Crown biomass prediction errors as a percentage of estimated mass; solid circles denote trees with crown mass estimates higher than predicted from the equations of Jenkins and others (2003) while open circles denote trees with estimates below predictions.

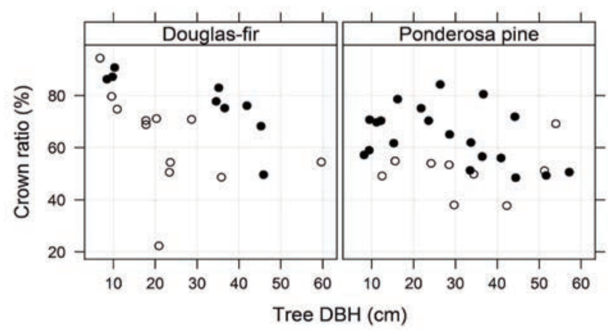

Figure 8—Tree size distribution and crown mass prediction errors associated with the equations of Jenkins and others (2003); solid circles denote trees with higher than predicted crown mass estimates while open circles denote trees with estimates below predictions.