# AN ABSTRACT OF THE DISSERTATION OF 

Joshua Andrew Clark for the degree of Doctor of Philosophy in Forest Engineering presented on December 8, 2009

Title: Forest Biomass Estimation with Hemispherical Photography for Multiple Forest Types and Various Atmospheric Conditions


#### Abstract

approved:

Glen E. Murphy

The importance of accurately identifying inventories of domestic energy, including forest biomass, has increasingly become a priority of the US government and its citizens as the cost of fossil fuels has risen. It is useful to identify which of these resources can be processed and transported at the lowest cost for both private and public landowners. Accurate spatial inventories of forest biomass can help landowners allocate resources to maximize forest biomass utilization and provide information regarding current forest health (e.g., forest fire potential, insect susceptibility, wildlife habitat range). This research has indicated that hemispherical photography (HP) may be an accurate and low cost sensing technique for forest biomass measurements.


In this dissertation:

- It is shown that HP gap fraction measurements and both above ground biomass and crown biomass have a linear relationship.
- It is demonstrated that careful manipulation of images improves gap fraction estimates, even under unfavorable atmospheric conditions.
- It is shown that estimates of Leaf Area Index (LAI), based on transformations of gap fraction measurements, are the best estimator for both above ground forest biomass and crown biomass.
- It is shown that many factors negatively influence the utility of HP for biomass estimation.
- It is shown that biomass of forests stands with regular spacing is not modeled well using HP.

As researchers continue to explore different methods for forest biomass estimation, HP is likely to remain as a viable technique, especially if LAI can be accurately estimated. However, other methods should be compared with HP, particularly for stands where LAI is poorly estimated by HP.
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Forest Biomass Estimation with Hemispherical Photography for Multiple Forest Types and Various Atmospheric Conditions

By<br>Joshua Andrew Clark

# A DISSERTATION 

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Doctor of Philosophy dissertation of Joshua Andrew Clark
Presented on December 8, 2009.

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

Joshua Andrew Clark, Author

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# Forest Biomass Estimation with Hemispherical Photography for Multiple Forest Types and Various Atmospheric Conditions 

## CHAPTER 1: INTRODUCTION

Optimal assessment and utilization of biomass, including forest biomass, has become an increasing priority for many groups, including the United States government and its citizens, for a variety of reasons. Forest biomass is currently significant not only within the energy production and consumption sectors but also within areas as diverse as climate change, job creation, and the health of the forest ecosystem. The volume of biomass utilized is expected to increase rapidly over the next decade and beyond. According to the USDA, agricultural biomass within the continental United States has the current capacity to provide a billion dry tonnes of biomass annually for energy production.

Currently, there is a variety of methods used to estimate forest biomass. Older, more established techniques involve estimating tree biomass components with allometric equations based on easily measured tree components, such as DBH. Unfortunately, these allometric models are for specific forest types and are applicable only to very similar forest stands.

As a supplement and potential future alternative to these older methods, measurements based on remote sensing technology have increasingly been utilized to estimate several metrics that define forest health and structure. Metrics including crown cover, species composition, leaf area index (LAI), net primary production NPP, and above ground biomass, can be estimated using various models of canopy characteristics at landscape and regional levels. These measurements help landowners understand both spatial location as well as temporal changes of forest biomass. Remote sensing is available from a wide range of sensors - the optimal sensor for a particular application
depends on a variety of factors, including the analyst's budget, the forest metric to be measured, the level of expertise/familiarity with the sensor, and the desired temporal/spatial resolution. Sensors are typically from one of the following groups, and are often combined:

- Satellite based measurements typically use hyperspectral information, but cannot distinguish vertical structure.
- Laser-based measurements (including both ground-based and aerial Light Detection and Ranging (LiDAR)) can distinguish vertical structure, but have a single band of information.
- Ground based measurements (including commercially available tools that estimate LAI and other forest canopy characteristics) use single or multiple bands of information.

This dissertation is a detailed study of forest biomass assessment using gap fraction measurements taken directly from hemispherical photography. The primary hypothesis for this overall study is that hemispherical photography can accurately estimate both above ground biomass as well as canopy (including crown and branch) biomass. Identifying crown/branch biomass is of particular interest, since it can be used as a surrogate for forest residues that may be available following a harvest operation. Previous studies (Zheng et al 2007) have shown a moderate correlation $\left(\mathrm{R}^{2} \approx 0.6\right)$ between above ground forest biomass and LAI, which may be estimated directly from hemispherical photography by making several simplifying assumptions. It is less clear whether crown/branch biomass may be accurately estimated, and partially depends on how crown/branch biomass is defined.

Most studies that use hemispherical photographic measurements to measure LAI use uniform canopy lighting conditions, due to specific model assumptions. These assumptions are easier to conform to when making limited measurements on an
experimental basis, but become more difficult if applied at a large operational scale by either public or private landowners. Other model modifications are also necessary because of nonrandom clumping that occurs within the forest canopy, which makes it difficult to estimate a three-dimensional forest canopy with a one-dimensional hemispherical photograph.

When conducting photographic measurements for this study, hemispherical photographs were taken under a wide variety of atmospheric settings, including sunny, rainy, cloudy, and partly cloudy conditions. Photographs from these studies were then adjusted with imaging software using empirically derived methods to correct for nonuniform lighting conditions. When using this approach, it is possible to check whether hemispherical photograph measurements are robust to heterogeneous lighting conditions within the same image, and whether this technique is applicable to different lighting conditions between photographs.

Results and conclusions from this overall study will aid future researchers in ascertaining the strengths and weaknesses of hemispherical photography for forest biomass estimates, particularly for the species within this study. From this research, an analyst can compare the strengths and weaknesses of hemispherical photography to alternative sensors from other studies. This will allow landowners to decide whether hemispherical photography is best suited to estimate forest biomass in a future application, or if another remote sensing technique may be more appropriate. A typical hemispherical photograph is depicted in Figure 1.1.


Figure 1.1: Hemispherical Photograph

The dissertation is written in a manuscript form, and is composed of three distinct manuscripts. Each manuscript can stand alone, and the manuscripts are ordered in a distinct sequence that advances from a simple analysis to an analysis that is more complex. This is partially due to the increasing complexity recognized and understood by the author. This manuscript should give the reader an improved knowledge of general hemispherical photography applications while also increasing the reader's familiarity with techniques available for forest biomass estimates. The specific forest types from the studies for this dissertation included Douglas-fir, mixed conifer (Ponderosa pine, Incense-cedar, and White fir), and ponderosa pine / lodgepole pine mixed stands.

The next three chapters (Chapters 2-4) are the bulk of the dissertation, and are roughly summarized in Figure 1.2.


Figure 1.2: Overview of Forest Type and Species by Study Area

First, Chapter 2 describes an initial study within a commercial Douglas-fir plantation that tests the overall feasibility of using hemispherical photography to estimate the above ground and crown biomass of destructively sampled plots with a specific size (circular area, 0.04 hectare). A brief overview of hemispherical photography is included in this chapter, along with some simple estimates and descriptions of LAI. A description of a simple method to obtain gap fraction from hemispherical photographs is included. Since the ratio of LAI to forest biomass will change from stand to stand, the discussion includes a rationale for using LAI along with other stand covariates while showing the limitations of LAI as a predictor of forest biomass. In addition, another study was conducted in the MacDonald-Dunn Experimental Forest (near Corvallis, OR) to test the robustness of gap fraction measurements within the same
plot at various sun elevation angles for a Douglas-fir stand. Analysis and results are including in this chapter.

Next, Chapter 3 describes a more extensive study with a similar objective as Chapter 2, but with multiple forest types, and includes additional metrics in order to improve LAI estimates. This study includes the plots from the first study, and combines them with destructively sampled plots from commercial mixed conifer forest (Ponderosa pine, Incense-cedar, White fir) near Burney, CA. An empirically derived technique to extract gap fraction from the photographs using imaging software is presented, which was required due to the heterogeneous lighting conditions between and within images. In addition, LAI estimates based on increasingly complex models are used to improve estimates of canopy structure. In addition, the photographs are closely analyzed to test whether gap fraction from photographs can be used to estimate forest biomass instead of using the more complex estimate of LAI as a covariate.

Finally, Chapter 4 uses the image processing techniques derived from Chapter 3 to estimate forest biomass for plots within a ponderosa/lodgepole pine stand but with nondestructive estimates of biomass. These plots differed not only in forest type, but also were within regularly spaced stands, as opposed to naturally spaced stands in the previous two studies. A linear regression model based on a logarithmic relationship was created as before in Chapter 3 to test whether the model is applicable to regularly spaced stands. Finally, the models created from Chapter 3 were used to estimate biomass for plots from Chapter 4 to test the robustness of biomass estimates between forest types.

Chapter 5 includes a brief discussion of the analysis and results of the entire study. The entire study is tied together, while the findings are integrated to provide insight into any conflicting results from the studies. There is also a summary of the entire
dissertation, along with overall conclusions and a discussion on the potential of future research.

# CHAPTER 2: EVALUATION OF HEMISPHERICAL PHOTOGRAPHY FOR FOREST BIOMASS MEAUREMENT IN A DOUGLAS-FIR PLANTATION 

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## Introduction

Biomass measurement and efficient utilization has become an increasing priority for the United States government and its citizens. Forest biomass is currently significant not only within the energy production and consumption sectors but also within areas as diverse as climate change, job creation, and overall forest health.

A 2005 USDA study (Perlack et al 2005) has shown that biomass (including forest biomass) is a viable alternative to fossil fuels, with the potential to replace up to $30 \%$ of petroleum usage by 2030. In 2008, fossil fuels supplied $84 \%$ of the United States’ energy demand, with $45 \%$ of those fossil fuels derived from petroleum sources (Energy Information Administration 2008). Biomass could provide an alternative domestic energy source for current oil and petroleum imports - in 2008, 66\% of petroleum used in the United States was imported, including 16\% from the Persian Gulf region (Energy Information Administration 2009).

The same USDA study has also shown that the combined domestic fuel potential of agricultural biomass (one billion dry tons per year) and forest biomass ( 368 million dry tons per year) is enormous (Perlack et al 2005). Forest biomass potential is based on sustainable productive capacity, and biomass estimates from this study include intensively managed areas. It is useful to identify which biomass resources can be processed and transported at the lowest cost, for both private and public landowners (USDA Forest Service 2005). Accurate spatial inventories of forest biomass can help landowners allocate resources to maximize forest biomass productivity while also providing information regarding current forest health (e.g., forest fire potential, insect susceptibility, wildlife habitat range).

Currently, the most common estimations of plot-level forest biomass from groundbased measurements are made with allometric equations that are created for specific
species (e.g., Gholz et al 1979). These allometric equations model forest biomass based on an easily measured component of a tree, normally DBH and potentially total height. These estimations provide reasonable equations of total biomass, but are less reliable when estimating crown and branch biomass. Biomass models based solely on DBH are easiest to use in the field, but assume that tree shapes and stem form are identical. Stem form and shape can be further defined with variables including total height and crown size (e.g., Garber and Maguire 2003), but require time-intensive measurements.

Allometric estimations from specific studies tend to be site specific, although a national allometric model has been successfully compiled (Jenkins et al 2003). In order to estimate plot biomass from allometric equations, components from each tree must be measured or estimated. Manually intensive measurements are also required to accurately estimate aboveground biomass for understory vegetation (shrubs, etc). For stands with relatively high value, biomass inventories from allometric equations may be worthwhile. However, in lower value stands, the landowner may prefer a faster method, even if this method sacrifices accuracy that could be obtained with models that require multiple tree-level measurements.

Ground-based remote sensing techniques would provide a faster alternative biomass measurement for lower-value stands when compared to allometric techniques. Hemispherical photography had the highest correlation to crown bulk density in a prior study comparing multiple ground-based methods (Keane et al 2005). However, it is unclear how robust this technique would be when measuring above ground biomass and crown biomass with varying weather and sun conditions.

To explore the potential role of hemispherical photography in forest biomass measurements, this paper will:

- Identify techniques currently used to measure forest biomass.
- Describe advances within hemispherical photography (HP) and its current usage in forest measurements.
- Analyze results from a pilot study within a Douglas-fir (Pseuduotsuga menziesii) stand that relate HP measurements with forest biomass for various stand ages and weather conditions.
- Compare these results to a specific allometric equation derived from similar Douglas-fir stands as well as a generalized allometric equation (Jenkins et al 2003).


## Current Methods for Biomass Estimation

Forest biomass can be estimated using either destructive or nondestructive sampling. With destructive sampling, each tree is felled and weighed. Destructive sampling is the most accurate method, and the standard to which other methods are compared. However, destructive sampling is neither quick nor cost-effective, and cannot be utilized for standing tree inventories.

Nondestructive sampling techniques overcome these limitations but sacrifice accuracy. Nondestructive measurements can be made either directly (measurements involve touching trees) or indirectly (trees are not touched). Direct nondestructive methods to measure forest biomass have been used for decades (Whitaker and Woodwell 1968). This method involves using destructive sampling for a small area, then developing allometric relationships for that area between an easily measured tree component (usually DBH or total height) and biomass components. Software packages, including BIOPAK (Means et al 1994), have compiled hundreds of models for different stand species, ages, and locations. These equations allow the user to quickly estimate biomass for a stand by directly measuring a single component (such as DBH) from each tree.

Unfortunately, it is difficult for the end user to apply a specific equation to a stand dissimilar from an individual study's scope, which leads to model error (Jenkins et al 2003). In an attempt to overcome this limitation, a recent comprehensive compilation of 2640 individual biomass regression equations from studies within the United States (Jenkins et al 2003) has yielded not only a general relationship between biomass and DBH (Eqn. 1), but also general relationships between the ratio of crown biomass to total biomass and DBH (Eqn. 2). Eqn. 1 was applied to species, while Eqn. 2 was defined for hardwoods/softwoods only, since the studies used in this compilation do not have a consistent definition of crown biomass (Jenkins et al 2003).

$$
\begin{array}{cl}
\text { Total Forest Biomass } & =\mathrm{e}^{(\beta 0+\beta 1 * \ln (\mathrm{DBH}))}+\varepsilon \\
(\text { Crown Biomass/Total Biomass }) & =\mathrm{e}^{(\alpha 0+\alpha 1 / \mathrm{DBH})}+\varepsilon \tag{2}
\end{array}
$$

Since the relationships are exponential and include DBH as the sole tree dimension, the equations are sensitive to trees with DBH that are extremely large or small.

Indirect methods for biomass estimation include all methods where trees are measured remotely, normally at a stand level. Some estimates using this method must utilize allometric equations for actual estimation. The primary aerial-based tools currently used in estimating forest biomass are satellite-based optical moderate resolution sensors, such as the Land Remote-sensing Satellite (Landsat) Enhanced Thematic Mapper $+(\mathrm{ETM}+)$. The ETM + measures reflection magnitudes of different wavelengths, then use spectral vegetation indices (such as Normalized Difference Vegetation Index (NDVI), Difference Vegetation Index (DVI), or Soil-Adjusted Vegetation Index (SAVI)) to estimate biomass, based on the regression between the vegetation index and biomass at predetermined plots (e.g., Zheng et al 2007). A nationwide dataset of plots from the FIA is useful, and these plots have been used in several regional studies when making biomass estimations.

Alternatively, other more precise (and more expensive) technology, such as Light Detection and Ranging (LiDAR), can be used to measure individual tree components (such as tree crown diameter) directly, relate tree crown diameter or height to basal area, then use allometric equations to relate basal area to forest biomass (Maltamo et al 2004).

## Advantages of Hemispherical Measurements

Several studies suggest that hemispherical photography estimates of forest characteristics are more desirable than estimates using other "in-situ" (ground based) methods. Hemispherical photography was suggested as best for long-term monitoring of arid ecosystems (White et al 2000), canopy structure measurement (Leblanc et al 2002), and crown bulk density measurement (Keane et al 2005). Another advantage of HP is its ability to quickly estimate leaf area index (LAI), light transmittance, and canopy gaps (Rich 1990; Hale and Edwards 2002). Fournier et al (2003) describes five advantages of HP over other in-situ measurements, including

- Ability to capture and compare images at different exposures
- Permanent recording of spatial information (Hooper 1976)
- Ability to analyze canopy-level foliage clumping
- Ability to visually inspect data
- Relative robustness to varying sky conditions

Several ground-based instruments have been designed to measure LAI. These tools measure either indirect light diffusion (LAI-2000) or direct light transmittance (DEMON, TRAC, sunfleck ceptometers). The most popular instrument, the LAI-2000 (Li-Cor Biosciences), measures five separate zenith angle regions instantaneously, given cloudy or early/late conditions. Other instruments, which measure LAI at the sun's zenith, rely on average direct transmittance of sunlight; measurements are taken throughout a day during sunny conditions, since LAI must be calculated from several
zenith angles for an accurate reading. In past studies, HP has been measured in uniformly cloudy conditions (e.g., Keane et al 2005; Frazer et al 2001), since ambient brightness levels significantly affect light transmittance measured with HP. Given uniform lighting conditions, HP has been shown to be an effective tool for LAI estimation in various stand conditions, including LAI within a coniferous forest (Chen et al 1997) and LAI for single urban trees (Peper and McPherson 1998). It is possible that branch biomass may be estimated by HP-based metrics, and then allometric equations may be used to extrapolate to overall biomass, which is how SAR (radar) band measurements have been applied (Dobson et al 1995).

## Hemispherical Photography Based Measurements for Forest Biomass Estimates

Gap fraction is directly obtained from hemispherical photographs by estimating the amount of light measured from each pixel. All pixels brighter than a given threshold are defined as gaps, while pixels below this threshold are blocked by forest components. The resulting "gap fraction" is obtained as follows: $\frac{\text { pixels classified as gaps }}{\text { total number of pixels }} * 100 \%$. However, gap fraction is not a measurement of canopy structure, but has been shown to carry information that can be used to estimate metrics directly related to forest canopy structure. Unfortunately, simple gap fraction measurements do not account for total gap sizes (or clumping) which greatly affects leaf surface area (Lang and Yueqin 1986). Gap fraction measurements also do not account for gap differences across zenith angles within the canopy.

LAI has been utilized as a metric to estimate canopy architecture. The main two components that affect LAI measurements are (a) foliage angle distribution and (b) foliage distribution (Chen et al 1997). Foliar crown biomass is linearly related to LAI (Keane et al 2005). If it is assumed that branch biomass is proportional to needle biomass (Brown 1978; Keane et al 2005), it may be possible to find a linear
relationship between LAI and crown biomass. This study will also test whether there is a linear relationship between LAI and total forest biomass.

This potential relationship does not seem as obvious, but it may still be possible to estimate total forest biomass given crown biomass. It is difficult to generalize a linear relationship between LAI and crown biomass (CBB), for several reasons. First, different silvicultural treatments and associated vertical crown structure and crown closure will result in significantly different LAI:CBB ratios. In addition, different geographic regions and species mixes may have different interactions that result in drastically different ratios. Finally, phenological differences between years and seasons provide additional variation that is difficult to account for, especially when attempting to make quick estimates with little supplemental stand structure information.

It is difficult to convert gap fraction measurements from hemispherical photographs directly into LAI. Photographs taken in the visible light spectrum cannot easily differentiate between tree canopy, shrubs, and tree boles. Gap fraction estimates can actually be used to calculate Plant Area Index (PAI), which is the sum of LAI and Wood Area Index (WAI). The resulting PAI is often used as a surrogate for Leaf Area Index (Bréda 2003). Separation of PAI into LAI and WAI is not possible unless the bands of the photograph can be manipulated to separate tree components based on their spectral signatures. This separation with spectral bands is possible if a tool similar to a multiband vegetation imager (MVI) is used (Kucharik et al 1997). An MVI can differentiate the reflective characteristics of tree boles and leaves using spectral signatures. No attempt is made in this study to separate PAI into LAI and WAI.

PAI can be related to gap fraction with Beer-Lambert's law (Jarvis and Leverenz 1983; Marshall and Waring 1986),

$$
\begin{equation*}
P(\theta)=e^{-G(\theta)^{*} \Omega(\theta) * * A I / \cos (\theta)} \tag{3}
\end{equation*}
$$

where $\theta=$ zenith angle (where $0^{\circ}$ is perpendicular to the camera lens and $90^{\circ}$ is parallel to the ground), $\mathrm{P}(\theta)=$ canopy gap fraction, $\mathrm{G}(\theta)=$ projection of foliage relative to the ground, and $\Omega(\theta)=$ a clumping index, which varies by zenith angle. Since it is difficult to estimate, and because it changes from site to site, $G(\theta)$ is often estimated as a constant ( 0.5 ) for all zenith angles for coniferous canopies (Monteith et al 1969). The clumping index can be estimated by using a logarithmic ratio: $\Omega(\theta)$
$=\ln [P(\theta)] / / \ln [P(\theta)]$, where $P(\theta)$ is the mean gap fraction over all azimuths and $\ln [P(\theta)]$ is the logarithmic mean gap fraction of all azimuths within a particular zenith angle (Lang and Yueqin 1986). If there are no gaps at a given zenith angle, a gap equivalent to one pixel is used in calculations to avoid calculations of $\ln (0)$, which results in an undefined value (van Gardingen et al 1999). Ignoring clumping effects has resulted in gross underestimation of LAI (50\% or more) in previous studies (Lang and Yueqin 1986). Accounting for clumping with logarithmic averages has reduced underestimation to $15 \%$ while decreasing the variation in estimation (Lang and Yueqin 1986). See Figure 2.1 for a graphical depiction of zenith angles and azimuths. The figure shows the convention that zenith angle is $0^{\circ}$ at the angle normal to the lens to $90^{\circ}$ at ground level.


Figure 2.1: Hemispherical Image Divided into 5 Zenith Angles and 36 Azimuth Angles

A simple inversion of Eqn. 3 results in

$$
\begin{equation*}
\mathrm{PAI}=-\frac{\ln (P(\theta)) * \cos (\theta)}{G(\theta) * \Omega(\theta)} \tag{4}
\end{equation*}
$$

Several studies (Bonhomme and Chartier 1972, Anderson 1981, Chen et al 1986, Wang and Miller 1987) have utilized this one-dimensional inversion model, known as Campbell's inversion, to obtain LAI. This model has the same canopy geometry assumptions as the Beer-Lambert Law, but requires estimation of gap fraction at multiple zenith angles. Other recent studies (Mussche et al 2001) have shown that this
method leads to underestimation of LAI, and suggest other models (negative binomial, Markov) for more accurate estimation. However, binomial models require canopy measurements not easily obtainable with hemispherical photography in forests (Mussche et al 2001).

Eqn. 3 can be inverted using Campbell's method to solve for PAI (Campbell and Norman 1989):

$$
\begin{equation*}
\mathrm{PAI}=-\int_{0}^{\pi / 2} \frac{\ln (P(\theta)) * \cos (\theta)}{G(\theta) * \Omega(\theta)} \sin (\theta) d \theta \tag{5}
\end{equation*}
$$

Since gap fractions for larger zenith angles are more difficult to accurately measure with this technique, the largest zenith angles are removed to estimate PAI. A correction factor can be included to compensate partially for an underestimation of PAI (Eqn. 6), (Davi et al 2008). This underestimation does not affect the regression analysis, since it is just a linear adjustment for a covariate. Many resources explain PAI calculations in more detail (e.g., Gower et al 1999; Thomas and Winner 2000).

$$
\begin{equation*}
\text { PAI }=-\sum_{i=1}^{j} \frac{\ln \left(P\left(\theta_{i}\right)\right) * \cos \left(\theta_{i}\right)}{G\left(\theta_{i}\right) * \Omega\left(\theta_{i}\right)} \sin \left(\theta_{i}\right) *\left(\frac{1}{1-\cos \left(\theta_{j}\right)}\right), \text { where } \mathrm{i}=\text { zenith angle } \tag{6}
\end{equation*}
$$

In Equation $6, \mathrm{j}$ is the maximum angle used to estimate PAI. The maximum angle $\left(\theta_{\mathrm{j}}\right)$ has been empirically selected at $60^{\circ}$ in previous studies (Thomas and Winner 2000).

Keane et al (2005) used a weighted average (w) across zenith angles with an equation similar to Equation 6, but excluding a clumping factor, and used a weighted average of gap fractions over zenith angles (Eqn. 7).

$$
\begin{equation*}
\mathrm{w}=\frac{\sum_{i=1}^{j} \text { Gap Fraction }_{i}}{j} \tag{7}
\end{equation*}
$$

where i is the gap fraction at a given zenith angle, and j is the total number of zenith angles used in the calculation.

## Limitations of Hemispherical Photography

HP measurements are not exact, and are often limited by the equipment used (including camera spatial, radiometric, and spectral resolution and software), as well as weather conditions, time of day, crown closure, ground slope, and a host of other factors. A 2001 study comparing a film camera configuration and a digital camera configuration (Nikon Coolpix 950 with FC-E8 fisheye) showed that color blurring in the digital pictures resulted in measurement errors in canopy gaps, edge detection, the ability to replicate results, and led to "blooming", especially near the zenith and in sunny conditions. However, black and white digital pictures tended to minimize abnormal chromatic effects. (Frazer et al 2001). In addition, XGA and VGA resolutions resulted in much lower canopy openness measurements when compared with uncompressed TIF photographs. Frazer et al (2001) gives an excellent overview of limitations for the Nikon 950/FC-E8 lens combination, which is similar to the configuration used in this project.

## Methods

## Materials Used

For all experiments, the digital camera configuration included a Nikon Coolpix 950 with an FC-E8 Fisheye lens. Regent Instruments supplied the camera/lens configuration, a matching leveling mount, and the Basic version of their software. Regent Instruments verified the lens-camera configuration, since each lens/camera combination must be manually checked. The camera was mounted on a tripod at a height of 1 meter. It has been previously shown that this fisheye lens will result in a small yet significant distortion (Frazer et al 2001).

Software (such as the Winscanopy package used in this study) can be used to divide the picture into zenith rings and azimuth sections. More advanced versions of the software uses multiple thresholds to categorize pixels as canopy, partial canopy, and non-canopy, while more basic versions (such as the one used in this study) utilize a single threshold to group pixels as either canopy or non-canopy.

## Forest Biomass and Hemispherical Photograph Metrics Defined

Forest biomass has been defined differently in several studies: stump mass, root mass, shrub mass, and dead branch mass may or may not be included in the measurement (Jenkins et al 2003; Brown 1997). For this study, all branches (both dead and live) as well as shrubs greater than one meter in height are included, while stump and root biomass are not included. The biomass for this study is further broken into two types:

- Branch, top, and shrub biomass, which includes all branches and tree tops less than 8 cm in diameter as well as all shrubs greater than one meter tall
- Bole biomass, which includes all bole biomass as well as all biomass from branches greater than 8 cm in diameter. Because the landowner was going to sell all merchantable tree components, no merchantable components greater than 8 cm in diameter were chipped.

Six potential metrics from three equations were examined to estimate forest biomass each was assigned a Hemispherical Photo Metric (HPM) value in order to differentiate between metrics. Each covariate refers to a zenith range, but uses an average zenith angle when calculating each HPM. The first three HP metrics attempt to derive a "partial" PAI from specific zenith angles from each photograph. The final three HP metrics use gap fraction from specific zenith angles for each photograph.

- HPM1: Partial PAI from top three zenith angles, each angle as covariate (Eqn. 4).
- HPM2: Partial PAI from top two zenith angles as single covariate (Eqn. 6)
- HPM3: Partial PAI from top three zenith angles as single covariate (Eqn. 6)
- HPM4: Gap fraction of top two zenith angles, each as covariate (Eqn. 7).
- HPM5: Gap fraction of top three zenith angles, each as covariate (Eqn. 7).
- HPM6: Gap fraction of the zenith angle between $18^{\circ}$ and $36^{\circ}$.

Methodology to Test Effects of Sun Angle in MacDonald-Dunn Research Forest: Most recent experiments conducted with hemispherical photography assume uniform cloudy conditions (Keane et al 2005; Frazer et al 2001). However, a variety of weather conditions naturally exists when measuring forest characteristics on a regular basis. A separate experiment was conducted within the MacDonald-Dunn Research Forest near Corvallis, OR to determine how gap fraction measurements are affected by sun angle. In this experiment, 12 plots were initially chosen, but three plots were removed because they were on steeper slopes ( $>40 \%$ ), which require complex HP corrections (Luisa et al 2008, Montes et al 2007). Since the plots from the destructively sampled slopes were on relatively flat areas, it was decided to ignore plots with steeper slopes for this study. For each plot, between six and nine pictures were taken at various times of the day, with a correlated sun angle for the date and time. Finally, a regression analysis between HPM1 and sun angle was developed (Eqn. 8).

$$
\begin{equation*}
H P M=\beta_{0}+\sum_{i=1}^{9} \beta_{i} * \text { Plot }_{i}+\beta_{10} * \cos \left(\theta_{\text {Sun }}\right)+\varepsilon=\sum_{i=1}^{9} \beta_{i} * \text { Plot }_{i}+\beta_{\text {Sun }} * \cos \left(\theta_{\text {Sun }}\right)+\varepsilon \tag{8}
\end{equation*}
$$

Covariates from each plot were included to exclude differences between plots.
However, variation within plots was not accounted for, since there were relatively few observations. As a result, there is potential for autocorrelation effects within plots for this experiment. To calculate sun elevation angle, an automated calculator from the National Oceanic and Atmospheric Administration (NOAA) was used, given time of day, date, and latitude/longitude as inputs.

Methodology for Destructive Sampling for Molalla Plots:
This study involved destructively sampling fifteen plots near Molalla, OR (45.13N, 122.50 W ), which is approximately 55 km SE of Portland, OR. All plots were on intensively managed commercial timberland owned by Port Blakely. The dominant species was Douglas-fir (Pseuduotsuga menziesii), with some co-dominant/mostly intermediate bigleaf maple (Acer macrophyllum) present in the older sites and an understory of primarily vine maple (Acer circinatum). The fifteen sites were further separated into three groups based on age class (five plots of 20 years, five plots of 39 years, and five plots of either 66 or 67 years). Each plot was selected away from clearings and roads, but each plot was close enough to road access so that limbs and tops could be physically dragged to a mobile chipper.

The data collection methodology for this study closely follows a previous study that explored the relationship between HP-measured gap fraction and canopy bulk density (Keane et al 2005). Before felling any trees, diameter at breast height (DBH) was measured, and its corresponding basal area (BA) was calculated. Next, before removing the trees from a plot, the trees were sorted from smallest to largest DBH, and the cumulative BA was found. Each tree was assigned a quartile (Q1, Q2, Q3, or Q4) after comparing the cumulative BA and the total BA. For example, if the cumulative BA was less than $1 / 4$ of the total BA, it was placed in the first quartile. Table 2.1 shows how trees were assigned to quartiles. Each of the sixty quartiles from the fifteen plots were photographed and used in the subsequent image analysis.
Dividing the sample size into quartiles increased sample size, but the quartiles may not be independent samples.

- $0 \%$ basal area removed
- $25 \%$ basal area removed
- $50 \%$ basal area removed
- $75 \%$ basal area removed
- $100 \%$ basal area removed.
(FINAL)

| Diameter (cm) | BA ( $\mathrm{cm}^{\wedge}$ ) | Cumulative BA | Assigned Quartile | 1/4 Total BA | 68.33 |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 12 | 18.85 | 18.85 | 1 | 1/2 Total BA | 136.66 |
| 14 | 21.99 | 40.84 | 1 | 3/4 Total BA | 204.99 |
| 16 | 25.13 | 65.97 | 1 | Total BA | 273.32 |
| 20 | 31.42 | 97.39 | 2 |  |  |
| 20 | 31.42 | 128.81 | 2 |  |  |
| 22 | 34.56 | 163.36 | 3 |  |  |
| 26 | 40.84 | 204.20 | 3 |  |  |
| 44 | 69.12 | 273.32 | 4 |  |  |

Table 2.1: Technique for Assigning Each Tree to a Quartile

For each quartile, destructive sampling was accomplished as follows:

- If first quartile: chip and weigh all brush/understory biomass.
- Hand fell all trees assigned to the given quartile.
- Measure bole diameter at specific height intervals for each tree in order to estimate bole volume.
- Drag all limbs and tops less than 8 cm diameter over bark (DOB) to a mobile chipper standing outside the plot.
- Chip all limbs and tops into a large bucket.
- Suspend the bucket, weigh with a digital scale and record the weight.

If a tree had limbs or forks greater than 8 cm DOB, each limb or fork was measured at specific intervals to estimate volume. Sections were cut from randomly selected trees to attain wood density in order to convert bole volume to bole biomass. Chip samples were obtained from each quartile and dried in a kiln in order to convert green crown biomass measurements to bone-dry estimates.

To obtain the biomass of each tree bole, the diameter of the bole at different heights was measured, and then in-house software (VALMAX) was used to

- linearly interpolate the diameter at 10 cm intervals along the bole
- approximate volume of each 10 cm cross-section
- take density estimates from the destructively sampled disks and approximate total biomass of each 10 cm cross-section.

Figures 2.2 and 2.3 show the cumulative crown and total biomass for each quartile - DFL, DFM, and DFS correspond to the 66/67 year, 39 year, and 20-year-old stands, respectively. Total biomass decreases from Q1 to Q4 as it is removed from the plot. Notably, when compared to the other plots, DFL5 has one of the greatest total biomass and the smallest crown biomass simultaneously. This allocation of biomass within the plot may be one of the reasons that this plot did not fit the model based on gap fraction. Table 2.2 details biomass totals for each plot.

AGB (tonnes/ha) per Quartile


Figure 2.2: Above Ground Biomass for Each Quartile


Figure 2.3: Crown Branch Biomass for Each Quartile

| Molalla Oven Dry Biomass (kg per plot) |  |  |  |
| :--- | ---: | ---: | ---: |
|  | Total Above Ground | Limbs and Tops | Bole to 8cm ob |
| DFL1 | 14988 | 2591 | 12397 |
| DFL2 | 9930 | 1639 | 8291 |
| DFL3 | 16267 | 2708 | 13559 |
| DFL4 | 16913 | 1700 | 15213 |
| DFL5 | 17401 | 1028 | 16373 |
| DFM1 | 11414 | 1832 | 9582 |
| DFM2 | 12016 | 1999 | 10017 |
| DFM3 | 10515 | 1502 | 9013 |
| DFM4 | 16193 | 2328 | 13865 |
| DFM5 | 15576 | 2390 | 13186 |
| DFS1 | 6940 | 1723 | 5217 |
| DFS2 | 5442 | 1394 | 4048 |
| DFS3 | 6803 | 1721 | 5082 |
| DFS4 | 8017 | 2020 | 5997 |
| DFS5 | 7368 | 1786 | 5582 |

Table 2.2: Above Ground Biomass and Crown Branch Biomass for Each Plot

## Photo Processing and Analysis:

Both color and black and white photographs were taken for each quartile. Original color .TIF images taken from each quartile had three bands - red, green, and blue. Previous studies have shown that if a single color band is used to estimate gap fraction, the blue band is most effective, since blue provides the highest contrast between sky and canopy (Jacquemoud and Baret 1990). Images were analyzed to see if using an orthogonal transformation between the three bands would gain more information. It appeared that some marginal improvements could be made by including all three bands. However, for this initial study, only the blue channel was used in order to simplify the analysis. All pictures were manipulated in Photoshop CS3 (Adobe) using the following procedure, with the same settings used for all pictures:

- Removal of the red and green bands, leaving a grayscale image
- Application of a noise filter, which helped to remove distortion within the sky, which for some photos had a gradient between cloud and sky.
- Application of a high pass filter, with a $3 \times 3$ kernel used to sharpen the pictures, with the same calibration used by Kucharik et al (1997).
- Enhancement of contrast and brightness. Since the entire image darkened during the sharpening process, lightening each photograph improved visual clarity.

The resulting image was black-and-white, with $2^{8}$ (256) brightness levels, or Digital Numbers (DN's).

Next, all pictures were processed using Winscanopy 2006a-Basic edition (Regent Instruments). Winscanopy is a software package commonly used to extract plant canopy characteristics (e.g. Macfarlane et al 2007). Photographs were divided into five equal zenith angles $\left(Z 1=0^{\circ}-18^{\circ}, Z 2=18^{\circ}-36^{\circ}\right.$, etc, where $0^{\circ}$ is perpendicular to the ground) and thirty-six equal azimuths of $10^{\circ}$ each (for PAI logarithmic averaging clumping analysis).

Next, a DN between 1 and 256 was chosen for each image to act as a single threshold level. Pixels with a higher DN were assigned as non-canopy, while pixels with lower DN's were assigned as canopy. This study used a constant threshold of 130 for most photographs, as recommended by Frazer et al (2001). Other studies have attempted to set a different DN threshold for each photograph, but this process introduces operator bias, and confusion when fine-tuning the threshold for each photograph, so manual adjustments were avoided when possible. However, for 10 of the 60 photos (17\%), the threshold was manually shifted downward after visual inspection, usually due to direct overhead sunlight. Overhead sunlight tended to darken the image, especially at large zenith angles, which would lead to underestimation of gap fraction.

In general, black and white digital photographs are preferred for uniform conditions (Frazer et al 2001). This study initially compared gap fractions between (a) color and (b) black and white photographs that were taken at the same time. Black and white photos from this study were not as robust to varying lighting conditions as color photographs when compared visually side-by-side, so they were not used in the final analysis.

Of the fifteen plots in Molalla, thirteen were used to create a regression model, and two plots were randomly selected for a validation model. After initial analysis, one plot (DFL5) was removed from the crown/branch biomass model, so only twelve plots were used to create a crown/branch biomass model. Analysis showed that the Cook's distance for all linear models was much higher for DFL5. As shown, for example, in Figure 2.4, the Cook's distance for the linear model of Plot vs. CBB is much higher for DFL5. All HP metric regressions greatly overestimate crown/branch biomass for DFL5. HP measures PAI, not LAI: it is not robust to large changes in LAI without a corresponding change in PAI. Basically, DFL5 has a much higher AGB:CBB ratio compared to other plots in the study, and HP metrics do not appear capable of differentiating this ratio. Assuming that the PAI:LAI ratio is linearly related to crown/branch: total biomass ratio, HP would not accurately estimate biomass for DFL5, since LAI changed significantly compared to PAI (Figure 2.5).


Figure 2.4: Cook's Distance for each plot showing that DFL5 is an Outlier


Figure 2.5: Ratio of Total Biomass to Crown Branch Biomass for all Plots

## Allometric Equations

Two allometric equations were used in estimating both crown and total forest biomass.
The first equation was taken from a study used in BIOPAK software (BIOLIB10
library). The equations were derived from a study of Douglas-fir stands near Blue River, OR (Fujimori et al 1976) with stand conditions similar to the current study. The Fujimori study divided total biomass into five separate allometric equations in the form of Eqn. 1. Three of the allometric equations (which estimated dead branch, live branch, and foliage biomass) were summed to obtain crown/branch biomass. The other two allometric equations (which estimated bole bark and bole wood biomass) were summed with the first three equations to obtain total forest biomass. Adding estimates of forest components to obtain total biomass does not necessarily give an accurate estimate (Parresol 1999; Parresol 2001), and less intuitive nonlinear models have been used to approximate tree biomass (e.g., Brandeis et al 2006).

The second equation was taken from Jenkins et al (2003), which combines hundreds of studies to estimate forest biomass. Crown/branch biomass was estimated by using allometric equations in the form of Eqn. 2. Equations for each species in the form of Eqn. 1 were combined with crown/branch biomass to obtain total forest biomass.

Actual biomass was obtained by destructive sampling were used as the actual biomass and compared to allometric estimates. Biomass estimates from the first quartile for each plot included both crown biomass from all trees in the first quartile, as well as all understory brush and suppressed trees greater than one meter in height. Including the brush biomass could potentially lead to overestimation of biomass if results from this study are applied to plots to find the biomass of only crown and branch biomass, or total biomass excluding shrubs.

## Relationship Between Sun Angle and HP Measurements:

For the nine plots in the McDonald-Dunn Forest, after accounting for plot differences, there is a statistical difference in PAI for all zenith angles, with much smaller coefficients and weaker correlation for the smallest two zenith regions (Table 2.3). Large variations in measurement and a strong dependence on sun angle were found for
the larger two zenith rings. The increased variability for the largest two zenith regions may indicate that it is undesirable to include these larger angles in this biomass regression for HPM1. Smaller variability for the two smaller angles indicates a diminished effect from sun angle, though a statistical difference is still noted.

| Zenith <br> Ring | $\boldsymbol{\beta}_{\text {sun }}$ | Adj <br> $\mathbf{R}^{\mathbf{2}}$ | Sun Angle <br> p-value | Effect on PAI as Sun angle <br> significant? | with horizon increases |
| ---: | ---: | ---: | ---: | ---: | ---: |
| $0^{\circ}-18^{\circ}$ | 0.0307 | 0.98 | 0.03 | Yes | Measured PAI increases |
| $18^{\circ}-36^{\circ}$ | 0.19 | 0.94 | 0.09 | Marginal | Measured PAI increases |
| $36^{\circ}-54^{\circ}$ | -0.332 | 0.77 | $<0.00001$ | Yes | Measured PAI decreases |
| $54^{\circ}-72^{\circ}$ | -0.497 | 0.73 | $<0.00001$ | Yes | Measured PAI decreases |

Table 2.3: Significance of Sun Angle in Hemispherical Photograph Measurements

There is a higher degree of variation in the larger zenith rings for several reasons. First, the outer rings are physically larger and encompass a broader range of both sky brightness levels and color variation, particularly when the sun is on the horizon. Sky color tends to be homogenous over the smaller area of the smaller zenith rings. Some of the variation could be reduced by using different techniques with more advanced cameras. A camera with higher spectral resolution would increase the ability to differentiate more gaps in the canopy with more subtle color differences. Using a camera with higher spatial resolution would improve detection of smaller gaps in the canopy, which are more numerous farther from the zenith.

## HP Metrics and Branch Biomass:

For the primary study area near Molalla, OR, only the PAI from the $1^{\text {st }}$ zenith ring ( $0^{\circ}$ $18^{\circ}$ from normal) and the $2^{\text {nd }}$ zenith ring ( $18^{\circ}-36^{\circ}$ from normal) were statistically significant in the regression model for HPM1. The $2^{\text {nd }}$ ring accounts for most of the variability, with the $1^{\text {st }}$ ring slightly improving estimates. These zenith rings showed little effect due to sun angle in the McDonald-Dunn experiment, so an attempt to
account for sun angle was not included in the final biomass analysis for any metric. As shown in Figure 2.6, the correlation between HP metrics and the $3^{\text {rd }}$ ring shows much lower correlation.

Comparison of HP Derived Metrics with In(Crown/Branch Biomass)


Figure 2.6: Linear Relationship between HP Metrics and ln (Crown/Branch Biomass)

## HPM and Total Biomass Relationship:

Unfortunately, total biomass could not be easily estimated with HPM1, or any other HPM metric in this study. Again, the $2^{\text {nd }}$ ring was statistically significant, but resulted in a lower adjusted $\mathrm{R}^{2}$ value when compared to the Branch Biomass regression.

Regression models that estimated total biomass using only HP metrics resulted in a wide range of $\mathrm{R}^{2}$ values, as shown in Figure 2.8. However, adding average plot height as a covariate, which may be easily estimated while timber cruising, greatly improved $R^{2}$ values. As shown in Figure 2.7, HP measurements from the $1^{\text {st }}$ and $2^{\text {nd }}$ ring showed higher correlation to total biomass when compared to the $3^{\text {rd }}$ ring.

## Comparison of HP Derived Metrics with In(Total Biomass)



Figure 2.7: Linear Relationship between HP metrics and ln (Total Biomass)

## Summary of Regression Results

The regression equation for each HP metric depends on the number of covariates used in estimating biomass. HPM1 and HPM5 use each of the three rings as a covariate, while HPM2, HPM3, and HPM6 use a single covariate. HPM4 uses two rings as separate covariates. In equations $9,10,11$, and $12, Z 1$ corresponds to the measurement from ring 1, etc. Corresponding regression coefficients are listed in Table 2.4.
ln (Crown/Branch Biomass) estimations (including DFL5)

- $\mathrm{A}+\mathrm{B}^{*} \mathrm{Z} 1+\mathrm{C}^{*} \mathrm{Z} 2+\mathrm{D}^{*} \mathrm{Z} 3$ : Used by HPM1, HPM5
- A + B*HPM : Used by HPM2, HPM3, HPM6 Eqn. 9b
- $\mathrm{A}+\mathrm{B} * \mathrm{Z} 1+\mathrm{C} * \mathrm{Z} 2 \quad$ : Used by HPM4 Eqn. 9c
$\ln$ (Crown/Branch Biomass) estimations (excluding DFL5)
$\begin{array}{llrl}\bullet & \mathrm{E}+\mathrm{F} * \mathrm{Z} 1+\mathrm{G}^{*} \mathrm{Z} 2+\mathrm{H}^{*} \mathrm{Z} 3 & : \text { Used by HPM1, HPM5 } & \text { Eqn. 10a } \\ \text { - } & \mathrm{E}+\mathrm{F}^{*} \mathrm{HPM} & : \text { Used by HPM2, HPM3, HPM6 } & \text { Eqn. 10b } \\ \text { - } & \mathrm{E}+\mathrm{F}^{*} \mathrm{Z} 1+\mathrm{G}^{*} \mathrm{Z} 2 & : \text { Used by HPM4 } & \text { Eqn. 10c }\end{array}$
$\ln$ (Total Biomass) estimations (excluding plot average height as covariate)
- $\mathrm{I}+\mathrm{J} * \mathrm{Z} 1+\mathrm{K} * \mathrm{Z} 2+\mathrm{L} * \mathrm{Z} 3:$ Used by HPM1, HPM5

Eqn. 11a

- I + J*HPM : Used by HPM2, HPM3, HPM6

Eqn. 11b

- $\mathrm{I}+\mathrm{J} * \mathrm{Z} 1+\mathrm{K} * \mathrm{Z} 2 \quad:$ Used by HPM4

Eqn. 11c
$\ln$ (Total Biomass) estimations (including plot average height as covariate)

- $\quad \mathrm{M}+\mathrm{N} * \mathrm{Z} 1+\mathrm{O} * \mathrm{Z} 2+\mathrm{P} * \mathrm{Z} 3+\mathrm{Q} * \ln ($ height $):$ Used by HPM1, HPM5 Eqn. 12a
- $\quad \mathrm{M}+\mathrm{N}^{*} \mathrm{HP}+\mathrm{Q}^{*} \ln$ (height) $:$ Used by HPM2, HPM3, HPM6 Eqn. 12b
- $\quad \mathrm{M}+\mathrm{N}^{*} \mathrm{Z} 1+\mathrm{O} * \mathrm{Z} 2+\mathrm{Q}^{*} \ln ($ height $):$ Used by HPM4

Eqn. 12c

The coefficient of determination for each metric is summarized in Figure 2.8 - the standard error for each coefficient is listed parenthetically below the coefficient. HPM4 and HPM5 had the highest correlation coefficients, while HPM3 had the lowest correlation.


|  | $\left\lvert\, \begin{array}{l\|} \hline \frac{1}{2} \\ \frac{2}{6} \end{array}\right.$ | ｜ | $\left\|\begin{array}{l\|} \hline \frac{1}{0} \\ \frac{2}{x} \end{array}\right\|$ | ｜ | ｜ | $\stackrel{\square}{\square}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\stackrel{\rightharpoonup}{0} \stackrel{0}{\mathrm{E}}$ | $\begin{array}{ll} \therefore 0 \\ 0 & 0 \\ 0 \end{array}$ | $\stackrel{3}{2}: \begin{gathered} 0 \\ 9 \\ 9 \end{gathered}$ | 岛気家 | ¢ | Or | ¢ |
| $\stackrel{F}{\stackrel{F}{+}}$ | $\therefore \begin{array}{ll} \therefore \\ 0 \\ E \end{array}$ | $y_{2}^{2}$ | $0$ | $0$ | 家 | 泡 |
|  |  | 言商 | $\stackrel{\sim}{\circ}$ |  | $\stackrel{\stackrel{\rightharpoonup}{0}}{\text { a }}$ | $0^{(1)}$ |
|  |  |  |  |  |  |  |
| $\left\lvert\, \begin{aligned} & \stackrel{0}{+} \\ & \vec{E} \end{aligned}\right.$ | $0 \begin{aligned} & 0 \\ & 0 \\ & 0 \\ & 0 \end{aligned}$ |  | $0$ | の | On | （10） |
| $\stackrel{F}{\stackrel{F}{+}}$ |  | $\begin{aligned} & 0 \\ & \vdots \\ & 0 \\ & 0 \\ & 0 \end{aligned}$ | $\stackrel{\rightharpoonup}{\dot{O}}$ | $0$ | 家 | $0^{-17}$ |
|  |  | ¢ | 安 |  | $\stackrel{0}{0}$ | － |
|  |  |  |  |  |  |  |
| $\stackrel{\underset{\omega}{\circ}}{\stackrel{0}{\omega}}$ | $\therefore \underset{\sim}{\circ}$ | $\stackrel{c}{\circ}$ | $0$ | （1） | $\bigcirc$ | － |
| $\begin{aligned} & \stackrel{F}{f} \\ & + \\ & \hline \end{aligned}$ |  | Cos | $\stackrel{0}{\square}$ |  | （1） | $\mathrm{O}_{0}^{\circ}{ }^{-1}$ |
|  | \％ | $\underset{\sim}{4}$ | $\stackrel{\square}{\square}$ |  | － | $\overbrace{}^{\text {8 }}$ |
|  | 予 | 倍 |  |  |  |  |
| $\left\lvert\, \begin{gathered} 0,0 \\ \hline \mathbf{y} \\ \hline \end{gathered}\right.$ | Sosp | $\underset{\sim}{\infty}$ | $\bigcirc$ | －ic | $\bigcirc$ | $)^{3}$ |
| $\underset{\sim}{\underset{G}{F}}$ |  | Sic | $\stackrel{\rightharpoonup}{9}$ | So | Sis |  |
| $0$ |  | $0$ |  | $0$ | $5$ | $\bigcirc_{0}^{\circ} 0$ |
|  | $\stackrel{\sim}{\square}$ | － |  |  |  | $\bigcirc 0^{\circ}$ |
|  | （ | $\bigcirc$ | ¢ |  | $\stackrel{\circ}{0}$ | $0^{\circ} 8$ |

Figure 2.8: $R^{2}$ Adjusted Coefficients for Each HP metric


## Validation of Regression Equations

In order to validate the regression equations, two plots (DFL4 and DFM1) were selected at random to validate the model. All four quartiles from each plot were used in the validation of the HP metrics. Each HP metric was analyzed using the prediction model described in Eqn. 13, with corresponding correlation coefficients shown in Figure 2.10. HPM4 and HPM5 showed the best prediction capability (Coefficient A nearest to 0 combined with coefficient $B$ closest to 1 , and adjusted $R^{2}$ relatively high compared to other metrics), while HPM3 had the lowest predictive capability. Positive A values indicate that predicted biomass from all HP metrics underestimated both crown/branch biomass and total biomass (Table 2.5), and is graphically shown in Figure 2.9. In order to consider how precise and unbiased the validation model is, Freese's test (e.g., Gregoire and Reynolds 1988; Robinson and Froese 2004) was considered and applied to this study. The Freese test showed a bias for each HP metric.

$$
\begin{equation*}
\text { Predicted Biomass }=\mathrm{A}+\mathrm{B} * \text { Actual Biomass } \tag{13}
\end{equation*}
$$

|  | Crown/Branch <br> (with DFL5) |  | Crown/Branch <br> (No DFL5) |  | Total <br> (no height) |  | Total <br> (with height) |  |
| :--- | ---: | :---: | ---: | :---: | :---: | :---: | :---: | :---: |
| Metric | A | B | A | B | B | A | B |  |
| HPM1 | 573 | 0.35 | 646 | 0.42 | 4726 | 0.24 | 5204 | 0.32 |
| HPM2 | 613 | 0.34 | 613 | 0.33 | 4782 | 0.19 | 5275 | 0.30 |
| HPM3 | 1060 | -0.01 | 1154 | -0.01 | 6835 | 0.02 | 7728 | 0.49 |
| HPM4 | 314 | 0.61 | 382 | 0.68 | 4299 | 0.32 | 4266 | 0.42 |
| HPM5 | 302 | 0.62 | 380 | 0.68 | 4498 | 0.31 | 4429 | 0.44 |
| HPM6 | 707 | 0.41 | 708 | 0.52 | 5211 | 0.28 | 6151 | 0.32 |

Table 2.5: Regression Coefficients from Validation Model


Figure 2.9: Comparison of Expected to Actual Biomass from Validation Plots (kg/plot)


Figure 2.10: Linear Validation RMSE for Each HP Metric

## Allometric Equations

As expected, allometric equations approximated total above ground biomass well (when compared to HP metrics) using Freese's test, yet with more variation for branch/foliage biomass estimations, due at least partially to the range of tree densities, heights, and diameters used between plots. As seen in Figure 2.11, the BIOPAK equations tended to underestimate true biomass, while Jenkins tended to overestimate true biomass for DFL and DFM plots.


Figure 2.11: Predicted vs. Actual Biomass for Allometric Models (kg/plot)

| Model | Biomass Type | $\mathbf{n}$ (quartiles) | $\mathbf{R}^{\wedge} \mathbf{2}$ | Residual Error (kg) |
| :--- | :--- | :---: | :---: | :---: |
| Jenkins | Total Above Ground | 60 | 0.96 | 765.6 |
| Jenkins | Crown, Branches | 60 | 0.66 | 492.4 |
| BIOPAK | Total Above Ground | 60 | 0.97 | 771.0 |
| BIOPAK | Crown, Branches | 60 | 0.76 | 242.1 |

Table 2.6: Predictive Capabilities of Allometric Models

The estimation from BIOPAK is based on a much smaller sample size than Jenkins, yet each method was equally adequate in describing variation (similar adjusted $\mathrm{R}^{2}$ ) when estimating total biomass. However, BIOPAK tended to more closely predict branch/crown biomass for DFM and DFL plots. Jenkins predicted branch/crown biomass well for DFS plots, overestimated the biomass for each quartile for all DFM/DFL plots to varying degrees.

## Discussion and Conclusions

The regression models of several HP metrics show that there is some promise in using HP for estimating crown/branch biomass, excluding bole biomass. HPM4 and HPM5 in particular, which were based on the top two or three zenith angle ranges, showed the most promise in estimating AGB and CBB. However, none of the metrics were strong predictors of total forest biomass. In order to predict total forest biomass more accurately, it is necessary to include at a minimum a plot-level characteristic (such as average plot height) as a covariate.

Using the average of the top two and top three zenith angles (HPM4 and HPM5, respectively) resulted in the highest correlation with both crown/branch and total biomass, while an estimate of PAI over the top three zenith angles (HPM3) resulted in the lowest correlation. This indicates that it may be possible to estimate biomass with relatively simple calculations, instead of using more complex calculations (such as inversion/derivation of PAI from gap fraction).

Validation for each HP metric showed that several of the metrics have reasonably strong predictive capability. However, the small sample size of the validation model $(\mathrm{n}=8)$ should be expanded before a particular HP metric is chosen as the best predictor of biomass. All models built from each HP metric tended to overestimate biomass for
plots with relatively low biomass, and underestimated biomass for plots with relatively high biomass.

The scope for this model appears to be limited, especially when estimating crown/branch biomass. DFL5, which had much lower crown/branch biomass but similar total biomass compared to the other plots, was a serious outlier in all HP metric regressions. All HP metrics overestimated the true crown/branch biomass for DFL5. Several potential factors may include:

- Regressions are based on an exponential function, which can lead to overestimation for small values and underestimation for large values. A larger study with a broader range of biomass could increase the robustness of prediction.
- All HP metrics estimate PAI, not LAI. The LAI to PAI ratio is much smaller for DFL5 (assuming LAI to PAI ratio is linearly related to crown/branch to total biomass). This issue may be solved using more advanced measurement techniques (such as MVI) to separate PAI into LAI and WAI. A previous study (Barclay et al 2000) showed that the contribution of WAI to PAI estimates appear to be minimal, but may introduce bias in estimates for mature unthinned stands with closed canopies.
- Since the plot has a very small CBB but large AGB, there is a distinct possibility that a disturbance to the crown has reduced the LAI and branch biomass. This cannot be captured by an HP image, and would be difficult to define without detailed tree level and stand structure measurements.
- The average height of DFL5 is taller than other plots, meaning more vegetation from just outside the plot is measured by all HP metrics. This could lead to overestimation of crown/branch biomass.
- The last quartile of DFL5 is the most serious outlier, as noted by its Cook's distance. For the last quartile, most of the original forest biomass within the
plot has been removed, while the forest biomass for the area immediately surrounding the plot does not change. It is possible that the metric is not robust to plots with biomass of non-uniform horizontal distribution.

Attempts to integrate sun angle into the regression model for each HP metric resulted in greater variability in biomass estimation. The reasons that including sun angle did not improve the regression model may include:

- Cloud cover for photos in this study ranged from complete to none.
- A "corona effect" was apparent for several images when the sun was completely visible through the canopy.
- Higher quartiles had relatively low canopy cover. This increased the amount of direct sunlight reaching the camera, which increased gap fraction estimates.

It is possible that including sun angle as a covariate would improve estimations if the above factors were more constant. However, it is better to use this technique in uniform cloudy conditions.

Of the Jenkins and BIOPAK allometric models, both predicted total forest biomass relatively well when compared to HP metrics, but were less accurate in predicting crown/branch biomass. Between the two models, the BIOPAK model showed greater ability to predict crown/branch biomass. This is reasonable, since the BIOPAK model is taken from a site similar to the current site, while the Jenkins model is built from a wider range of forest types. From these results, it is shown that crown/branch biomass may be more site-dependent than total biomass. This is also at least partly because the allometric models are based on DBH, which is less predictive for CBB compared to AGB. It is possible that the crown/branch to total biomass ratio of this site was different than the BIOPAK study, leading to underestimation of crown/branch biomass.

It is not clear why Jenkins would consistently overestimate branch/crown biomass for DFM and DFL plots, but not DFS plots. DFM and DFL plots included more shrub biomass in the crown/branch biomass estimate, but this should lead to lower predicted crown/branch biomass when compared to total crown/branch biomass.

One reason why the allometric equations would perform poorly for CBB is that they are based solely on DBH. Using models based solely on DBH assumes that all trees have the same average height and average crown length. However, trees in stands with high density will be taller with shorter crowns when compared to stands with low density. Since these stands were highly managed, it is likely that these stands had lower than average density due to silvicultural history. If this were the case, then CBB would be underestimated, as was the case for BIOPAK and Jenkins. In order to more closely estimate CBB, it would be necessary to use allometric equations based on stands with similar stocking and crown size when compared to the Molalla stands.

One limitation of this study is that only one forest type is tested. Future work will include analysis of mixed conifer stands from northern California, which should lead to more understanding of the relative power of each metric. In addition, a wider range of HP derived measurements will be modeled with forest biomass.

This study indicates that if a more exact estimate of total biomass is desired, allometric equations based on DBH may provide the best estimate, at a cost of more time intensive timber cruising. However, if crown/branch biomass estimations are needed using ground-based methods, it may be more appropriate to use HP metrics. HP metrics appear to work best in stands with little variation in horizontal and vertical stand structure.

Unfortunately, HP metrics are poor indicators of CBB and AGB when used alone, and require additional stand covariates (such as average stand height) to improve biomass
estimates. Due to stand structure differences, allometric equations based solely on DBH provide poor estimates of forest biomass (especially CBB). Improved equations may be obtained with more time-intensive measurements. Additional covariates would include more measurements taken at the tree level, such as total tree height and crown height. Further analysis is needed to understand which HP metric is best suited for estimating both total and crown/branch biomass.

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# CHAPTER 3: MEASUREMENT OF FOREST BIOMASS USING HEMISPHERICAL PHOTOGRAPHY METRICS FOR DOUGLAS-FIR AND MIXED CONIFER SITES, WITH COMPARISONS TO CONVENTIONAL ALLOMETRIC BIOMASS MEASUREMENTS 

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## Introduction

The importance of accurately identifying inventories of domestic energy, including forest biomass, has increasingly become a priority of the US government and its citizens as the cost of fossil fuels has risen. A recent USDA study has shown that the combined annual domestic fuel supply potential of agricultural biomass (one billion dry tons per year) and forest biomass ( 368 million dry tons per year) is enormous (Perlack et al 2005). It is useful to identify which of these resources can be processed and transported at the lowest cost for both private and public landowners. Accurate spatial inventories of forest biomass help landowners allocate resources to maximize forest biomass utilization and provide information regarding current forest health (e.g., forest fire potential, insect susceptibility, wildlife habitat range). Accurate spatial estimates of forest residual biomass (including branch and crown biomass) help landowners identify areas with higher fire risk while quantifying biomass that could potentially be processed as forest residuals from a harvest operation.

Currently, allometric models that estimate forest biomass at a tree level provide reasonable estimates of total above ground biomass (AGB) on a plot-level basis. When using tree-level allometric equations to obtain plot-level biomass, manually intensive measurements (usually DBH , at a minimum) are required from each tree to accurately estimate AGB and crown and branch biomass (CBB). With these allometric models, it is also possible to estimate CBB , a potential surrogate measurement for residuals from harvesting operations, while quantifying the potential amount available for bio-energy and other uses. However, current ground based methods of biomass estimation are less reliable when estimating CBB and require manually intensive timber cruising measurement of all trees within a plot - to accurately estimate biomass for a given plot. For high value stands, biomass inventories from manually intensive allometric
equations may be economically viable, but in lower value stands, a faster method to define forest biomass may be desirable.

Other recent studies have aimed to test the feasibility of aerial remote sensing technology (such as Light Detection and Ranging, or LiDAR) as a more efficient method for determining forest canopy characteristics while monitoring seasonal and annual changes at landscape and regional scales. However, these techniques are currently relatively expensive, and may be less economically attractive for stands with relatively low value (Zheng and Moskal 2009).

Ground-based remote sensing techniques would provide a faster alternative biomass measurement for lower-value stands when compared to allometric techniques. Hemispherical photography had the highest correlation to crown bulk density in a prior study comparing multiple ground-based tools (Keane et al 2005). Most previous studies with hemispherical photography use homogenous atmospheric conditions, and do not consider corrections that may be necessary if using this technique on a larger scale. It is unclear how feasible, accurate, and robust hemispherical photography would be when measuring above ground biomass and crown biomass with varying weather and sun conditions, and whether the model would be able to accurately estimate biomass for multiple forest types.

This study aims to test the potential of estimating both AGB and CBB at the plot level with a simple camera/hemispherical lens combination. Measuring biomass inventories with this combination would ideally be made without making detailed tree-level measurements. From this particular toolset, gap fraction can be easily estimated. Once gap fraction is known, it can be transformed into a model that uses a one-dimensional gap fraction measurement as an input, and transforms this input into a description of a three dimensional forest canopy. This transformed metric can then be used to make predictions for both AGB and CBB.

To explore the potential role of hemispherical photography in measuring forest biomass, this paper will:

- Identify techniques currently used to measure forest AGB and CBB not only at the tree and plot levels, but also at landscape and regional levels.
- Analyze and interpret results from a study that involved destructively sampling biomass from two separate forest types with various species composition, stand ages, and weather conditions:
- Douglas-fir (Pseuduotsuga menziesii) plantation in northwest Oregon
- Mixed conifer stand composed of a mix of Ponderosa pine (Pinus ponderosa) with understory of Incense-cedar (Libocedrus decurrens) and White fir (Abies concolor) in northern California.
- Identify HP metrics with highest linear regression fit for AGB and CBB, as well as a validation of those metrics.
- Compare these result from HP metrics to two specific allometric models:
- Model built from similar stands used in BIOPAK (Means et al 1994)
- Model compiled from a national compilation (Jenkins et al 2003).


## Current Methods for Biomass Estimation

Forest biomass estimates can be made using one of two methods: destructive or nondestructive sampling. Destructive sampling techniques, which are the most accurate, involve manually felling trees and weighing individual tree components (e.g., live branches, dead branches). Plot level estimates can be made by felling and measuring each tree in the plot, or by taking a statistical sample, then estimating total biomass from that sample (Whitaker and Woodwell 1968). Tree-level estimates of biomass have been created using this method. However, destructive sampling is neither fast nor cost-effective, cannot be utilized for standing tree inventories, and has
been utilized less often as most studies now rely on previously derived allometric relationships.

Nondestructive sampling techniques overcome the limitations of destructive sampling techniques while sacrificing accuracy. Nondestructive measurements can be taken either directly (where measurements are made by touching the trees, or where tree components such as total height and crown width are individually measured for each tree) or indirectly (normally with remote sensing technology) to estimate biomass. Direct nondestructive methods to measure forest biomass have been used for decades (Whitaker and Woodwell 1968). With this method, one or more tree characteristics that are easily accessible (such as DBH, height, or basal area) are measured, and then allometric regression equations from a previous destructive sampling study are used to estimate the biomass components and total biomass of each tree. Software packages, such as BIOPAK (Means et al 1994), have collected equations for different stand types, which allow for biomass estimation of various tree components given the DBH. Unfortunately, it is difficult for the end user to apply a specific equation to a stand dissimilar from an individual study's scope without introducing estimation bias and error due to limitations in estimating stand structure with DBH as the only covariate (Jenkins et al 2003). In addition, since there is no standard definition of tree boles, crown, stump height, and other components, it is often difficult to understand exactly what is estimated for a given equation. In an attempt to overcome these limitations and confusion, a comprehensive compilation of 2640 individual biomass regression equations from studies within the United States was developed (Jenkins et al 2003). This compilation yielded not only a general relationship between AGB and DBH (Eqn. 1), but also estimated linear relationship between DBH and the ratio of crown biomass: total biomass with a biomass expansion factor (BEF) (Eqn. 2). Jenkins applies Eqn. 1 for individual species, while Eqn. 2 is more generalized, and is separated into hardwoods/softwoods only, since studies do not have a consistent definition of crown biomass.

$$
\begin{align*}
\text { Total Biomass } & =\mathrm{e}^{(\beta 0+\beta 1 * \ln (\mathrm{DBH}))}+\varepsilon  \tag{1}\\
(\text { Crown Biomass/Total Biomass }) & =\mathrm{e}^{(\alpha 0+\alpha 1 / \mathrm{DBH})}+\varepsilon \tag{2}
\end{align*}
$$

Since the relationships are exponential, the equations are sensitive to trees with very large or small DBH, which limits the inferential scope of these equations. The regression models from Jenkins have been widely used in national forest inventories. The US Environmental Protection Agency estimates national forest carbon inventory based on the Jenkins equations (US EPA 2008). The most recent national Forest Inventory and Analysis (FIA) biomass database (FIADB4, released in May 2009 (USDA Forest Service 2009)) also uses Jenkins equations to estimate forest biomass components except for bole biomass, which is based on volume estimates (Heath et al 2009).

Indirect methods of forest biomass estimation include all methods where trees are measured from a distance. Empirically based plot level estimates of biomass have become more important as remote sensing techniques have become more prevalent. Remote sensing techniques (including aerial LiDAR (Roberts et al 2005) and terrestrial LiDAR (Takeda et al 2008, Hosoi and Omasa 2006)) have been used in recent studies to estimate crown structure. Aerial LiDAR techniques in particular rely on regression equations that relate tree crown diameter or height with basal area, and then use basal area to quantify forest biomass, potentially with regression techniques derived from pipe model theory (Chiba et al 1998).

Recently, remote sensing techniques have been used to expand from traditional locally based allometric and empirical models to modern landscape and regional processbased models (Zheng and Moskal 2009). Plot level estimates from empirical models can be used as inputs for process based modeling on the landscape and regional scales. Satellite-based hyperspectral information has been used to estimate forest canopy
structure as well as forest biomass, given forest biomass at specific points. One study of particular interest combined ground-based estimates of LAI with Normalized Difference Vegetative Index (NDVI, Steven et al 1983) measurements from Moderate Resolution Imaging Spectrometer (MODIS) to estimate AGB (Zheng et al 2007) at a regional level.

Recent theory has shown that some properties of foliage are spectrally invariant (Smolander and Stenberg 2005), and has been use to estimate LAI and other canopy characteristics with satellite data that is used to estimate bidirectional reflection factor (BDRF). This theory, known as radiation budget theory, shows that photon-vegetation reflectance interactions are constant, and that gap fraction is a function of photon escape and "recollection" probabilities within a forest canopy. This theory has been used to bypass ground-based measurements in estimating canopy characteristics such as LAI (Hu et al 2006).

## What Metric from Hemispherical Photography Best Estimates Forest Biomass?

 The metric most often obtained from HP is gap fraction. Gap fraction is directly obtained from digital hemispherical photographs by estimating the intensity of light measured from each pixel. All pixels brighter than a given threshold are defined as gaps, while pixels below this threshold are blocked by forest components. The resulting gap fraction measurement is calculated as $\frac{\text { pixels classified as gaps }}{\text { total number of pixels }} * 100 \%$ for a given interval of zenith angles, where zenith angle ranges from $0^{\circ}$ to $90^{\circ}$, and is defined as $0^{\circ}$ for the angle normal to the camera lens (or at the center of the image). Without adjustments, gap fraction does not describe specific information about canopy structure, but information from gap fraction can be used to obtain a metric that describes canopy structure. Keane et al (2005) has shown a correlation between gap fraction at specific zenith ranges and crown bulk density. This study will compareforest biomass with gap fraction estimates of three zenith ranges $\left(0^{\circ}\right.$ to $30^{\circ}, 0^{\circ}$ to $60^{\circ}$, and $0^{\circ}$ to $90^{\circ}$ ).

See Figure 3.1 for a graphical depiction of zenith and azimuth angles in an HP image. The figure shows how zenith angle increases from $0^{\circ}$ at the angle normal to the camera and increases to $90^{\circ}$ at a horizontal angle.


Figure 3.1: Hemispherical Image Divided into 5 Zenith Angles and 36 Azimuth Angles

It is not clear when using gap fraction from a range of zenith angles if a better model could be built by increasing the number of zenith angles (as separate covariates) or by using only a specific range of zenith angles. This study will attempt to answer this question by attempting to find an optimal number of rings as well as an optimal zenith angle range for both AGB and CBB , using the following technique:

- Include site as an indicator variable for all models.
- Create $n$ different regression models between gap fraction and biomass, where $n$ is the number of equally spaced rings in the image. $n=1,2, \ldots, 25$ for this test.
- For each of the $1,2, \ldots, n$ models, begin with the innermost ring and derive the mean square error (MSE) and Akaike's information criterion (AIC) for that model. Next, include the ring adjacent to the center ring as a separate covariate, then derive MSE and AIC. Iteratively repeat, until the outermost ring is included.
- Compare all models and choose the model with the best fit according to MSE and AIC estimates.

Accurate estimation of plant biomass has been actively pursued since the turn of the $20^{\text {th }}$ century. Boysen-Jensen, regarded as the founder of the science of plant dry mass production (Hirose 2004), noted that estimation of dry mass production should focus on the $\mathrm{CO}_{2}$ assimilation of leaves (Boysen-Jensen 1932). Boysen-Jensen also studied canopy photosynthesis in relation to stand structure, and suggested that leaf arrangement is critical in a natural stand structure. Monsi and Saeki (1953) took this a step further, using Beer's Law of exponential decay to derive a radiative transfer (RT) model that estimated light attenuation within a plant canopy. Their model assumes that the canopy is a turbid medium, and assumes the random distribution of canopy phytoelements (leaves, twigs, etc.). It also assumes that light is diffused throughout the plant canopy, with no heterogeneous areas of sunlight and shade (Monsi and Saeki 1953). Their basic model is summarized in Eqn. 3.

$$
\begin{equation*}
I=I_{0} e^{-k^{*} L} \tag{3}
\end{equation*}
$$

Where
$I=$ photosynthetic photon flux density (PPFD) at any point within or below the canopy
$k=$ canopy light extinction coefficient

$$
\begin{aligned}
& L=\text { Leaf Area Index }(L A I) \\
& I_{0}=\text { the PPFD above the canopy } .
\end{aligned}
$$

The Monsi-Saeki model, based on a Poisson statistical model with an infinite number of horizontal layers in the canopy, implies that LAI is closely related to the amount of sunlight penetrating the canopy $\left(\mathrm{I} / \mathrm{I}_{0}\right)$, assuming no transmittance or reflectance from canopy phytoelements. Monsi and Saeki also showed that maximum photosynthesis could be achieved in a plant canopy for any given $k$ by varying $L$ (given their model assumptions), and showed that maximum photosynthesis occurred for higher L values when stands had low $k$ values, and vice versa.

LAI has been widely utilized as a metric to estimate canopy architecture (Tappeiner et al 2007). Several studies (Bonhomme and Chartier 1972; Anderson 1981; Chen et al 1986; Wang and Miller 1987, Campbell and Norman 1989) have utilized this model, also known as Campbell's inversion, to obtain LAI. Other recent studies (Mussche et al 2001) have shown that this method leads to underestimation of LAI, and suggest other models (negative binomial) for more accurate estimation. However, these models require canopy characteristics that are difficult to estimate with hemispherical photography (Mussche et al 2001; Neumann et al 1989).

The most important attributes of canopy structure that affect LAI measurements are (a) foliage angle distribution and (b) leaf spatial distribution (Chen et al 1997). Foliar crown biomass may be linearly related to LAI (Keane et al 2005). If it is assumed that CBB is proportional to needle biomass (Brown 1978; Keane et al 2005), it may be possible to find a linear relationship between LAI and CBB. This study will also model a linear relationship between LAI estimates and AGB. Even though LAI alone may not be a strong indicator of AGB, LAI combined with other covariates (such as average stand height) may provide an approximation of AGB. There are several
limitations in using this approach, but this appears to be the most reasonable approach when using HP technology.

Assuming that gap fraction is equivalent to $\mathrm{I} / \mathrm{I}_{0}$,

$$
\begin{equation*}
P(\theta)=e^{\left[-G(\theta) / \cos (\theta)^{*} L\right]} \tag{4}
\end{equation*}
$$

where
$P(\theta)=$ the gap fraction at average zenith angle $\theta$ and
$G(\theta)=$ the foliage angle distribution by estimating the projection of leaves perpendicular to incident photons at zenith angle $\theta$.

It is assumed that $\mathrm{G}(\theta) / \cos (\theta)=\mathrm{k}(\theta)$.
$\mathrm{G}(\theta)$ has been modeled (Warren-Wilson 1963) for flat leaves, but this function is very difficult to estimate given a one-dimensional image of the canopy. If cross sections of phytoelements are assumed to be circular (a close assumption for needle foliage), then it may be assumed that $\mathrm{G}(\theta)$ is a function of the angle between the perpendicular angle to a given foliage element $(\delta)$ and the zenith angle $(\theta)$, which can be estimated with $\cos (\delta-\theta)$ (Montes et al 2007). $\delta$ is the zenith angle where incoming light is most attenuated per unit length, and is a function of canopy geometric features. It has been previously shown that $\mathrm{G}(\theta) \approx 0.5$ at zenith angle $57.5^{\circ}$ (Warren-Wilson 1963), regardless of canopy leaf angle distribution. Montes et al (2007) proposed that that $G(\theta)$ could be estimated with the following equation:

$$
\begin{equation*}
G(\theta)=\frac{0.5}{\cos (57.5-\delta)} * \cos (\theta-\delta) \tag{5}
\end{equation*}
$$

Equation 5 is equal to 0.5 when the angle is $57.5^{\circ}$, and estimates the foliage angle distribution such that the distribution is at a maximum at the angle $\delta$. This is merely an approximation, but provides a simple approximation of a nonlinear distribution (Montes et al 2007).

It is well known that the Poisson model of Monsi-Saeki leads to underestimation of LAI, often $50 \%$ or more (Lang and Yueqin 1986). This underestimation is due to assumptions of the original model, which does not account for foliage clumping (Kucharik et al 1999). This model also does not account for gap differences between zenith angles within the canopy. Foliage clumping can be modeled by converting the Poisson model of Monsi-Saeki into a Markov model, where the probability of contacting a specific layer becomes dependent on whether a layer above or below is contacted (Nilson 1971). Assuming the number of horizontal canopy layers is infinite, gap fraction can be estimated as

$$
\begin{equation*}
P(\theta)=e^{\left[-G(\theta) / \cos (\theta)^{*} L_{1}^{*} \Omega_{0}\right]} \tag{6}
\end{equation*}
$$

where $\Omega_{0}$ is a clumping coefficient. The "effective" LAI, or $L_{\text {ef }}$, is now calculated as $\mathrm{L}_{\text {ef }}=\Omega_{0}{ }^{*} \mathrm{~L}_{1}$. If $\Omega_{0}$ is $<1$, foliage is clumped, while if $\Omega_{0}$ is $>1$, foliage is evenly distributed (not random).

Accounting for clumping in this way has reduced underestimation of LAI to $15 \%$ in prior studies, while also decreasing estimation variation (Lang and Yueqin 1986). It is assumed that $\Omega_{0}$ includes clumping at both the foliage level as well as the shoot level. However, HP does not have the spatial resolution to resolve foliage at the shoot level, and additional information is needed to estimate a shoot clumping factor when estimating LAI from HP (Stenberg 1996). It is assumed that shoot level clumping is a constant between plots, which means that estimates are assumed to be biased, but will not have increased variance.

Montes et al (2007) proposed a function to estimate $\Omega_{0}$ with a function that maximizes the clumping effect at small zenith angles.

$$
\begin{equation*}
\Omega(\theta)=\Omega_{0} * \cos ^{2}(\theta)+\sin ^{2}(\theta) \tag{7}
\end{equation*}
$$

Montes et al (2007) again modifies the model so that the clumping effect dominates for smaller zenith angles, while the clumping coefficient is weighted heavier for larger angles. When weighting the coefficients this way, the effect of WAI is minimized at smaller angles, since more bole/branch pixels are expected at larger angles. This means that foliage clumping is weighted heavier at smaller angles, where more foliage is expected. Once foliage clumping is included in the model, gap fraction at each zenith angle can now be estimated using the following equation:

$$
\begin{equation*}
P(\theta)=e^{-L_{1} *\left(\Omega_{0}{ }^{*} \cos ^{2}(\theta)+G(\theta)^{*} \sin ^{2}(\theta)\right) / \cos (\theta)} \tag{8}
\end{equation*}
$$

At this point, $L, \Omega_{0}$, and $G(\theta)$ can be solved simultaneously using iterative regression of least squares of this nonlinear function (Montes et al 2007). The range for $\theta$ is $0^{\circ}$ $90^{\circ}$, while the clumping index is expected to be less than one. Each image was divided into fifteen equally spaced zenith angles, and then the following objective function was minimized for each image to obtain L and $\mathrm{L}_{\mathrm{ef}}$ :

$$
\begin{equation*}
\min \left\{\sum_{i=1}^{15}\left[e^{-L L^{*}\left(\Omega_{0}^{*} \cos ^{2}\left(\theta_{i}\right)+G(\theta)^{*} \sin ^{2}\left(\theta_{i}\right)\right) / \cos \left(\theta_{i}\right)}-P\left(\theta_{i}\right)\right]^{2}\right\} \tag{9}
\end{equation*}
$$

where $\mathrm{P}(\theta)$ is HP estimated gap fraction. One constraint included in this model is that $\mathrm{G}(\theta)$ is equal for all quartiles within the same plot. Montes et al (2007) also modeled estimates of LAI under moderate slopes, but this adjustment was not attempted in this study. There is potential of covariance between the three variables that are solved simultaneously, but the solution procedure minimizes the function as a whole, so no bias is introduced in the solution procedure.

Keane et al (2005) used a weighted average of gap fraction, multiplying the zenith angle of each gap fraction by $\sin (\theta)$ to estimate LAI. An alternate estimate of the clumping index can be estimated by using a logarithmic ratio: $\Omega(\theta)=\ln [P(\theta)] / \ln [P(\theta)]$,
where $P(\theta)$ is the mean gap fraction over all azimuths and $\ln [P(\theta)]$ is the logarithmic mean gap fraction of all azimuths within a particular zenith angle (Lang and Yueqin 1986). When using this approximation, it is assumed that individual foliage elements are much smaller ( $<10 \%$ ) than the area of a given azimuth/zenith section (Lang and Yueqin 1986). If there is no gap, a gap equivalent to one pixel was used to avoid zero gap fractions and undefined log functions (van Gardingen et al 1999).

It is not possible to convert gap fraction measurements from hemispherical photographs directly into LAI. HP metrics cannot easily differentiate between tree canopy, shrubs, and tree boles; instead, the metrics calculate Plant Area Index (PAI), which is the sum of LAI and Wood Area Index (WAI). The resulting PAI is often used as a surrogate for LAI, and while not equivalent, is often used interchangeably (Bréda 2003). Separation of PAI into LAI and WAI is possible if a photographic instrument such as a multiband vegetation imager (MVI) is used (Kucharik et al 1997). An MVI can differentiate the reflective characteristics of tree boles and leaves using spectral signatures. No attempt was made in this study to separate PAI into LAI and WAI, and all references to LAI in results are equivalent to PAI.

## Limitations of Hemispherical Photography

HP measurements are not exact, and are often limited by the equipment used (including camera spatial, radiometric, and spectral resolution and software), as well as weather conditions, time of day, crown closure, ground slope, and a host of other factors. A 2001 study comparing a film camera configuration and a digital camera configuration (Nikon Coolpix 950 with FC-E8 fisheye lens) showed that color blurring in the digital pictures resulted in measurement errors in canopy gaps, edge detection, problems in replicating results, and "blooming" (glare), especially near the zenith and in sunny conditions. However, black and white digital pictures tended to
minimize abnormal chromatic effects in a previous study (Frazer et al 2001). It is also difficult to estimate conifer foliage biomass due to a penumbral effect (Bréda 2003). XGA and VGA resolutions resulted in much lower canopy openness measurements when compared with uncompressed TIFF photographs. Frazer et al (2001) gives an excellent overview of other limitations for the Nikon 950/FC-E8 lens combination, which is very similar to the camera configuration used in this project.

## Methods

## Materials Used

For all experiments, the digital camera configuration included a Nikon Coolpix 950 with an FC-E8 Fisheye lens. Regent Instruments supplied the camera/lens configuration, a matching leveling mount, and the "Winscanopy Basic 2006" version of their software. Regent Instruments verified the lens-camera configuration, since each lens/camera combination must be manually checked. The camera was mounted on a tripod at a height of 1 meter. It has been previously shown that this fisheye lens will result in a small yet significant distortion (Frazer et al 2001).

Software (such as the Winscanopy package used in this study) can be used to divide an image into equally spaced zenith rings and azimuth sections. Advanced versions of the software use multiple thresholds to classify each pixel as canopy, partial canopy, or non-canopy, while more basic software versions (including the version used in this study) utilize a single threshold to assign pixels as either canopy or non-canopy.

## Forest Biomass and Hemispherical Photograph Metrics Defined

Forest biomass has been defined differently in several studies: stump mass, root mass, shrub mass, and dead branch mass may or may not be included in the measurement (Jenkins et al 2003, Brown 1997). In this study, all branches (both dead and live) as well as shrubs greater than one meter in height are included, while stump and root
biomass are not included. CBB measurements for this study include all branches and tree tops less than 8 cm in diameter as well as all shrubs greater than one meter tall. AGB measurements for this study include CBB as well as bole biomass and all biomass from branches greater than 8 cm in diameter.

Eight potential metrics were examined to estimate forest biomass - each was assigned a Hemispherical Photo Metric (HPM) index, as follows:

- HPM1: Gap Fraction of zenith angle $0^{\circ}-30^{\circ}$
- HPM2: Gap Fraction of zenith angle $0^{\circ}-60^{\circ}$
- HPM3: Gap Fraction of zenith angle $0^{\circ}-90^{\circ}$
- HPM4: Gap Fraction with the combination of zenith rings and zenith range with the best MSE and AIC fit
- HPM5: Weighted estimate of LAI (Keane et al 2005) with clumping coefficient
proposed by Lang, using zenith angle $0^{\circ}-30^{\circ}$.
- HPM6: Weighted estimate of LAI (Keane et al 2005) with clumping coefficient
proposed by Lang, using zenith angle $0^{\circ}-90^{\circ}$.
- HPM7: $\mathrm{L}_{\mathrm{ef}}=\mathrm{L}^{*} \Omega_{0}$, from least-squares estimate. (Eqn. 8, 9).
- HPM8: $\mathrm{L}_{1}$, from least squares estimate. (Eqn. 8, 9).


## Methodology for Destructive Sampling of Douglas-fir and Mixed Conifer Stands

 The study included 28 destructively sampled plots. All plots were circular, with an area of 0.04 hectare, or a radius of 11.28 meters; all trees with their boles located within the plot were included in biomass estimates. Fifteen plots were located near Molalla, OR ( $45.13 \mathrm{~N},-122.50 \mathrm{~W}$ ), which is approximately 55 km SE of Portland, OR, while thirteen plots were located near Burney, CA (41.33N, $-121.70 \mathrm{~W})$. The Molallaplots were selected from intensively managed commercial Douglas-fir timberland owned by Port Blakely, while Hambone plots were chosen from commercial mixed conifer timberland managed by Roseburg Forest Products. All plots were selected away from forest edge, but in relatively accessible areas so that limbs and tops could be manually dragged to a mobile chipper. Tables 3.1 and 3.2 give detailed stand properties for plots from each site.





The data collection methodology for this study closely follows the methodology from a study that explored the relationship between HP-measured gap fraction and canopy bulk density (Keane et al 2005). Before felling any trees, diameter at breast height (DBH) was measured, and its corresponding basal area (BA) was calculated. Next, trees were sorted from smallest to largest, and the cumulative BA was found. Each tree was assigned to a quartile (Q1, Q2, Q3, or Q4) after comparing the cumulative BA and the total BA. For example, if the cumulative BA was less than $1 / 4$ of the total BA, the tree was assigned to and felled in the first quartile. Table 3.3 shows how trees were assigned to quartiles. The quartiles were then each photographed and used in the subsequent image analysis.

- $0 \%$ basal area removed
(Q1)
- $25 \%$ basal area removed
- $50 \%$ basal area removed
- $75 \%$ basal area removed
- $100 \%$ basal area removed.
(FINAL)

| Diameter (cm) | BA (cm^2) | Cumulative BA | Assigned Quartile | 1/4 Total BA | 68.33 |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 12 | 18.85 | 18.85 | 1 | 1/2 Total BA | 136.66 |
| 14 | 21.99 | 40.84 | 1 | 3/4 Total BA | 204.99 |
| 16 | 25.13 | 65.97 | 1 | Total BA | 273.32 |
| 20 | 31.42 | 97.39 | 2 |  |  |
| 20 | 31.42 | 128.81 | 2 |  |  |
| 22 | 34.56 | 163.36 | 3 |  |  |
| 26 | 40.84 | 204.20 | 3 |  |  |
| 44 | 69.12 | 273.32 | 4 |  |  |

Table 3.3: Technique for Assigning Each Tree to a Quartile

For each quartile, destructive sampling was accomplished as follows:

- If it was the first quartile: chip and weigh all brush/understory biomass.
- Hand fell all trees assigned to the given quartile.
- Measure bole diameter at specific height intervals for each tree in order to estimate bole volume.
- Drag all limbs and tops less than 8 cm diameter over bark (DOB) to a mobile chipper standing outside the plot.
- Chip all limbs and tops into a large bucket.
- Suspend the bucket and record the weight in kg with a digital scale.

All tree limbs and forks greater than 8 cm DOB were not chipped, but measured at specific intervals to estimate volume. Sections were cut at specific intervals from randomly selected trees to attain wood density in order to convert bole volume to bole biomass. Chip samples were obtained from each quartile and dried in a kiln in order to convert green biomass to dry biomass estimates.

To obtain the biomass of each tree bole, the diameter of the bole at different heights was measured, and then proprietary software (VALMAX, Murphy 2009) was used to:

- Linearly interpolate the DOB at 10 cm intervals along each bole.
- Approximate the volume (and biomass) of each 10 cm cross-section.
- Approximate the total biomass of bole by summing up the volume of all crosssections.

Figures 3.2 and 3.3 show the crown and above ground biomass for each quartile stand ages for DFL, DFM, and DFS correspond to 66 and 67 years, 39 years, and 20 years, respectively. Notably, DFL5 and MCM4 have the greatest initial total biomass and smallest crown biomass simultaneously, leading to model difficulties to be described later. MCL and MCM plots correspond to relatively dense stands with varying ranges of height, while MCS plots correspond to relatively sparse stands with
much shorter average height. Tables 3.4 and 3.5 detail biomass totals for plots from each site.

## AGB (tonnes/ha) per Quartile



Figure 3.2: Cumulative Above Ground Biomass per Quartile for Each Plot


Plot

Figure 3.3: Cumulative Crown Branch Biomass per Quartile for Each Plot

| Molalla Oven Dry Biomass jkg per plot |  |  |  |
| :--- | ---: | ---: | ---: |
|  | Total Above Ground | Limbs and Tops | Bole to 8cm ob |
| DFL1 | 14988 | 2591 | 12397 |
| DFL2 | 9930 | 1639 | 8291 |
| DFL3 | 16267 | 2708 | 13559 |
| DFL4 | 16913 | 1700 | 15213 |
| DFL5 | 17401 | 1028 | 16373 |
| DFM1 | 11414 | 1832 | 9582 |
| DFM2 | 12016 | 1999 | 10017 |
| DFM3 | 10515 | 1502 | 9013 |
| DFM4 | 16193 | 2328 | 13865 |
| DFM5 | 15576 | 2390 | 13186 |
| DFS1 | 6940 | 1723 | 5217 |
| DFS2 | 5442 | 1394 | 4048 |
| DFS3 | 6803 | 1721 | 5082 |
| DFS4 | 8017 | 2020 | 5997 |
| DFS5 | 7368 | 1786 | 5582 |

Table 3.4: Summary of Molalla Biomass Measurements

| Hambone Oven Dry Biomass (kg per plot) |  |  |  |
| :---: | :---: | :---: | :---: |
|  | Total Above <br> Ground | Limbs and <br> Tops | Bole to <br> 88 cm ob |
| MCL1 | 17001 | 2647 | 14354 |
| MCL2 | 7135 | 1825 | 5311 |
| MCL3 | 17920 | 2446 | 15474 |
| MCL4 | 9490 | 1791 | 7700 |
| MCM1 | 13877 | 2933 | 10944 |
| MCM2 | 13003 | 3152 | 9851 |
| MCM4 | 3244 | 971 | 2273 |
| MCM5 | 5349 | 1558 | 3791 |
| MCS1 | 2329 | 879 | 1450 |
| MCS2 | 1869 | 777 | 1092 |
| MCS3 | 5672 | 1937 | 3736 |
| MCS4 | 5754 | 1828 | 3927 |
| MCS5 | 5173 | 1690 | 3484 |

Table 3.5: Summary of Hambone Biomass Measurements

Effect of Sun Elevation Angle on Measurements:
A separate study was previously conducted within the MacDonald-Dunn Research Forest near Corvallis, OR to test for correlation between sun angle and gap fraction measurements, ceteris paribus. Measurements were taken at different times of day for nine plots in stand that were predominantly Douglas-fir. These measurements showed that there were statistically significant ( p -value $<0.1$ for all zenith angle ranges), yet small magnitude, estimates of gap fraction for larger zenith angles as the sun elevation angle varies. However, it is difficult to apply these known differences to plots in the current study, because there are many uncontrolled variables that this study could not quantify, such as cloud cover, canopy cover blocking the sun, and sunlight intensity. This study also could not quantify how gap fraction is affected by the azimuthal location of biomass within the plot relative to the plot center and to the sun elevation and angle due to heterogeneous lighting conditions within the forest canopy. The stand structure itself, as well as whether or not a tree bole or other obstruction was blocking the sun also significantly affected the applicability of sun angle to this model.

## Photo Processing and Analysis

This study initially compared gap fractions between color and black and white photographs that were taken at essentially the same time. Black and white photos have been recommended for HP estimations of forest canopy given uniform conditions (Frazer et al 2001). Black and white photos from this study were not as robust to varying lighting conditions as color photographs, since information was lost when saving as black-and-white, so only color images were used in the final analysis. Multiple photographs were taken for each plot using both center-weighted focus and a Nikon proprietary weighted 'matrix' focus. The matrix focus setting visually resulted in sharper images over the full range of zenith angles and was usually favored over the center-weighted focus in the final analysis.

Original TIF images taken from each plot had three channels - red, green, and blue with resolution of 3.2 MP each. The estimated radius for each image was 730.9 pixels. Previous studies have shown that the blue channel is most effective (Jacquemoud and Baret 1990). However, due to direct sunlight and heterogeneous lighting within the canopy, the blue channel alone did not accurately estimate gap fraction when visually inspected. The blue channel intensity showed obvious overestimation of gap fraction for sunlit canopy as well as underestimation of gap fraction for darker portions of images at larger zenith angles. Images were analyzed to check whether a combination of the three channels would improve gap fraction estimates. Analysis of the three channels showed a high correlation between all three channels for each pixel, which is probably because the same CCD sensor is used for the same pixel for all three channels for the Coolpix 950 (Nikon).

Typical determination of gap fraction from HP for a gray scale image is simple. The user selects a Digital Number (DN) between 1 and $2^{B}$ for each image to act as a single threshold level, where B is the number of bits per pixel. Pixels with a higher DN are assigned as non-canopy, while pixels with lower DN's are assigned as canopy (Figure 3.4). Some studies use a constant threshold of 130 when $B=8$, as recommended by Frazer et al (2001). Other studies have attempted to identify a different threshold for each individual photograph, while other studies have attempted to define threshold as a function of zenith angle, but these techniques tend to introduce operator bias, and are more time consuming and tedious when working with large numbers of images. Techniques that are more sophisticated set two thresholds and assign pixels between these two thresholds a partial gap fraction, based on the DN of each pixel (Figure 3.4). However, all of these techniques assume that the sky is always relatively brighter than the canopy, therefore, work poorly in conditions with sunlit canopies, tree boles, or sky conditions where there is a wide color gradient from one side of an image to the other, or where canopy pixels may be brighter than sky pixels.


Figure 3.4: Single Threshold vs. Multiple Threshold Techniques

An empirically derived method proposed here may lead to more accurate gap fraction measurements at varying solar angles and weather conditions while minimizing the effects of heterogeneous lighting conditions. Even though some of the techniques are time consuming, most of the steps can be automated for large-scale analysis.

All RGB images are first manipulated in Photoshop CS3 (Adobe) using the following procedure, with the same settings used for all pictures:

- Application of a noise filter, which helps to remove distortion from areas with cloud cover and helps reduce the impact of the high pass filter along gradients with sharp contrast.
- Application of a high pass filter, with a $3 \times 3$ kernel used to sharpen the images, using settings found to work best for HP images in LAI estimations by Kucharik et al (1997).

Next, all images are manipulated in ENVI 4.5 with the following steps to extract gap fraction:

- Orthogonal transformation between the three bands, using Principal Components Analysis (PCA), as described in Joliffe (2002).
- Separation of each image into 15 classes, using an ISODATA unsupervised classification method (Richards and Jia 2006).
- Manually grouping each of these 15 classifications into one of 2 groups: sky or canopy.

Finally, the modified images are processed using Winscanopy 2006a-Basic edition (Regent Instruments). Images are divided into fifteen equal zenith ranges $\left(0^{\circ}-6^{\circ}, 6^{\circ}\right.$ $12^{\circ}$, etc, where $0^{\circ}$ is the angle normal to the camera lens, in the center of the image) and 36 equally spaced azimuths of $10^{\circ}$. Azimuth angle is important when calculating HP metrics based on log-averages of azimuths, instead of the average (such as in HPM5 and HPM6). It is not important for any other metric in this study. However, it is critical to understand the relationship between azimuth and slope aspect when estimating LAI for areas with slopes (Montes et al 2007).

Statistical analysis was conducted with the R statistical package. An adjusted correlation coefficient was used when describing model fit. The adjustment is calculated as

$$
R_{\text {adjusted }}^{2}=1-\left(1-R^{2}\right) * \frac{n-1}{n-p-1},
$$

Where p is the total number of covariates (not including the constant term), and n is sample size.

Of the 28 plots, 23 plots were used to create a regression model, and five plots were randomly selected for a validation model. After initial analysis, two plots (DFL5 and MCM4) were removed from the crown/branch biomass model, so that only 21 plots were used to create a crown/branch biomass model. These two plots had relatively higher Cook's distance when compared to other plots. All HP metric regressions greatly overestimate crown/branch biomass for DFL5 and MCM4. HP measures PAI, not LAI: it is not robust to large changes in LAI without a corresponding change in PAI. Assuming that the PAI:LAI ratio is correlated to the CBB:AGB ratio, HP may not accurately estimate biomass for DFL5 or MCM4, because the PAI:LAI ratio is higher for these plots. The CBB:AGB ratio also may significantly vary due to its relationship to stand age, canopy structure, and spacing.

## Allometric Equations

Two allometric equations are used in estimating both crown and total forest biomass. The first equation was taken from the most similar study within BIOPAK software (BIOLIB10 library). The equations for the Douglas-fir stands are derived from a study of Douglas-fir near Blue River, OR (Fujimori et al 1976) while the equations for other conifer species were taken from a group of similar studies, as described by Gholz et al (1979). The equations from BIOPAK divided total biomass estimates for each species into estimates of five separate components. Three of these components (dead branch, live branch, and foliage biomass) were combined to obtain an estimate of CBB. Estimates of the other two components (bole bark and bole wood biomass) were combined with the first three components to obtain AGB estimates for each tree.

The second group of allometric equations was taken from Jenkins et al (2003), which combines hundreds of studies throughout the United States to estimate forest biomass. CBB is estimated with allometric equations in the form of Eqn. 2. Equations for each species in the form of Eqn. 1 were combined with the CBB estimate to obtain AGB.

## Results

Test for Differences within First Quartile Plots
Due to the sampling design of this study, samples taken from all quartiles include both forest canopy as well as any shrub cover that were originally removed in the first quartile. The first portion of this analysis tests

- Whether a correlation exists between HPM metrics and both AGB and CBB for plots from the first quartile only.
- Whether estimates of plots with increased shrub cover are significantly different from plots with minimal shrub cover.


## Linear Relationship between HP Derived Metrics and $\operatorname{In}(A G B)$



Figure 3.5: Select HP metrics vs. In (AGB) for $1^{\text {st }}$ Quartile Plots

Linear Relationship between HP Derived Metrics and $\ln (C B B)$


Figure 3.6: Select HP metrics vs. $\ln (C B B)$ for $1^{\text {st }}$ Quartile Plots

Results, as seen in Figures 3.5 and 3.6, show that increased understory cover greatly reduces the correlation between biomass and HP metrics. Conversely, plots with little shrub cover resulted in a much higher correlation between HP metrics and forest biomass. However, there is still considerable variation for all HPM estimates, much of which is between forest types. An ANOVA test showed a significant difference of regression slopes between forest types, even after sites most affected by understory
were removed from the analysis. This indicates that best estimates of forest biomass with HP only occur when there is a minimal amount of understory. In addition, including components such as stand age and silvicultural treatments can further improve biomass estimations, which has been noted in previous studies (Zheng et al 2007). In addition, information about stand structure (such as stand density, total height, and vertical structure) would further improve biomass estimates. It is also possible that increasing the camera height from one meter to a height above the brush level would improve biomass estimates, but this may lead to camera leveling issues, and would also deviate from most other HP experiments, which use a camera height of about one meter.

## Test for Optimal Zenith Range of HPM4 metric for AGB and CBB estimations

In order to determine the optimal number and range of zenith rings to include in the analysis for HPM4, the number of rings were varied between 1 and 25 and compared. A graphical comparison of potential models is shown in Figures 3.7 and 3.8.


Figure 3.8: Comparison of Potential Models for Crown Branch Biomass



Results from this test show two separate phenomena that occur as the number of total zenith angles are increased. First, as the total number of zenith angles increase from 1 to about 12, MSE and AIC metrics for models tend to decrease. As the total number of zenith angles increase from 13 to 15 , MSE and AIC are much higher at low zenith angles but improve dramatically up to a point. This occurs because the top angles $\left(0^{\circ}\right.$ to $10^{\circ}$ in particular) have very high gap fractions for all plots, and there is little correlation between plots. However, MSE and AIC improve quickly as more angles are included and do not improve at all when the outermost angles are included. MSE and AIC are both near optimal values as the total number of rings approaches 15. A smaller zenith range from the normal is observed for best CBB estimation when compared to the range observed for best AGB estimation. Hence, HPM4 includes five gap fraction estimates from $0^{\circ}$ to $30^{\circ}$, which should most accurately represent CBB based on MSE and AIC criterion, while HPM4 includes 10 equally spaced gap fraction estimates from $0^{\circ}$ to $60^{\circ}$ as the best predictor of AGB.

## Model Fit for HP metrics and $A G B, C B B$ :

Model results from each HP metric showed that the LAI estimate (HPM7) was the best estimator when combined with a site indicator variable and mean stand height as an additional covariate. None of the metrics estimated either AGB or CBB well without additional covariates. As seen in Figures 3.9 and 3.10, all HP metrics had high variance and low fit. However, once other covariates are included, correlation coefficients improve for all metrics (Figure 3.11).

## Correlation for Select HP Metrics vs AGB



Figure 3.9: Exponential Relation between HP metrics and Above Ground Biomass


Figure 3.10: Exponential Relation between HP metrics and Crown Branch Biomass

## Summary of Regression Results

HPM 1-8 all have identical regression forms, except for HPM4, which has multiple covariates. The linear model between HP metrics and forest biomass is shown in Equation 10. Regression coefficients are listed in Tables 3.6 and 3.7. Only the regression coefficients for the models that include mean stand height are included, since models excluding mean stand height had much lower correlation.
$\ln (\mathrm{AGB}, \mathrm{CBB}(\mathrm{kg}))=\mathrm{A}+\Sigma(\mathrm{HPM}) * \mathrm{Bi}+$ Douglas-fir$* \mathrm{C}+\ln ($ height $) * \mathrm{D}^{*} \mathrm{I}_{\mathrm{DF}}$ (10)
where $I_{D F}$ is an indicator variable for Douglas-fir stands ( 1 for Molalla stands, and 0 for Burney stands). Standard errors are included below each corresponding coefficient.

|  | A | B1 | B2 | B3 | B4 | B5 | C | D |
| :---: | :---: | :---: | :--- | :--- | :--- | :--- | :--- | :---: |
| HPM1 | 8.64 | -2.82 |  |  |  |  | -0.56 | 0.01 |
|  | $(0.38)$ | $(0.22)$ |  |  |  |  | $(0.13)$ | $(0.12)$ |
| HPM2 | 9.40 | -3.59 |  |  |  |  | -0.54 | -0.37 |
|  | $(0.39)$ | $(0.30)$ |  |  |  |  | $(0.13)$ | $(0.12)$ |
| HPM3 | 9.47 | -5.52 |  |  |  |  | -0.44 | -0.47 |
|  | $(0.46)$ | $(0.59)$ |  |  |  |  | $(0.15)$ | $(0.14)$ |
| HPM4 | 8.56 | 0.07 | -0.82 | -0.66 | -1.76 | -1.00 | -0.50 | 0.01 |
|  | $(0.39)$ | $(2.38)$ | $(3.33)$ | $(3.09)$ | $(2.51)$ | $(2.55)$ | $(0.14)$ | $(0.13)$ |
| HPM5 | 7.71 | 0.12 |  |  |  |  | 0.07 | -0.48 |
|  | $(0.72)$ | $(0.07)$ |  |  |  |  | $(0.26)$ | $(0.22)$ |
| HPM6 | 6.81 | 0.13 |  |  |  |  | -0.27 | -0.40 |
|  | $(0.65)$ | $(0.03)$ |  |  |  |  | $(0.21)$ | $(0.20)$ |
| HPM7 | 6.36 | 0.83 |  |  |  |  | -0.32 | -0.24 |
|  | $(0.40)$ | $(0.07)$ |  |  |  |  | $(0.13)$ | $(0.11)$ |
| HPM8 | 5.74 | 0.82 |  |  |  |  | -0.20 | -0.27 |
|  | $(0.45)$ | $(0.08)$ |  |  |  |  | $(0.14)$ | $(0.14)$ |

Table 3.6: Crown Branch Biomass Regression Coefficients

|  | A | B1 | B2 | B3 | B4 | B5 | B6 | C | D |
| :---: | :---: | :---: | :---: | :---: | :---: | :--- | :--- | :--- | :---: |
| HPM1 | 7.57 | -3.41 |  |  |  |  |  | -0.83 | 1.03 |
|  | $(0.38)$ | $(0.21)$ |  |  |  |  |  | $(0.12)$ | $(0.11)$ |
| HPM2 | 8.64 | -4.68 |  |  |  |  |  | -0.88 | 0.58 |
|  | $(0.38)$ | $(0.33)$ |  |  |  |  |  | $(0.14)$ | $(0.13)$ |
| HPM3 | 8.78 | -7.39 |  |  |  |  |  | -0.79 | 0.44 |
|  | $(0.38)$ | $(0.61)$ |  |  |  |  |  | $(0.16)$ | $(0.14)$ |
| HPM4 | 8.55 | 0.03 | -0.62 | -0.05 | -0.98 | -0.73 | 0.78 | -0.04 | 0.69 |
|  | $(0.38)$ | $(0.70)$ | $(1.02)$ | $(0.65)$ | $(.084)$ | $(0.45)$ | $(0.44)$ | $(0.14)$ | $(0.11)$ |
| HPM5 | 6.39 | 0.20 |  |  |  |  |  | -0.16 | 0.40 |
|  | $(0.38)$ | $(0.06)$ |  |  |  |  |  | $(0.23)$ | $(0.19)$ |
| HPM6 | 5.18 | 0.17 |  |  |  |  |  | -0.57 | 0.53 |
|  | $(0.38)$ | $(0.02)$ |  |  |  |  |  | $(0.19)$ | $(0.18)$ |
| HPM7 | 4.76 | 1.04 |  |  |  |  |  | -0.56 | 0.74 |
|  | $(0.38)$ | $(0.06)$ |  |  |  |  |  | $(0.12)$ | $(0.12)$ |
| HPM8 | 4.15 | 0.96 |  |  |  |  |  | -0.37 | 0.70 |
|  | $(0.38)$ | $(0.07)$ |  |  |  |  |  | $(0.14)$ | $(0.11)$ |

Table 3.7: Above Ground Biomass Regression Coefficients

Correlation coefficients for each metric are summarized in Figure 3.11. HPM2, HPM4, and HPM7 had the highest correlation coefficient, while HPM5 and HPM6 showed the weakest correlation. Because of the weak correlation, HPM5 and HPM6 were not included in any validation models. HPM7 showed a positive correlation with both AGB and CBB, which indicated that as LAI increased, both AGB and CBB increase as well.
Figure 3.11: $R^{2}$ Adjusted Coefficients for Each HP Metric


## Validation of Regression Equations

In order to validate regression equations, twenty quartiles were randomly selected from the original data- 12 quartiles from Douglas-fir stands and 8 quartiles from mixed conifer stands for a validation model. Quartiles were used instead of plots to increase the number of data points. If quartiles were not used, there would only be a total of 15 points in the dataset, which would make it very difficult to draw any conclusions. Quartiles were used instead, at the risk of introducing a lack of independence in the dataset.

Each HP metric was used to predict AGB and CBB with the coefficients obtained in Table 3.7. The model that included average stand height was used in the validation model. Initial analysis showed that the predictive ability of the model was poor for plots with the most understory cover, so the points with the most understory cover were excluded from the validation model, but the points are still shown in Figures 3.12 and 3.13. Of all HP metrics, HPM7 had the highest predictive capability for AGB and CBB, while all other metrics tended to overestimate relatively low biomass and underestimate relatively high biomass, which is a common phenomenon noted in exponential models of biomass. Table 3.8 shows that HPM7 also has the least bias of all estimates for both AGB and CBB.


Figure 3.12: Validation of Select HP Metrics for Above Ground Biomass Estimation


Figure 3.13: Validation of Select HP Metrics for Crown Branch Biomass Estimation

Positive A values combined with B values $<1$ from most of the HP metrics again show the bias of most HP metrics when overestimating relatively low biomass and underestimating relatively high biomass for both AGB and CBB. The notable exception is HPM7, which appears to have the least bias of all HP metrics. Figure 3.14 shows that HPM4 had the least variance for CBB, while HPM7 had relatively low variance for both AGB and CBB , compared to other HP metrics.

$$
\begin{equation*}
\text { Predicted Biomass }=\mathrm{A}+\mathrm{B}^{*} \text { Actual Biomass } \tag{12}
\end{equation*}
$$

|  | CBB |  |  | AGB |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Metric | A | B | Adj. R^2 | A | B | Adj. R^2 |
| HPM1 | 242 | 0.71 | 0.87 | 1561 | 0.56 | 0.56 |
| HPM2 | 206 | 0.68 | 0.73 | 602 | 0.64 | 0.68 |
| HPM3 | 152 | 0.76 | 0.62 | -252 | 0.85 | 0.71 |
| HPM4 | 237 | 0.70 | 0.91 | 2930 | 0.25 | 0.38 |
| HPM5 | 1116 | -0.02 | 0 | 2876 | 0.34 | 0 |
| HPM6 | 1077 | -0.09 | 0 | 5918 | -6.47 | 0.17 |
| HPM7 | 28 | 0.98 | 0.80 | 138 | 0.91 | 0.80 |
| HPM8 | 130 | 0.87 | 0.76 | 992 | 0.72 | 0.63 |

Table 3.8: Regression Coefficients from Validation Models


Figure 3.14: Coefficient of Determination for Validation Models

## Allometric Equations

As expected, even though allometric equations approximated AGB well, the equations approximated CBB with much less reliability. This is due at least partially to the range of tree densities, heights, and diameters used between plots. Both the Jenkins and BIOPAK models clearly have less predictive power for CBB. Results are summarized in Figure 3.15 and Table 3.9.


Figure 3.15: Allometric Predictions of Forest Biomass for Hambone and Molalla Sites

| Model | Biomass Type | A | B | n | R^2 |
| :--- | :--- | ---: | ---: | :--- | :--- |
| Jenkins | CBB | 65 | 1.19 | 112 | 0.72 |
| Jenkins | AGB | 393 | 0.97 | 112 | 0.96 |
| BIOPAK | CBB | -15 | 0.97 | 112 | 0.65 |
| BIOPAK | AGB | 25 | 0.92 | 112 | 0.96 |

Table 3.9: Predictive Capabilities of Allometric Models

## Discussion and Conclusions

The regression models of HP metrics show that there is promise in using HP for estimating both AGB and CBB, especially with the HP estimation of LAI. However, there are several caveats. First, only canopy and vegetative structures that meet the LAI model assumptions are most accurate, which means that randomly distributed canopies with little understory are most closely modeled. Second, even for this small sample size, different forest types (forest age, stand density, etc) showed statistical differences, which means that including other stand characteristics reduces estimation variance. In order to predict both CBB and AGB more accurately, it is necessary to include at least one basic forest stand characteristic (mean stand height) as a covariate.

The metric with the highest predictive capability for both AGB and CBB was HPM7, which was the LAI estimate. Other metrics based on solely gap fraction models (HPM1, HPM2, HPM3) had similar correlation to HPM7 when creating a model, yet had less predictive ability. HPM4, which had the highest linear relationship to AGB and CBB in the original model, did not predict AGB or CBB well. Since a higher number of covariates were used to create HPM4 estimates, it appears that HPM4 is able to model a given set of data relatively well. One way to test this in future work would be to find the Variance Inflation Factors (VIF) for alternative models. If there is a relatively high number of VIF's $(>10)$, then there may be an issue of poor extrapolation, especially as the number of VIF's increase.

When the predictive model is used, it becomes obvious that stand structure differences between plots reduce the predictive capability of HPM4, even in similar stand types, so it is possible that the number of VIF's is high. Models with the worst correlation include those with single covariates created from logarithmic estimates of LAI. These metrics used constants to approximate clumping factors as well as foliage angle distributions, which led to relatively poor estimators and predictors of both AGB and CBB.

Results show that metrics that estimate canopy structure (such as LAI) are superior in modeling AGB and CBB, when compared to modeling AGB and CBB with simple gap fraction measurements. This indicates that the radiative transfer (RT) model of a forest canopy has at least some correlation to the amount of biomass within the canopy, and to a lesser extent, the total amount of biomass in the stand. It is expected that much variation will exist in modeling a highly heterogeneous forest canopy, when compared to other vegetative canopies (such as agricultural crops), which the RT model was originally intended to simulate (Campbell and Norman 1989).

The scope for the HPM7 (LAI) model has definite limitations, especially when estimating AGB. Three plots (DFL4, DFL5, and MCM4) were outliers for all HP metrics, and were not included in building the model, since Cook's distance was higher for these three plots. DFL5 and MCM4 had much lower crown/branch biomass but similar total biomass compared to other plots (Figure 3.2). Both plots were extreme outliers in all HP metric models and were removed (eight quartiles in total). In addition, the predictive model did not accurately estimate AGB or CBB for DFL4.

There are several potential reasons that HP failed to estimate biomass accurately for these three plots:

- Regressions are based on an exponential function, which can lead to overestimation for small values and underestimation for large values. A larger study with a broader range of biomass could increase the robustness of prediction. It is possible that a separate model for low biomass will be more accurate. It is also possible that another model (not exponential) will prove to be a better estimator of CBB and AGB. However, a better model was not found in this study.
- All HP metrics estimate PAI, not LAI. The LAI to PAI ratio is smaller for DFL5 and MCM4 (assuming LAI to PAI ratio is linearly related to crown/branch to total biomass ratio). This issue may be solved using more advanced measurement techniques (such as MVI) to separate PAI into LAI and WAI. However, the least squares estimate of LAI weights zenith angles so that smaller zenith angles are more important in estimating LAI (Montes et al 2007). Since smaller angles are less affected by woody biomass, LAI estimates should be less affected. Differentiating between branch wood and foliage may be difficult, but separating out boles should be relatively easier, given the suitable sensing technology. A previous study (Barclay et al 2000) showed that the contribution of WAI to PAI estimates appear to be minimal, but may introduce bias in estimates for mature unthinned stands with closed canopies.
- The final quartile of DFL5 and MCM4 remaining is the most serious outlier of the four quartiles, with the highest Cook's distance. For the last quartile, most of the original forest biomass within the plot has been removed, while the forest biomass for the area immediately surrounding the plot does not change. It is possible that the metric is not robust to plots with biomass of non-uniform horizontal distribution. This is corroborated from HPM7 estimates - when using the least squares method to estimate HPM7, these plots had the largest residuals after finding the optimal solution.
- DFL4 and DFL5 were subjected to different silvicultural treatments, compared to all other plots. These two plots were in a different area from the other DFL
plots, and appeared to have more canopy openings compared to the other DFL plots. Assuming that these two plots had less canopy closure, this could explain why these plots were outliers. Silvicultural treatments that affect canopy closure that lead to significantly different canopy structures violates an assumption of the radiative transfer model, which assumes homogeneous canopy structure.
- The effect of using quartiles, not plots, in the validation test is uncertain. This may also contribute as to why the HP metrics does not accurately estimate biomass.

Additionally, there are some difficulties associated with automating the image analysis procedure used in this study. The ISODATA classification method was most effective in separating canopy and sky, when visually comparing the ISODATA method to using a constant threshold for each image. However, categories had to be manually manipulated into the two main categories based on visual appearance. Most categories are simple to visually differentiate and assign, but if measurements were to be made on a larger scale, some kind of shape recognition algorithm would need to be implemented to efficiently allocate pixels to canopy or sky, which is beyond this particular study. When using multiple classifications, it is possible to combine a partial threshold technique for pixels within some of the classifications. For instance, pixels within a classification that tends to appear at the fringe of the canopy could have a smaller weighting when compared to pixels within denser portions of the canopy. However, it is not clear what weight should be used, so weighting was not attempted in this study.

Including sun angle as a covariate for the regression model for each HP metric did not improve model estimates. There are several potential causes for this increased variation:

- Cloud cover ranged from complete to none.
- The effect of sunlight on images was not necessarily a function of sun angle.
- Very low canopy cover for higher quartiles led to increased direct sunlight reaching the camera. This could lead to artificially high gap fraction measurements.

It is possible that including sun angle as a covariate would improve estimations if the above factors were more controlled or homogenous.

The BIOPAK and Jenkins models yielded similar estimates of AGB and CBB, but the Jenkins model had less variation than BIOPAK (using adjusted $\mathrm{R}^{2}$ as the statistical metric). Both BIOPAK and Jenkins models predicted both AGB and CBB relatively well compared to HP metrics. However, HP metrics provided estimates that were less variable than estimates based on BIOPAK or Jenkins.

This study indicates that if a more exact estimate of AGB is desired, allometric equations may provide the best estimate, but at a cost of more time intensive tree level timber cruising. In the plots for this trial, for example, it would have meant measuring up to 3000 stems per hectare for some of the sample plots. However, if accurate CBB estimations are needed, it may be more appropriate to use HP methods, depending on the forest canopy structure and amount of understory. It is recommended when using HP to estimate CBB to clear any understory surrounding the camera in order to get a more accurate estimate. Significant understory that appears within the top $30^{\circ}$ appears to affect CBB estimates, while a wider area must be cleared to estimate AGB.

There is potential for using a double-sampling strategy that combines both HP and allometric equations in timber cruising application. One potential strategy could use HP at all sample points within a stand, while detailed tree measurements on a
subsample of these points could supplement the HP measurements. This combination could provide both speed and accuracy in measuring and monitoring forest biomass.

Since the HP metric that best estimated AGB and CBB was the LAI estimate, it is important to consider other methods of deriving LAI. There are at least four commercial canopy analyzers capable of accurately measuring LAI (Bréda 2003). Two analyzers do not measure gap fraction sunfleck in the PAR waveband (SunSCAN, Delta-T Devices Ltd, Cambridge, UK; AccuPAR, Decagon Devices, Pullman, WA). The other two devices use gap fraction theory to estimate LAI (LAI2000, Li-Cor, Lincoln, NE; DEMON, CSIRO, Canberra, Australia). These tools use a model based on a negative binomial distribution rather than a Poisson distribution to estimate LAI. This model becomes less practical in a forest canopy, because calibration of FPAR is required both above and below a forest canopy for the LAI2000 (Strachan and McGaughey 1996). Multiple measurements at different times of day are required for the DEMON measurement tool (Lang and Yueqin 1986). It is possible that LAI estimates from one of these tools would be preferable to the more labor-intensive methods used in this study.

Strengths and weaknesses in the models based on the Poisson and binomial distributions could be leveraged to obtain improved estimates of LAI, which may improve biomass estimates as well. Models based on negative binomial and Poisson distributions can be used in conjunction to optimize LAI estimates (Nilson 1971), although negative binomial models introduce variables that are difficult to estimate with HP (Neumann et al 1989). Other studies (Bréda 2003) attempt to measure Photosynthetic Proton Flux Density (PPFD) from both above and below the canopy simultaneously to estimate gap fraction and more accurately estimate LAI, but this is difficult in a forest environment, especially in closed canopies. It appears that the Markov model developed from a Poisson distribution is currently the best model available for estimating forest canopy with a 2-D image (Montes et al 2007).

Future work will include analysis of lodgepole/ponderosa pine plots in the Pringle Falls Experimental Forest, OR, which should lead to improved understanding of the relative robustness of each HP metric, given other forest types.

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# CHAPTER 4: BIOMASS ESTIMATIONS FOR REGULARLY SPACED PONDEROSA/LODGEPOLE PINE PLOTS USING HEMISPHERICAL PHOTOGRAPHY 

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## Introduction

Forest biomass estimations have become an increasing concern for government agencies as well as private landowners, and the economic and environmental impacts of forest land management has become increasingly realized. Accurately estimating the spatial arrangement and density of forest biomass and landscape, regional, and national levels is a key to accurately identifying, estimating allocating and utilizing biomass.

Government agencies are interested in providing citizens with a reliable, relatively clean domestic energy source. The US Department of Agriculture (USDA) has released several reports showing the growing potential of biomass as an energy source (e.g., Perlack et al 2005). Regional reports, including a survey by the Oregon Forest Resources Institute (Lord et al 2006), identify forest land with high fire risk, and attempt to simultaneously solve three challenges from this forest land: restore forest health, find renewable energy alternatives, and provide economic stimulus to rural communities. Public and private landowners are also interested in accurately assessing the spatial arrangement and density of forest biomass in order to realize the optimal potential of economic utilization, fire and disease risk. Since total forest biomass is closely related to the carbon (C) accumulation of a forest, it is important to properly estimate biomass to assess carbon flux over time (Zheng et al 2007).

Currently, there are several methods used to determine forest biomass at a plot level, with varying degrees of speed and accuracy. One method commonly used is to measure the diameter of all trees within the plot, then use allometric equations to derive biomass estimates for tree components, including crown, branch, foliage, and bole biomass. These allometric equations are found by destructively sampling plots, and tend to be site and species specific (Gholz et al 1979). However, recent nationwide compilations of allometric equations have combined these specific studies
in order to derive generalized allometric estimates of biomass for many species within the United States (Jenkins et al 2003).

Another method of forest biomass estimation uses pipe model theory (Shinozaki et al 1964a; Shinozaki et al 1964b). This theory assumes that the basal area of each tree is linearly related to the sum of the sapwood area (at ground level) for a given plot. It also assumes that above ground biomass is linearly related to the sapwood area. Once regression coefficients are known for a given species/stand type, above ground biomass can be directly estimated from basal area estimates. Previous studies have verified a high correlation between basal area and above ground biomass (Shinozaki et al 1964a; Shinozaki et al 1964b). Application of models based on pipe model theory do not differ substantially from allometric relationships and suffer from the same weakness - the same amount of basal area and crown biomass held at widely differing average stand heights translates into large differences in biomass estimates.

As remote sensing technology has become more prevalent and more easily accessible, several techniques have been used to measure forest biomass (and other closely related stand metrics) at a plot level with remotely sensed data. There are several excellent overviews of the emerging importance of remote sensing in estimating forest canopy components (Zheng and Moskal 2009).

Linear relationships between metrics derived from hemispherical photography (HP), including LAI, have been shown to correlate with above ground biomass in a forest (Zheng et al 2007). The Zheng study showed that a linear relationship between LAI and AGB existed at a plot level, with an $R^{2}$ of 0.6 . However, the study also showed that LAI alone could not closely estimate biomass, partially due to variability of crown structure within and between plots. Other factors (such as average stand height or stand age) must be included in order to estimate above ground biomass more closely. It is unclear from previous studies how robust a similar model would be if there was
high variability between stand conditions, or if stands had artificial regular spacing between trees.

Once plot level biomass is known, it is possible to expand the biomass estimates to a regional or national scale with measurements taken from medium range ( 30 m pixel resolution) satellites (such as ETM + ). Reflection intensity at near infrared (NIR) and visible wavelengths can be used to estimate vegetative indices (e.g., Normalized Difference Vegetation Index) in order to estimate forest biomass (Zheng et al 2007).

## Metrics Based on Gap Fraction Measurement

Gap fraction is defined as the percentage of total gaps within the canopy, and is determined at a particular zenith angle. For hemispherical photography, the measured gap fraction is equivalent to the number of pixels at a particular zenith angle that are classified as gaps in the canopy. A pixel is defined as a gap if the radiation at a specific wavelength is higher than a minimum threshold of intensity. All pixels below this threshold are presumed blocked by the forest canopy, and are classified as canopy. The resulting gap fraction measurement is calculated
as $\frac{\text { pixels classified as gaps }}{\text { total number of pixels }} * 100 \%$.

Light that is ultimately measured by the camera sensor may come from several light sources (Cescatti 1997a; Cescatti 1997b), including

- Direct sunlight not affected by the canopy.
- Sunlight transmitted through one or more layers of foliage and branches within the forest canopy
- Sunlight reflected from foliage and branches
- A combination of reflected and transmitted sunlight within the forest canopy

All pixels brighter than a given threshold are defined as gaps, while pixels below this threshold are blocked by forest components.

HP metrics to be used in this study will come from previous studies that have already shown reasonable correlation to other stand characteristics. Several metrics are taken from a study by Keane et al (2005), which showed a high correlation between hemispherical photography measurements and canopy bulk density, when compared to other in situ measurements. Two measurements will come from the Lang-Xiang logaverage method (Lang and Yueqin 1986) of estimating leaf area index (LAI). Finally, the last two metrics used are taken from Montes et al (2007) study, which was used to estimate effective leaf area for a stand of Scots pine.

LAI has been utilized as a metric to estimate canopy architecture, which can be broken down into (a) foliage angle distribution and (b) general foliage spatial distribution, including clumping factors (Chen et al 1997). Foliar crown biomass is linearly related to LAI (Keane et al 2005). If it is assumed that branch biomass is proportional to needle biomass (Brown 1978; Keane et al 2005), it may be possible to find a linear relationship between LAI and crown biomass. This study will also create a model based on linear regression to test the accuracy and robustness of LAI (from HP measurements) in predicting forest biomass. This relationship does not seem as obvious, but it may still be possible to estimate total forest biomass given crown biomass, especially if other stand variables (such as average plot height) are included as covariates.

It is not possible to convert gap fraction measurements from hemispherical photographs directly into LAI. HP metrics cannot easily differentiate between tree canopy, shrubs, and tree boles, so it actually calculates Plant Area Index (PAI), which is the sum of LAI and Wood Area Index (WAI). The resulting PAI is often used as a surrogate for Leaf Area Index (Bréda 2003). Separation of PAI into LAI and WAI is
possible if a photographic instrument such as a multiband vegetation imager (MVI) is used (Kucharik et al 1997). An MVI can differentiate the reflective characteristics of tree boles and leaves using spectral signatures. No attempt is made in this study to separate PAI into LAI and WAI.

Assuming that gap fraction is equivalent to $\mathrm{I} / \mathrm{I}_{0}$,

$$
\begin{equation*}
P(\theta)=e^{-K(\theta)^{*} L} \tag{1}
\end{equation*}
$$

where $\mathrm{P}(\theta)$ is the gap fraction at average zenith angle $\theta$ and $\mathrm{K}(\theta)$ is the extinction coefficient of light in the forest canopy at zenith angle $\theta$, and L is the LAI of the forest canopy. It is assumed that $G(\theta) / \cos (\theta)=k(\theta)$.
$\mathrm{G}(\theta)$ has been modeled (Warren-Wilson 1963) for flat leaves, but this function is very difficult to estimate given a one-dimensional image of the canopy. If cross sections of phytoelements are assumed to be circular (a close assumption for needle foliage), then it may be assumed that $G(\theta)$ is a function of the normal to foliage element $(\delta)$ and the zenith angle $(\theta)$, which can be estimated with $\cos (\delta-\theta)$ (Montes et al 2007). $\delta$ is the zenith angle where incoming light is most attenuated per unit length, and is a function of canopy and foliage geometric features. It has been previously shown that $\mathrm{G}(\theta) \approx 0.5$ at zenith angle $57.5^{\circ}$ (Warren-Wilson 1963), regardless of the distribution of canopy leaf angle. Montes et al (2007) proposed that that $\mathrm{G}(\theta)$ could be estimated with the equation

$$
\begin{equation*}
G(\theta)=\frac{0.5}{\cos (57.5-\delta)} * \cos (\theta-\delta) \tag{2}
\end{equation*}
$$

It is well known that the Poisson model of Monsi-Saeki leads to underestimation of LAI, often $50 \%$ or more (Lang and Yueqin 1986). This underestimation is due to assumptions of the original model, which does not account for foliage clumping (Kucharik et al 1999). The model also does not weight the differences between gaps at different zenith angles within the canopy. Foliage clumping can be modeled by
converting the Poisson model of Monsi-Saeki into a Markov model, where the probability of contacting a layer is independent of contacting a layer above or below (Nilson 1971). Assuming the number of horizontal canopy layers is infinite, gap fraction can be estimated as

$$
\begin{equation*}
P(\theta)=e^{\left([-G(\theta) / \cos (\theta)]^{*} L_{1}^{*} \Omega_{0}\right)} \tag{3}
\end{equation*}
$$

where $\Omega_{0}$ is a clumping coefficient. The effective LAI, or $\mathrm{L}_{\mathrm{ef}}$, is now calculated as $\mathrm{L}_{\mathrm{ef}}$ $=\Omega_{0} * \mathrm{~L}$. If $\Omega_{0}$ is $<1$, foliage is clumped, while if $\Omega_{0}$ is $>1$, foliage is evenly distributed (not random). Accounting for clumping in this way has reduced underestimation of LAI to $15 \%$ in prior studies, while also decreasing estimation variation (Lang and Yueqin 1986). It is assumed that $\Omega_{0}$ includes clumping at both the foliage level as well as the shoot level. However, HP does not have the spatial resolution to resolve foliage at the shoot level. It is assumed that shoot level clumping is a constant between plots, which means that estimates are assumed to be biased, but will not have increased variance.

Other analyses (Bonhomme and Chartier 1972, Anderson 1981, Chen et al 1986, Wang and Miller 1987) have utilized this method, known as Campbell's inversion, to obtain LAI. In addition, recent studies (Mussche et al 2001) have shown that this method leads to underestimation of LAI, and suggest models based on other distributions (negative binomial, Markov) for more accurate estimation. However, these models require canopy characteristics not readily obtainable using hemispherical photography (Mussche et al 2001).

A constant clumping coefficient, $\Omega_{0}$, is used for all zenith angles (Montes et al (2007) proposed a function to estimate $\Omega(\theta)$ with a function that maximizes the clumping effect at small zenith angles.

$$
\begin{equation*}
\Omega(\theta)=\Omega_{0} * \cos ^{2}(\theta)+\sin ^{2}(\theta) \tag{4}
\end{equation*}
$$

This helps weight the clumping effects so that PAI is more heavily weighted at larger angles, and less weighted at smaller angles. This helps minimize the effect of WAI on LAI estimates (Fournier et al 1996). After foliage clumping is included in the model, gap fraction at each zenith angle can then be estimated.

$$
\begin{equation*}
P(\theta)=e^{-L_{1}{ }^{*}\left(\Omega_{0} \cos ^{2}(\theta)+G(\theta) \sin ^{2}(\theta)\right) / \cos (\theta)} \tag{5}
\end{equation*}
$$

At this point, $L_{1}, \Omega_{0}$, and $\mathrm{G}(\theta)$ can be solved simultaneously using iterative regression of least squares of this nonlinear function (Montes et al 2007). The range for $\theta$ is $0^{\circ}$ $90^{\circ}$, while the clumping index is expected to be less than one. Each image was divided into fifteen equally spaced zenith angles, and then the following objective function was minimized for each image to obtain $L_{1}$ and $L_{e f}$,

$$
\begin{equation*}
\min \left\{\sum_{i=1}^{15}\left[e^{-L_{1} *\left(\Omega_{0}{ }^{*} \cos ^{2}\left(\theta_{i}\right)+G(\theta) * \sin ^{2}\left(\theta_{i}\right)\right) / \cos \left(\theta_{i}\right)}-P\left(\theta_{i}\right)\right]^{2}\right\} \tag{6}
\end{equation*}
$$

where $\mathrm{P}(\theta)$ is HP estimated gap fraction. Montes et al (2007) also modeled estimates of LAI under moderate slopes, but this adjustment was not attempted in this study.

Simple gap fraction measurements do not account for total gap sizes (or clumping), which greatly affects leaf surface area (Lang and Yueqin 1986). Gap fraction also does not weight the differences between gaps at different zenith angles within the forest canopy.
A clumping index can be estimated by using a logarithmic ratio: $\Omega(\theta)$
$=\ln [P(\theta)] / \ln [P(\theta)]$, where $P(\theta)$ is the mean gap fraction over all azimuths and
$\ln [P(\theta)]$ is the logarithmic mean gap fraction of all azimuths within a particular zenith angle (Lang and Yueqin 1986). If there are no gaps, a gap equivalent to one pixel is
used to avoid zero gap fractions, which would lead to values of $\ln (0)$, which is undefined (van Gardingen et al 1999).
See Figure 4.1 for a graphical depiction of zenith angles and azimuths.


Figure 4.1: Hemispherical Image Divided into 5 Zenith Angles and 36 Azimuth Angles

Foliage biomass can be directly estimated from LAI using specific leaf area (SLA), where SLA is the dry weight of the leaf per unit area. Foliage biomass per unit area $=$ LAI*SLA, where LAI units are $\mathrm{m}^{2} / \mathrm{m}^{2}$ and SLA units are $\mathrm{kg} / \mathrm{m}^{2}$. However, SLA is not a constant within a forest canopy, and is dependent on variables such as previous silvicultural treatments, forest type, canopy height and light availability (Nobel et al 1975). It is a function of species, vertical and horizontal crown structure, crown shape, light intensity at the leaf surface, and a variety of other factors related to optimal canopy photosynthesis. Assuming that the biomass of limbs and branches is a linear
function of foliage biomass (Keane et al 2005), it may be possible to estimate the crown biomass if foliage biomass can be estimated.

## Limitations of Hemispherical Photography

HP measurements are not exact, and are limited by the equipment used (including camera spatial, radiometric, and spectral resolution and software), as well as weather conditions, time of day, canopy structure, ground slope, and a host of other factors. A 2001 study comparing a film camera configuration and a digital camera configuration (Nikon Coolpix 950 with FC-E8 fisheye lens) showed that color blurring in the digital pictures resulted in measurement errors in canopy gaps, edge detection, the ability to replicate results, and led to "blooming", especially near the zenith and in sunny conditions. However, black and white digital pictures tended to minimize abnormal chromatic effects. (Frazer et al 2001). In addition, XGA and VGA resolutions resulted in much lower canopy openness measurements when compared with uncompressed TIFF photographs. Frazer et al (2001) gives an excellent overview of limitations for the Nikon 950/FC-E8 lens combination, a configuration that is very similar to the configuration used in this project.

There have been several studies in the past that have measured LAI for regularly spaced trees, primarily in fruit orchards (e.g. Cohen and Fuchs 1987; Cohen et al 1997). However, these methods do not tend to use HP methods, and instead use other methods that use techniques that obtain direct sunlight, not diffuse sunlight. The models developed to estimate LAI from HP assume random distribution of canopy components, and are not as robust when canopy elements are distributed unevenly or uniformly.

This study will test the relationship between HP derived gap fraction measurements and not only above ground biomass (AGB), but also crown/branch/foliage biomass (CBB).
The analysis will consist of two parts. First, HP metrics and both CBB and AGB will be compared for the regularly spaced plots within this study area. Next, similar regression models previously derived from a site near Burney, CA with non-regular spacing will be used to test prediction capability of HP metrics between different sites and different spacing regimes.

## Methods

Study Site
A total of 39 plots were photographed in mid-October 2007 at two sites. Both sites are about 45 km southwest of Bend, in the Pringle Falls Experimental Forest, Deschutes National Forest. One site was located on Pringle Butte, where several spacing trial studies have been conducted (Garber and Maguire 2004; Garber and Maguire 2003; Seidel 1989). The other site was located near Twin Lakes, which was within the Bend Ranger District of the Pringle Falls Experimental Forest.

Thirty plots were located on Pringle Butte, which is located on a northwest facing slope at an elevation of $1400 \mathrm{~m}\left(43^{\circ} 44^{\prime} \mathrm{N}, 121^{\circ} 37^{\prime} \mathrm{W}\right)$. Ground slope for these plots ranged from $10-20 \%$, averaging $15 \%$ (Garber and Maguire 2003; Seidel 1989). The experimental design for these plots was a randomized split-plot design, where the 30 plots were divided into five initial spacing trials: $6,9,12,15$, and $18 \mathrm{ft}(1.8,2.7,3.7$, 4.6 , and 5.5 m ), with six plots for each spacing. Species composition for each plot was split into three factors: pure Ponderosa pine (Pinus ponderosa), pure lodgepole pine (Pinus contorta), or a 50:50 mix of the two species (Garber and Maguire 2003).

The remaining nine plots, part of a levels-of-stock study, were located near Twin Lakes. Species composition was pure lodgepole pine. These plots were part of a thinning experiment imposed on a naturally regenerated stands, with five different thinning regimes.

## Biomass Estimation

For each plot, an HP image will be recorded and analyzed. The following HP metrics will be extracted and applied for each plot:

- HPM1: Gap fraction for zenith angle $\left(0^{\circ}-30^{\circ}\right)$
- HPM2: Gap fraction for zenith angle $\left(0^{\circ}-60^{\circ}\right)$
- HPM3: Gap fraction for zenith angle $\left(0^{\circ}-90^{\circ}\right)$
- HPM4: Gap fraction of zenith angle $\left(0^{\circ}-90^{\circ}\right)$, broken into 12 equally spaced covariates.
- HPM5: Log-weighted average of gap fraction for zenith angle $\left(0^{\circ}-30^{\circ}\right)$, with 36 equally spaced azimuth sections used in calculating a gap fraction log average.
- HPM6: Log-weighted average of gap fraction for zenith angle $\left(0^{\circ}-90^{\circ}\right)$, with 36 equally spaced azimuth sections used in calculating a gap fraction log average.
- HPM7: Lef estimation (from Montes et al 2007 LAI least squares estimation )
- HPM8: $\mathrm{L}_{1}$ estimation (from Montes et al 2007 LAI least squares estimation)
- HPM9: $\ln$ (average height of all trees within the plot) - no HP measurement

All trees within each plot had detailed measurements from previous studies (Garber and Maguire 2004) that were used to estimate plot biomass for this study. Available data for each tree from previous studies included species, DBH, total height, and
crown height. The most recent tree-level measurements for the Pringle Butte plots were taken in 2004, while the most recent measurements for the Twin Lakes plots were taken in 2007. It is assumed that the biomass accumulation of the stand is minimal between the last available measurements and the time when the photographs were taken.

Bole biomass was estimated using a variable exponential taper model based on a study previously conducted on the Pringle Butte site (Garber and Maguire 2003). Separate taper models were used for ponderosa and lodgepole pine. With the taper model, the diameter inside bark (DIB) taper was estimated at 100 evenly spaced points along the stem, and each tree was divided into 100 sections. Once taper was modeled, the area at each point and volume of each section was estimated, assuming that the volume of each section was a frustum of a paraboloid.

Once bole volume was estimated, the dry biomass of each bole was found by estimating the specific gravity for each tree species. The specific gravity of each tree bole was assumed constant for trees in all plots. Specific gravity for lodgepole pine was approximated as 0.41 , while ponderosa pine was approximated as 0.40 , assuming oven dry weight and $12 \%$ moisture content (Hoadley 2000). Bole bark biomass was estimated using allometric equations from studies previously conducted in South Central Oregon (Gholz et al 1979; Little and Shainsky 1992). All calculations were conducted using Excel 2003.

Foliage biomass and branch biomass were calculated separately based on species specific equations (currently unpublished) developed from detailed studies of the Pringle Butte area (Maguire 2009). These equations were based on linear regression models that used covariates including DBH, total tree height, and crown height. Foliage biomass and branch biomass were summed to obtain a CBB estimate. Next, the bole biomass estimate and CBB estimate were combined to estimate AGB.

As shown in Figures 4.2 and 4.3, the estimated AGB tended to decrease as the spacing increased for plots, while CBB did not show as clear a trend between spacing trials. In Figures 4.2 and 4.3, the areas of the Twin Lakes plots are equal to each other, and estimated. Hence, the same expansion factor for all Twin Lakes plots was applied, and the AGB and CBB density of each plot is shown in Figures 4.2 and 4.3. In one of the Twin Lakes plots, there were multiple trees with DBH greater than the interpolation capability of the exponential function obtained from the spacing trial plots used to estimate CBB. This single plot from Twin Lakes was not included when building the regression model.

In the original Pringle Falls experiment, the number of trees per plot varied with tree spacing (Garber and Maguire 2004; Garber and Maguire 2003; Seidel 1989). More trees per hectare were planted in plots with closer spacing and the plot size was smaller for plots with closer spacing. An expansion factor was applied to all plots in the spacing trial to account for the difference between plots, and is shown in Table 4.1. The Twin Lakes plots did not include an expansion factor, but an indicator variable was used to differentiate those plots from the spacing trial plots.

| Spacing |  | Planted Trees | Plot Size |  | Expansion Factor |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| ft | m |  | acres | hectares | per acre | $\begin{gathered} \hline \text { per } \\ \text { hectare } \\ \hline \end{gathered}$ |
| 6 | 1.83 | 130 | 0.107 | 0.043 | 9.31 | 22.99 |
| 9 | 2.74 | 88 | 0.164 | 0.066 | 6.11 | 15.09 |
| 12 | 3.66 | 60 | 0.198 | 0.080 | 5.04 | 12.45 |
| 15 | 4.57 | 49 | 0.253 | 0.102 | 3.95 | 9.76 |
| 18 | 5.49 | 49 | 0.364 | 0.148 | 2.74 | 6.78 |

Table 4.1 Expansion Factors for Plots with Different Spacing


Figure 4.2: Above Ground Biomass Estimation by Plot Spacing ( $T=$ Twin Lakes)


Figure 4.3: Crown Branch Biomass Estimation by Plot Spacing ( $T=$ Twin Lakes)

## Photograph Analysis

Digital photographs of each plot were taken with a Nikon Coolpix 950 and an FC-E8 Fisheye lens. The camera/lens configuration was supplied by Regent Instruments, who also provided a matching leveling mount and the "Winscanopy Basic 2006" version of specialized gap fraction analysis software. Regent Instruments verified the lenscamera configuration, since each lens/camera combination must be manually checked.

Image radius is approximately 370.9 pixels. This lens will result in a small yet significant distortion (Frazer et al 2001).

Many of the images were affected by direct sunlight, which is undesirable when using hemispherical photography - diffuse lighting, such as on a cloudy day, is preferred (Kucharik et al 1997). However, limiting use of HP to these lighting conditions is impossible if this method is to be applied by private/public landowners on a larger scale. Most of the photographs in this analysis were taken in sunlit conditions to find whether gap fraction can still be extracted from a photograph. In order to improve each image, the following procedure was empirically developed and applied to all images, using the software packages listed:

Photoshop CS3 (Adobe):

- Application of a noise filter, which reduces distortion seen along the margins of cloud cover, tree boles, and sky with abrupt color gradients. This filter also helped reduce the impact of the high pass filter along borders within the image with sharp color contrast.
- Application of a high pass filter, with a $3 \times 3$ kernel used to sharpen the images, using settings found to be work best for HP images (Kucharik et al 1997).
ENVI 4.5 (ITT Visual Information Systems)
- Creation of an orthogonally transformed image between the three color bands, using Principle Components Analysis (PCA), as described by Joliffe (2002).
- Separation of each image into 15 classes, using an ISODATA unsupervised classification method (Richards and Jia 2006). The minimum threshold difference between classes was set to two after empirical testing. The algorithm usually converged after four iterations.
- Manually allocate each of these 15 classes into one of two groups: sky or canopy. A given class was not consistently allocated to a specific group from image to image, so each image was manually checked.

Photoshop CS3 (Adobe):

- Analyze each photograph individually to check for groups of misallocated pixels. Often tree trunks are the brightest objects in the image, and must be individually allocated as canopy. Following this analysis, each pixel is now either white (sky) or black (canopy).

Winscanopy Basic 2006 (Regent Instruments):

- Each image is divided into 36 azimuthal regions (for logarithmic averaging) and 12 zenith regions. The output of the analysis is a gap fraction for each zenith/azimuth section.

Normally, the most difficult pixels to classify correctly are those within a brightly lit canopy, or along woody branches/stems. The relative brightness between sky and brightly lit canopy is difficult to differentiate with the visible light spectrum, while stems tended to have wide color variation, and many reflected brightly, depending on the sun angle and stem location. Much of the variation would likely be reduced if sensors using NIR wavelengths were used in combination with visible light wavelengths.

## Model Analysis

Gap fraction output from Winscanopy Basic was input to Excel 2003 to calculate all HP metrics. Linear modeling, statistical analysis, and all plots were created from scripts using the R statistical software package. Adjusted correlation coefficients were used when testing the correlation of HP metrics with multiple covariates (such as site or average stand height).

To create the linear models based on data from the Pringle Falls site, the 39 original plots were subdivided into 28 plots for the original model, 10 plots for validation, and one plot removed due to biomass overestimation.

## Results

None of the HP metrics were highly correlated with either above ground biomass or crown/branch biomass; all metrics had adjusted $\mathrm{R}^{2}<0.6$. Correlation coefficients for most HP metrics were approximately 0.35 for crown/branch biomass and 0.55 for total above ground biomass. Figures 4.4 and 4.5 plot the linear correlations between HP metrics and biomass. The figures show that each metric is a poor estimator of either AGB or CBB when used as the only model covariate. Correlations for all metrics improved when including an additional indicator variable for location (Pringle Butte vs. Twin Lakes), even though the sites were in relatively close proximity to each other. When including mean stand height as a covariate, the correlation coefficient improved moderately for most metrics (Figure 4.6). However, stand height was used to estimate forest biomass - it is unclear how much of a confounding factor tree height may be when using it as an estimator for both actual biomass and estimated biomass. HMP9, which included only mean stand height and location as covariates, achieved the highest fit when compared to the other models.

## Exponential fit for Select HP Metrics vs AGB



Figure 4.4: Select HP Metrics vs. Above Ground Biomass

## Exponential fit for Select HP Metrics vs CBB



Figure 4.5: Select HP Metrics vs. Crown Branch Biomass

HP metrics had somewhat lower correlation fits for CBB. HPM1 and HPM2 showed fit improvement when mean stand height was included as an additional covariate.

HPM1-3, 5-8:

$$
\begin{equation*}
\ln (\text { Biomass })=\left(\mathrm{A}+\mathrm{HPM}^{*} \mathrm{~B} 1+\text { Site } * \mathrm{C}\right) \tag{7}
\end{equation*}
$$ with no height covariate

$\ln ($ Biomass $)=\left(\mathrm{D}+\mathrm{HPM}^{*} \mathrm{E} 1+\right.$ Site $^{*} \mathrm{~F}+\ln ($ mean_height $\left.) * \mathrm{G}\right)$,
with height covariate

HPM4:

$$
\begin{align*}
\ln (\text { Biomass })= & \left(\mathrm{A}+\Sigma \mathrm{HPM}^{*} \mathrm{Bi}+\mathrm{Site}^{*} \mathrm{C}\right) \\
& \text { where } i=1^{s t}, 2 n d \ldots 12^{\text {th }} \text { Zenith Ring }  \tag{9}\\
\ln (\text { Biomass })= & \left(\mathrm{D}+\mathrm{HPM} * \mathrm{Ei}+\mathrm{Site}^{*} *+\ln (\text { mean height }) * \mathrm{G}\right), \\
& \text { with height covariate } \tag{10}
\end{align*}
$$

HPM9:
$\ln ($ Biomass $)=\left(\mathrm{D}+\right.$ Site $^{*} \mathrm{~F}+\ln ($ mean height $\left.) * \mathrm{G}\right)$, with height covariate

Tables 4.2 and 4.3 show model coefficients for AGB and CBB, respectively, while Figure 4.6 compares correlation coefficients between models. Most of the HP metrics were not statistically significant after including the height covariate. Coefficients are only included in Tables 4.2 and 4.3 when the HP metric's coefficient is statistically significant ( $\mathrm{p}<=0.05$ ). Only the statistically significant coefficients for HPM4 are shown in Tables 4.2 and 4.3, but all coefficients were used in the validation model. Adjusted $\mathrm{R}^{2}$ values are shown for HP metrics without height as a covariate for all HP metrics. Adjusted $\mathrm{R}^{2}$ values are also included for HP metrics when height is statistically significant. Standard errors are included in parentheses immediately underneath each coefficient.

|  | A | B1 | B2 | B6 | Adj. <br> $R^{2}$ | $C$ | C | E 1 | F | G | Adj. <br> $R^{2}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| HPM1 | 12.43 | -0.85 |  |  | 0.21 | 0.16 |  |  |  |  |  |
|  | $(0.15)$ | $(0.29)$ |  |  |  | $(0.11)$ |  |  |  |  |  |
| HPM2 | 12.75 | -2.15 |  |  | 0.54 | 0.17 |  |  |  |  |  |
|  | $(0.14)$ | $(0.38)$ |  |  |  | $(0.08)$ |  |  |  |  |  |
| HPM3 | 12.73 | -3.93 |  |  | 0.56 | 0.24 |  |  |  |  |  |
|  | $(0.13)$ | $(0.66)$ |  |  |  | $(0.08)$ |  |  |  |  |  |
| HPM4 | 12.68 | 0.39 | -1.49 | -2.30 | 0.66 | 0.15 |  |  |  |  |  |
|  | $(0.13)$ | $(0.31)$ | $(0.68)$ | $(0.75)$ |  | $(0.07)$ |  |  |  |  |  |
| HPM5 | 11.95 | 0.04 |  |  | 0 | 0.09 |  |  |  |  |  |
|  | $(0.15)$ | $(0.10)$ |  |  |  | $(0.12)$ |  |  |  |  |  |
| HPM6 | 11.64 | 0.04 |  |  | 0.02 | 0.10 | 13.97 | 0.02 | -0.95 | 0.88 | 0.12 |
|  | $(0.26)$ | $(0.03)$ |  |  |  | $(0.12)$ | $(1.21)$ | $(0.03)$ | $(0.48)$ | $(0.41)$ |  |
| HPM7 | 11.32 | 0.37 |  |  | 0.47 | 0.20 |  |  |  |  |  |
|  | $(0.14)$ | $(0.07)$ |  |  |  | $(0.09)$ |  |  |  |  |  |
| HPM8 | 11.19 | 0.48 |  |  | 0.52 | 0.24 |  |  |  |  |  |
|  | $(0.15)$ | $(0.09)$ |  |  |  | $(0.09)$ |  |  |  |  |  |
| HPM9 |  |  |  |  |  |  | 14.43 |  | -1.07 | 0.97 | 0.14 |
|  |  |  |  |  |  |  | $(1.02)$ |  | $(0.45)$ | $(0.39)$ |  |

Table 4.2: Coefficients of Linear Regression for $A G B$

|  | A | B 1 | B 5 | B 6 | Adj. <br> $R^{2}$ | C | D | F | G | Adj. <br> $R^{2}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| HPM1 | 9.47 | 0.74 |  |  | 0.36 | -0.65 |  |  |  |  |
|  | $(0.23)$ | $(0.43)$ |  |  |  | $(0.16)$ |  |  |  |  |
| HPM2 | 9.54 | 0.89 |  |  | 0.32 | -0.63 |  |  |  |  |
|  | $(0.28)$ | $(0.77)$ |  |  |  | $(0.16)$ |  |  |  |  |
| HPM3 | 9.86 | -0.05 |  |  | 0.29 | 0.59 |  |  |  |  |
|  | $(0.27$ | $(1.40)$ |  |  |  | $(0.17)$ |  |  |  |  |
| HPM4 | 9.35 | -0.37 | 0.85 | -0.67 | 0.31 | -0.68 |  |  |  |  |
|  | $(0.30)$ | $(0.73)$ | $(2.14)$ | $(1.79)$ |  | $(0.18)$ |  |  |  |  |
| HPM5 | 10.11 | -0.18 |  |  | 0.34 | -0.62 |  |  |  |  |
|  | $(0.20)$ | $(0.13)$ |  |  |  | $(0.16)$ |  |  |  |  |
| HPM6 | 10.04 | -0.02 |  |  | 0.30 | -0.60 |  |  |  |  |
|  | $(0.37)$ | $(0.04)$ |  |  |  | $(0.17)$ |  |  |  |  |
| HPM7 | 9.94 | -0.05 |  |  | 0.29 | -0.61 |  |  |  |  |
|  | $(0.27)$ | $(0.14)$ |  |  |  | $(0.17)$ |  |  |  |  |
| HPM8 | 9.90 | -0.03 |  |  | 0.29 | -0.61 |  |  |  |  |
|  | $(0.31)$ | $(0.18)$ |  |  |  | $(0.18)$ |  |  |  |  |
| HPM9 |  |  |  |  |  |  | 8.15 | -1.21 | 0.75 | 0.35 |
|  |  |  |  |  |  |  |  |  | $(-$ |  |
|  |  |  |  |  |  |  | $(1.51)$ | $(0.66)$ | $1.21)$ |  |

Table 4.3: Coefficients of Linear Regression for CBB


Figure 4.6: $R^{2}$ Adjusted Coefficients for Linear Models of HP Metrics

## Validation:

All HP metrics were relatively poor predictors of AGB. Correlation between CBB and HP metrics was significantly higher for most metrics, especially HPM1, HPM2, and HPM4. Only the metrics with the best fit (HPM2, HPM4, HPM7, and HPM9) were in the following validation. HPM9, which estimates biomass based solely on mean stand height, was also included to compare HP metrics to a stand-based metric. Figure 4.7 graphically depicts the predicted AGB and CBB from HP metrics compared to the estimated biomass for each plot.


Figure 4.7: Predicted Biomass for Select HP Metrics vs. Estimated AGB \& CBB (kg/plot)

As seen in Figure 4.5, without including additional covariates, none of the HP metrics estimated either AGB or CBB well. Including mean stand height and site differences as additional covariates appeared to improve validation results for AGB, but did not improve to improve validation results for CBB. For each metric used in Figure 4.5, a linear model was created to compare predicted vs. estimated biomass, as shown in

Table 4.4. The following table showed that all metrics tended to overestimate when biomass was relatively low and underestimate when biomass was relatively high. It appears that HPM4 may be the best predictor for both AGB and CBB by combining the bias and variance of all predictors. However, all metrics have clear bias. In order to consider how precise and unbiased that the validation model is, Freese's test (e.g., Gregoire and Reynolds 1988; Robinson and Froese 2004) was considered and applied to this study. Freese's test showed a bias for each HP metric.

$$
\begin{equation*}
\text { Predicted Biomass }=\mathrm{A}+\mathrm{B} * \text { Estimated Biomass } \tag{10}
\end{equation*}
$$

|  | AGB |  |  | CBB |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Metric | A | B | Adj. R^2 | A | B | Adj. R^2 |
| HPM2, no height | 42010 | 0.69 | 0.3 | 1630 | 0.83 | 0.15 |
| HPM4, no height | 29890 | 0.77 | 0.58 | 5020 | 0.76 | 0.55 |
| HPM7, no height | 39930 | 0.68 | 0.31 | 4170 | 0.90 | 0.62 |
| HPM6, with height | 43080 | 0.66 | 0.15 | 3470 | 0.39 | 0.08 |
| HPM9 | 34040 | 0.73 | 0.35 | 7470 | 0.71 | 0.60 |

Table 4.4: Regression Coefficients from Validation Model


Figure 4.8: RMSE (kg/ha) for Validation Models

From the validation model, it is clear that no plot-based metric is a very good predictor of either AGB or CBB when compared to all derived HP metrics for this study. However, using HPM4 and mean stand height in combination resulted in a better fit for AGB, while using HPM4 without mean stand height is a better fit for CBB.

## Comparison to Previous Model

Models based on HP metrics have already been created in previous trials (Hambone study), based on destructively sampling predominantly ponderosa pine plots near Burney, CA. These models from previous trials were tested against biomass estimates from this study to determine how robust the previous models are when used for different sites. Estimates based on models built from HP estimates of that study have low predictive ability for biomass estimations for these sites (Figures 4.9 and 4.10).


Figure 4.9: Validation for Model Developed from Hambone Study (AGB) - kg/plot


Figure 4.10: Validation for Model Developed from Hambone Study (CBB) - kg/plot

The AGB predictions were all clearly biased, and tended to underestimate the actual biomass derived from destructive sampling. The CBB predictions also tended to underestimate actual biomass, but to a lesser degree. Neither AGB nor CBB were predicted well based on the models created from the prior study.

## Discussion/Conclusion

Linear models from this study comparing HP metrics to AGB and CBB showed that moderate changes in stand structure species, spacing, and a variety of other factors that affect crown structure greatly affect the predictive ability of the model. If hemispherical photography is to be used when estimating biomass for multiple stands, it is recommended that a baseline regression model is established for each stand type, and that key covariates are then included that differentiate between stand types. In addition, other measurement techniques may result in improved estimates of LAI when compared to HP estimates.

It is possible that gathering a large database of LAI estimations from a wide range of forest types would provide better predictions of biomass for a stand. However, HP methods are not recommended for all forest types, and it appears that separate models should be created for stands with regular spacing and stands with irregular or natural spacing. Other measurement tools that determine canopy structure in three dimensions, as opposed to HP (which estimates canopy structure from a twodimensional image), may improve LAI estimates by improving spatial information of the forest canopy.

Much of this work assumes that LAI alone is a relatively strong predictor of both CBB and AGB. However, LAI is limited when estimating the complex dynamics within a forest canopy, including the dynamics of foliage biomass, branch biomass, and bole biomass over the course of stand development. Without additional covariates to define stand structure (such as age or top height), the applicability of a linear regression model between LAI and biomass is greatly reduced.

Many studies have shown a moderate correlation $\left(\mathrm{R}^{2}>0.6\right)$ between LAI and AGB. Previous models of AGB and CBB built using the same methods for this study have shown a relatively higher correlation between LAI and AGB, yet estimated LAI from this plot is not highly correlated with AGB. There are several potential reasons for the discrepancy for these particular sites, with three related to the tree spacing:

- The trees from this study were regularly spaced, not randomly spaced, which violates assumptions for the Poisson-based radiative transfer model used to estimate LAI. It is possible to use another radiative transfer model, but it is difficult to implement with HP.
- In most of the plots, the center of the image was dominated by one or two trees, since the spacing was very wide when compared to stands from previous studies conducted in Douglas-fir plantation (Molalla, OR) and mixed-conifer plantation (Hambone, CA). This means that the HP metric for the entire plot was greatly affected by the vertical and horizontal foliage distribution and crown structure, height, crown shape, and foliage from a single tree. This leads to high variance between plots with similar biomass.
- For plots with wider spacing, the crown structure of each tree would cover fewer pixels than plots with more compact spacing. This leads to further bias, since trees further apart lead to lower gap fractions, but increased spacing is positively correlated to AGB.
- In general, increasing spacing is positively correlated to increased CBB and AGB of a given plot. However, increased spacing is also positively correlated with increasing gap fractions in the center of the photograph. It is possible that the site is not fully occupied, and that crown closure has not occurred in some or all plots.

The first point above violates a major assumption of Beer's Law, which is a key to the radiative transfer model used to calculate LAI. When using the Montes et al least
squares method to obtain $L_{\text {ef }}$, a $\Omega_{0}>1$ was consistently found for each plot. This indicates that the canopy cover could be uniformly spaced, not randomly spaced, which is an assumption made when calculating LAI. It could also indicate a greater degree of clumping at the scale of individual trees, but increased gaps between trees, especially if crown closure has not yet been reached. This nonrandom spacing is likely the reason that HPM1, HPM2, and HPM3 are poor predictors as well.

The last point was most easily seen by analyzing the relationship between AGB and the $\mathrm{L}_{\text {ef }}$ (HPM7) estimation. It is expected that HPM7 and CBB be positively correlated, since LAI should increase as biomass increases, and they are noted as positively correlated for this study. Still, the clumping factor used in obtaining LAI for HPM7 is greater than 1, which implies that LAI estimations are not accurate. It is quite possible that the model fit would improve if accurate LAI measurements were taken. Since LAI should also be correlated with basal sapwood area, it is expected that LAI should increase as CBB increases, which is observed in this study.

Little of the variation seen in the model is due to error in the tree-level biomass estimations. Tree-level biomass estimations for this study were based on site-specific regression models with sampling and equations based on crown responses to specific spacing. This should make both AGB and CBB estimates unusually robust when compared to simple allometric models (such as Jenkins or BIOPAK) based simply on DBH.

As noted in previous studies near Molalla, OR and Hambone, CA, there are limitations in defining and separating pixels using a camera with three wavelengths all in the visible light spectrum. It is suggested in future studies to use a measurement tool with infrared capabilities, which would provide more distinct differences between bands. An orthogonal image transformation should provide a higher contrast for the image, making it easier to classify pixels. It should also allow the user to subdivide canopy
pixels into foliage and woody biomass, based on the difference in wavelength reflectance.

It is possible that an accurate measurement of LAI would result in a model with better linear fit for both AGB and CBB. Within a limited range of stand structures (such as stand density), LAI could be an acceptable measure of AGB and CBB. However, without additional covariates, LAI estimates are limited. It is unclear from this study whether partitioning pixels into LAI and WAI would improve estimates of AGB and CBB. A previous study (Barclay et al 2000) showed that the contribution of WAI to PAI estimates appear to introduce minimal bias, but may introduce bias in estimates for mature unthinned stands with closed canopies.

Unfortunately, when using HP, it is not possible to accurately estimate LAI for the Molalla and Hambone trials. However, other remote sensing technology, such as ground-based LiDAR or aerial LiDAR, has been used to estimate LAI (Zheng and Moskal 2009), and may have produced more accurate estimates of LAI for these two trials. The final recommendation from this study when estimating biomass from stands that have regular spacing is that forest biomass density is better estimated through allometric equations or with estimations based on pipe-model theory. Another alternate recommendation is to use another tool to estimate LAI, and then build a model based on LAI.

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## CHAPTER 5: SUMMARY AND CONCLUSIONS

The data collection from the three study sites along with the detailed image analysis of hemispherical photographs combine to form the basis of this dissertation, which closely analyzes the potential of hemispherical photography for various forest types under various atmospheric conditions. There has been much research recently invested in estimating not only forest biomass, but also several closely related forest stand parameters, including LAI, NPP, and crown closure. Research of remote sensing techniques for forest biomass estimation has been expanding for both ground-based and aerial sensors.

This particular research helps analysts to understand the scope of inference and optimal forest types when using hemispherical photography when measuring both above ground biomass and crown biomass. This study synthesizes careful image analysis with an understanding of radiative transfer models that have been developed over the past few decades for plant canopy analysis. There are several conclusions that can be made from this study, all of which point to the potential of hemispherical photography in measuring forest biomass given uniform conditions, but also reveal significant limitations, particularly when canopy is obscured by shrub understory or when gaps in the canopy are not randomly spaced.

First, Chapter 2 summarizes the results of forest biomass estimates with hemispherical photography for a commercial Douglas-fir plantation. The analysis showed significant limitations of gap fraction estimations. While a linear model showed a relatively good fit for most plots ( $\mathrm{R}^{2} \approx 0.8$ ), one plot (DFL5) was a serious outlier. Further examination showed that this plot was not significantly different from other plots in a similar age group. This indicates that other factors more difficult to model, such as storm
breakage, silvicultural treatments, or other factors that significantly affect biomass are not detected with hemispherical photography.

Next, Chapter 3 expanded the model developed in Chapter 2 to include not only multiple forest types but also more accurate estimates of LAI, which is a key estimator of crown biomass. Several transformations of gap fraction measurement were compared to forest biomass. The metric that best estimated forest biomass was an estimate of LAI that used a least squares fit along multiple zenith angles to solve simultaneously for leaf angle distribution, clumping factor, and the estimate of LAI without accounting for clumping.

Another model was created based on gap fraction at several zenith angles, each as a covariate, to determine if a one-dimensional estimate of the forest canopy was sufficient to estimate biomass. A linear model showed the highest model correlation, but the predictive model was poor, indicating that heterogeneity between plots, even within similar forest stands introduced too much variation to sufficiently model biomass based on gap fraction alone. The final conclusion when comparing potential HP metrics was that a metric that attempts to model the three-dimensional canopy structure has the best predictive ability, while metrics based on purely onedimensional measurements may have high correlation coefficients, but have poor predictive capability.

Based on a thorough analysis, there are also several other stand conditions that may lead to highly inaccurate estimates. First, plots with more understory and brush (such as vine maple) led to underestimates of gap fraction and higher estimates of LAI. This does not necessarily mean that LAI estimates are inaccurate, but it indicates that high brush LAI does not necessarily indicate significantly increased overall forest biomass. This problem could be easily dealt with by clearing underbrush surrounding the camera before taking measurements. It is possible that elevating the camera would
decrease the effect of understory on LAI estimates, but this would also lead to logistical issues, such as camera leveling and the inability to look physically through the camera viewfinder, and would also decrease the field of view when detecting gaps at larger angles. In addition, it would lead to problems in uniform measurements when estimating LAI - all plots would need to be measured at an elevated height, regardless of understory cover. Finally, other HP studies measure LAI from heights similar to this study - adjusting the camera height to reduce the impact of shrub cover deserves further research.

Second, the biomass for three specific plots was significantly overestimated. The exact reason for this overestimation was not apparent, which becomes a troubling aspect to deal with in future research or when using this technique for practical application. The plots that were overestimated tended to be taller, older stands, with more vertical structure than typical stands, and it was unclear if these plots were subjected to different silvicultural treatments. There are many possibilities as to why this discrepancy in estimation could occur (storm damage, unusual tree growth or shape, or a higher percentage of branches facing the camera). Most overestimation was observed when there were relatively fewer trees per hectare, and for relatively older stands, which indicates that tree-to-tree variation for a few large trees may significantly affect HP estimates. One recommendation from this study is to make several measurements within close proximity to each other and average gap fraction estimations to attempt to reduce this variation. This technique has been used in several different studies that obtain forest LAI (Strachan and McGaughey 1996).

For both Chapters 2 and 3, local and nationally derived allometric equations were compared to the validation model from the model based on gap fraction and LAI estimates. It appears that the LAI model may have an improved estimate of crown/branch biomass, but a similar estimate of above ground biomass, based on a linear regression model.

Chapter 4 attempted to take these conclusions a step further, and show that the model developed successfully in Chapter 3 could be expanded to other forest types (ponderosa/lodgepole pine mix). However, the regular spacing of trees within the plots from this site violates assumptions made in radiative models used to derive LAI. This violation contributed to much lower correlations for not only the LAI estimate, but also much lower correlations for all of the other HP-derived metrics. This showed that hemispherical photography does not appear to estimate LAI or biomass for plots with regularly spaced trees. Although this result may be disappointing for this particular site, there still appears to be some promise for the plots with "natural" spacing, even with variable atmospheric conditions.

The next steps in this research should include several different strategies. First, it becomes apparent from the research that the most accurate forest biomass measurements are obtained when LAI estimates appear to be reasonably accurate. If an analyst wishes to measure forest biomass with ground-based measurements, other potential tools that measure LAI should be considered. In order to more accurately estimate LAI, there are several commercially available tools that could potentially be used; each has different calibration and usage requirements. A careful comparison between hemispherical photography and other LAI measurement tools should be conducted to determine if one or more of these tools should be used for LAI measurements.

In addition, the various tools that estimate LAI should be compared under different terrain/atmospheric conditions to find which tool is optimal under which conditions. In addition, additional studies are needed to test the accuracy of LAI estimates for areas with steeper slopes. Most plots within this study were located in areas with relatively flat or moderate slopes, but if the technique is to be widely used, it needs to accurately estimate LAI at steeper slopes. Terrestrial LiDAR is another ground-based technology
that may provide an alternative estimate of forest canopy structure, but no tool has yet been developed for commercial use.

Another avenue to explore is aerial-based estimation of both canopy structure and LAI. Previous research has shown that combining LiDAR with satellite-based hyperspectral information may provide reliable estimates of LAI. Other studies have shown that hyperspectral data from satellite information alone may be sufficient to estimate LAI, using a bidirectional reflectance distribution function BRDF, which returns the reflectance of forest canopy as a function of illumination and viewing geometry. However, depending on which satellite data is used, the spatial resolution may be coarser than desired if high-resolution data is desired.

It is possible that hemispherical photography may be a useful tool for measuring forest biomass for specific areas with little underbrush, and naturally spaced, even-aged stands. However, even for stands with conditions suitable for hemispherical photography, it appears that the model would have to be recalibrated for different forest types. It is not clear if phenological or seasonal changes would require recalibration for the model or if additional model covariates are needed in order to account for these differences (Kalacska et al 2005; Chen 1996). The clumping factor may change between seasons. Annual differences in rainfall may significantly affect LAI within the same plot. Image processing techniques developed from this research may help future research when attempting to evaluate images subjected to heterogeneous lighting. This research also verifies that LAI derived from hemispherical photography has a relatively high correlation to both above ground forest biomass and crown/branch biomass when compared to simple gap fraction estimates of forest canopy.

A final consideration when using the techniques outlined in this research is the time intensive manual work required in order to derive acceptable gap fraction estimates
from photographs with heterogeneous lighting conditions. It may be preferable to use another tool merely because it is more convenient. It is anticipated that simpler techniques can be used with uniform lighting that would improve efficiency with hemispherical photography.

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## APPENDIX A: FIELD MEASUREMENTS OF TREE DIAMETERS AND HEIGHTS FOR EACH PLOT

DBH measurements were all made for standing trees; other measurements were made after trees were felled. DOB measurements were made with calipers from the side of the tree most easily accessible. For trees with elliptical butt ends, multiple measurements were made with calipers and an average was taken. Only trees with $\mathrm{DBH}>8 \mathrm{~cm}$ are included.

Key: Plots beginning with DF are from the site near Molalla, OR. Plots beginning with MC are from the site near Hambone, CA.
Trees ending with ' $B$ ' are branches with a base $>10 \mathrm{~cm}$ that were too large to chip.
Qt. = Quartile in which the tree was removed. ( $1=$ removed first, $4=$ removed last $)$.
Sp. = Species. DF = Douglas-fir, BM = Bigleaf Maple, WF = White Fir, IC = Incence-cedar, PP =
Ponderosa Pine, SP = Sugar Pine
Diameter over Bark (DOB) measurements are all in cm.
Butt $=\mathrm{DOB}$ at butt end of first log. $\mathrm{DBH}=\mathrm{DOB}$ at 1.3 m .
$3 \mathrm{~m}, 6 \mathrm{~m}, 12 \mathrm{~m}, 18 \mathrm{~m}, 24 \mathrm{~m}, 30 \mathrm{~m}, 36 \mathrm{~m}$, and 42 m are DOB at the given height
Stump = stump height (m)
Green Crown, 8cm top, and Total Height are all measured in meters.

Table A.1. Field Measurements of Diameter and Height
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num

DFM2 43 DF 52.545 .142 .038 .532 .020 .09 .5
DFM2 $3 \quad 4$ DF 50.543 .539 .537 .032 .025 .013 .0
DFM2 25 DF 39.536 .231 .530 .025 .517 .59 .0
DFM2 26 DF $40.036 .530 .026 .020 .514 .5 \quad 5.0$

DFM2 $3 \quad 8 \quad$ DF 46.043 .435 .532 .528 .022 .010 .5
DFM2 $4 \quad 9 \quad$ DF 57.050 .141 .540 .530 .521 .011 .5
DFM2 4 10 DF 51.048 .841 .037 .032 .023 .011 .5

DFM2 212 DF 44.038 .634 .034 .528 .522 .012 .0


DFM3 21 DF 28.526 .923 .022 .015 .09 .5
 DFM3 $3 \quad 3 \quad$ DF 34.531 .128 .026 .521 .016 .04 .5
 DFM3 $2 \quad 5 \quad$ DF 28.026 .123 .022 .018 .513 .03 .5 DFM3 $4 \quad 6 \quad$ DF $39.534 .130 .027 .523 .015 .5 \quad 5.5$

DFM3 48 DF 35.532 .529 .028 .023 .017 .06 .5
DFM3 $3 \quad 9 \quad$ DF 37.530 .628 .525 .521 .513 .5
DFM3 $4 \quad 10$ DF 41.037 .132 .532 .025 .516 .04 .5
DFM3 211 DF 31.526 .428 .023 .018 .59 .5
DFM3 $3 \quad 12$ DF 30.027 .623 .022 .517 .59 .0


DFM3 $1 \quad 15$ DF 29.022 .521 .520 .517 .08 .0
DFM3 $3 \quad 16$ DF 30.529 .525 .023 .019 .011 .04 .5

DFM3 $1 \quad 18$ DF 24.024 .021 .520 .517 .011 .5
DFM3 219 DF 33.029 .527 .025 .019 .011 .0
DFM3 320 DF 30.527 .425 .022 .518 .510 .51 .5
DFM3 221 DF 30.027 .123 .022 .518 .010 .0
DFM3 $1 \quad 22$ DF 26.522 .420 .519 .015 .510 .0
DFM3 223 DF 32.527 .023 .521 .018 .010 .0
$\begin{array}{llll}0.3 & 13.4 & 24.2 & 27.8\end{array}$
$\begin{array}{llllll}0.2 & 13.8 & 26.8 & 29.8\end{array}$
$\begin{array}{llllll}0.2 & 13.9 & 24.4 & 28.6\end{array}$
$\begin{array}{lllll}0.2 & 13.2 & 22.3 & 26.4\end{array}$
$\begin{array}{lllll}0.3 & 15.0 & 23.2 & 27.5\end{array}$
$\begin{array}{lllll}0.2 & 14.2 & 25.8 & 29.7\end{array}$
$\begin{array}{llllllllllllllll}0.3 & 17.1 & 25.8 & 29.6\end{array}$
$\begin{array}{lllll}0.3 & 10.2 & 25.9 & 29.9\end{array}$
$\begin{array}{llllll}0.2 & 11.4 & 23.5 & 27.7\end{array}$
$\begin{array}{llllll}0.2 & 15.3 & 25.6 & 29.3\end{array}$
$\begin{array}{lllll}0.2 & 14.7 & 23.0 & 27.5\end{array}$
$\begin{array}{llllllllll}0.2 & 13.7 & 23.2 & 28.0\end{array}$
$0.2 \quad 15.0 \quad 19.0 \quad 24.2$
$\begin{array}{llllll}0.2 & 14.0 & 23.5 & 27.4\end{array}$

$\begin{array}{lllll}0.3 & 13.6 & 20.6 & 25.0\end{array}$
$0.2 \quad 17.0 \quad 21.0 \quad 26.3$
$\begin{array}{lllll}0.2 & 13.0 & 22.6 & 26.9\end{array}$
$\begin{array}{llllll}0.2 & 14.6 & 17.8 & 21.8\end{array}$
$\begin{array}{lllllllll}0.3 & 13.8 & 23.5 & 27.6\end{array}$
$\begin{array}{lllll}0.9 & 14.0 & 21.0 & 26.2\end{array}$
$\begin{array}{llllll}0.2 & 13.3 & 22.0 & 25.6\end{array}$
$0.2 \quad 13.0 \quad 19.0 \quad 23.3$
$\begin{array}{llllll}0.2 & 15.0 & 19.0 & 22.2\end{array}$
$\begin{array}{lllll}0.2 & 15.0 & 22.0 & 27.1\end{array}$
$\begin{array}{llllll}0.1 & 16.2 & 20.3 & 25.3\end{array}$
$\begin{array}{lllll}0.2 & 14.0 & 18.4 & 22.7\end{array}$
$\begin{array}{lllllllllllll}0.2 & 14.0 & 20.1 & 27.0\end{array}$
$\begin{array}{lllll}0.2 & 15.0 & 17.5 & 21.7\end{array}$
$\begin{array}{llllll}0.1 & 14.0 & 20.3 & 23.8\end{array}$
$\begin{array}{lllllllllllll}0.2 & 15.0 & 20.0 & 23.4\end{array}$
$\begin{array}{lllllllllllll}0.2 & 15.0 & 20.0 & 24.5\end{array}$
$\begin{array}{lllll}0.2 & 14.0 & 19.0 & 24.4\end{array}$
$\begin{array}{lllll}0.2 & 14.1 & 19.3 & 23.5\end{array}$
$0.2 \quad 15.0 \quad 19.0 \quad 24.4$

Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num

| DFM3 | 1 | 24 | DF | 27.523 .31 | 19.519 .515 .511 .0 | 0.5 | 0.2 | 14.7 | 19.7 | 24.2 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DFM3 | 1 | 25 | DF | 21.518 .21 | 16.015 .511 .05 .0 |  | 0.2 | 15.5 | 15.6 | 20.8 |
| DFM3 | 1 | 26 | DF | 27.524 .12 | 21.520 .018 .011 .0 | 0.0 | 0.2 | 16.0 | 19.6 | 24.0 |
| DFM3 | 2 | 27 | DF | 26.526 .123 | 23.021 .518 .010 .0 |  | 0.2 | 15.0 | 19.0 | 24.3 |
| DFM3 | 4 | 28 | DF | 33.532 .42 | 28.527 .523 .015 .5 | 4.0 | 0.2 | 15.7 | 22.3 | 25.8 |
| DFM4 | 3 | 1 | DF | 42.035 .93 | 31.031 .524 .018 .0 | 7.0 | 0.3 | 14.0 | 23.2 | 28.0 |
| DFM4 | 2 | 2 | DF | 39.534 .23 | 30.529 .023 .515 .5 | 7.0 | 0.2 | 14.8 | 23.5 | 28.4 |
| DFM4 | 4 | 3 | DF | 46.540 .53 | 36.035 .030 .022 .0 | 9.0 | 0.3 | 16.0 | 24.4 | 28.3 |
| DFM4 | 1 | 4 | DF | 39.033 .3 | 29.026 .520 .514 .5 | 3.5 | 0.3 | 15.0 | 21.0 | 26.4 |
| DFM4 | 2 | 5 | DF | 39.534 .93 | 31.526 .523 .516 .0 | 5.0 | 0.2 | 15.8 | 22.2 | 26.8 |
| DFM4 | 2 | 6 | DF | 41.534 .93 | 32.029 .024 .518 .0 | 8.0 | 0.3 | 16.3 | 24.1 | 28.0 |
| DFM4 | 1 | 7 | DF | 35.532 .22 | 27.525 .522 .015 .5 | 6.5 | 0.2 | 15.0 | 22.0 | 27.3 |
| DFM4 | 1 | 8 | DF | 36.030 .6 | 26.024 .018 .511 .5 | 3.5 | 0.2 | 14.0 | 22.0 | 25.8 |
| DFM4 | 1 | 9 | DF | 32.528 .72 | 25.024 .520 .516 .0 | 6.5 | 0.2 | 18.0 | 23.0 | 27.4 |
| DFM4 | 1 | 10 | DF | 39.532 .92 | 27.525 .520 .013 .5 | 2.5 | 0.2 | 18.0 | 21.0 | 25.5 |
| DFM4 | 2 | 11 | DF | 35.533 .32 | 28.527 .022 .516 .0 | 6.5 | 0.2 | 15.5 | 23.0 | 27.2 |
| DFM4 | 4 | 12 | DF | 49.540 .43 | 38.034 .027 .025 .0 | 8.5 | 0.3 | 14.0 | 24.2 | 28.1 |
| DFM4 | 3 | 13 | DF | 41.038 .3 | 33.030 .526 .517 .0 | 7.5 | 0.2 | 15.5 | 23.8 | 28.2 |
| DFM4 | 2 | 14 | DF | 39.033 .3 | 30.028 .521 .013 .5 | 2.0 | 0.2 | 16.0 | 21.0 | 25.5 |
| DFM4 | 3 | 15 | DF | 43.041 .3 | 35.535 .029 .523 .0 | 10.5 | 0.2 | 14.5 | 25.4 | 29.3 |
| DFM4 | 3 | 16 | DF | 44.541 .03 | 36.033 .527 .520 .0 | 9.5 | 0.3 | 10.3 | 24.5 | 28.0 |
| DFM4 | 1 | 17 | DF | 30.026 .6 | 23.022 .519 .013 .0 | 5.0 | 0.3 | 15.0 | 22.0 | 27.3 |
| DFM4 | 1 | 18 | DF | 39.031 .22 | 27.526 .021 .515 .0 | 4.0 | 0.2 | 10.2 | 22.0 | 26.4 |
| DFM4 | 3 | 19 | DF | 39.038 .6 | 32.525 .021 .014 .0 | 4.5 | 0.3 | 14.0 | 22.0 | 26.0 |
| DFM4 | 3 | 19.5 | DF |  | 22.017 .012 .5 | 1.5 | 5.0 | 15.0 | 20.5 | 25.1 |
| DFM4 | 3 | 20 | DF | 40.538 .4 | 35.031 .025 .017 .5 | 7.5 | 0.3 | 15.6 | 23.7 | 28.4 |
| DFM4 | 4 | 21 | DF | 51.044 .73 | 39.038 .532 .020 .5 | 10.5 | 0.3 | 9.0 | 25.0 | 29.2 |
| DFM4 | 2 | 22 | DF | 36.033 .8 | 29.027 .525 .517 .0 | 7.5 | 0.2 | 17.4 | 23.4 | 28.0 |
| DFM4 | 2 | 23 | DF | 38.534 .3 | 30.027 .524 .017 .0 | 7.0 | 0.2 | 10.0 | 23.8 | 28.4 |
| DFM4 | 3 | 24 | DF | 43.039 .23 | 35.533 .527 .519 .5 | 8.5 | 0.3 | 15.3 | 24.2 | 28.0 |
| DFM5 | 3 | 1 | DF | 51.542 .63 | 39.036 .532 .025 .0 | 15.51 .5 | 0.3 | 16.0 | 27.0 | 31.0 |
| DFM5 | 4 | 2 | DF | 51.045 .63 | 38.035 .528 .521 .0 | 11.0 | 0.3 | 15.8 | 25.2 | 29.7 |
| DFM5 | 1 | 3 | DF | 26.522 .41 | 19.017 .013 .08 .5 | 1.0 | 0.2 | 17.0 | 18.5 | 24.7 |
| DFM5 | 3 | 4 | DF | 42.542 .13 | 39.536 .031 .523 .0 | 13.51 .5 | 0.3 | 17.0 | 27.1 | 30.0 |
| DFM5 | 1 | 5 | DF | 31.529 .327 | 27.527 .023 .015 .0 | 4.0 | 0.7 | 12.0 | 22.0 | 25.8 |

Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num

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DFM5 2 6 DF 39.5 35.4 30.5 29.0 24.0 16.5 6.0
DFM5 2 7 DF 45.0 35.9 31.5 28.5 23.0 17.5 8.0
DFM5 2 8 DF 38.0 33.4 32.0 30.0 24.5 19.5 11.5
DFM5 1 9 DF 28.5 25.6 21.5 19.5 16.0 9.0 0.0 16.0 19.0 24.1
DFM5 1 10 DF 32.0 29.1 26.5 25.5 21.0 16.0 5.5 0.0 19.0 22.5 26.0
DFM5 1 11 DF 24.0 21.6 19.5 18.5 14.5 9.5 0.2 18.0 19.0 25.4
DFM5 1 12 DF 31.0 27.0 25.0 23.5 18.5 14.0 4.0 0.2 16.0 22.0 26.0
DFM5 1 13 DF 32.0 30.8 25.5 23.0 19.0 12.0 4.0 0.0 15.0 21.0 27.1
DFM5 1 14 DF 31.5 28.2 24.5 23.0 20.5 16.0 9.0 0.0 18.0
DFM5 4 15 DF 49.5 46.1 42.0 40.0 34.0 26.0 13.5 2.5 0.5 11.0 27.0 31.1
DFM5 3 16 DF 39.5 37.5 33.5 32.0 25.0 17.5 8.5 0.2 17.0 24.0 28.0
DFM5 1 17 DF 34.0 29.5 28.0 26.0 22.0 15.0 0.2 6.0 22.5 26.0
DFM5 3 18 DF 46.0 42.2 39.0 36.0 27.0 20.0 6.5 0.2 6.0 24.0 27.9
DFM5 2 19 DF 41.0 34.9 33.0 30.5 25.5 20.5 10.0 0.3 13.0 25.0 29.3
DFM5 220 DF \(39.534 .733 .032 .025 .018 .08 .5 \quad 0.311 .0 \quad 25.0 \quad 29.5\)
DFM5 4 21 DF 48.5 42.8 42.0 36.0 29.5 21.0 8.0
DFM5 4 22 DF 49.0 44.0 38.5 36.5 31.0 23.0 13.0 2.0
DFS1 3 1 DF 28.5 24.1 23.0 21.0 14.5 5.5
DFS1 3 2 DF 22.5 20.2 20.0 17.5 12.5 3.0
DFS1 1 3 DF 30.0 24.7 23.0 22.0 13.0 1.5
DFS1 1 4 DF 23.0 19.1 18.5 18.0 11.0 1.5
DFS1 2 5 DF 25.0 21.1 20.0 18.5 12.0 3.0
DFS1 1 6 DF 17.0 15.0 14.5 12.5 8.0
DFS1 2 7 DF 26.0 21.7 21.5 18.0 13.5 3.0
DFS1 1 8 D DF 20.5 18.8 18.0 16.5 10.5 1.5
DFS1 1 9 DF 20.0 18.8 16.0 14.5 9.5
DFS1 4 10 DF 27.5 26.1 23.5 21.5 15.0 6.0
DFS1 1 11 DF Dr 19.5 16.4 16.0 15.0 9.5 1.0
DFS1 4 12 DF 26.5 24.7 22.0 19.5 14.0 4.0
DFS1 1 13 DF 21.5 18.8 18.0 17.5 11.0 2.0
DFS1 4 14 DF 29.5 25.6 23.5 22.5 15.0 6.0
DFS1 1 15 DF 19.5 16.5 17.0 15.0 10.0 2.0
DFS1 2 16 DF 22.5 19.5 18.0 17.0 13.0 3.0
DFS1 2 17 DF 22.5 19.4 18.0 16.5 10.5 2.5
DFS1 4 18 DF 30.0 26.9 26.5 23.0 18.0 7.0
```

$0.3 \quad 17.0 \quad 22.0 \quad 27.0$
$\begin{array}{lllll}0.2 & 14.5 & 24.0 & 28.4\end{array}$
$\begin{array}{lllll}0.3 & 16.0 & 25.0 & 30.0\end{array}$
$0.2 \quad 16.0 \quad 19.0 \quad 24.1$
$0.3 \quad 19.0 \quad 22.5 \quad 26.0$
$\begin{array}{lllll}0.2 & 18.0 & 19.0 & 25.4\end{array}$
$0.2 \quad 16.0 \quad 22.0 \quad 26.0$
$0.2 \quad 15.0 \quad 21.0 \quad 27.1$
$0.2 \quad 18.0 \quad 25.0 \quad 29.5$
$0.3 \quad 11.0 \quad 27.0 \quad 31.1$
$0.2 \quad 17.0 \quad 24.0 \quad 28.0$
$\begin{array}{llll}0.2 & 6.0 & 22.5 & 26.0\end{array}$
$\begin{array}{lllll}0.2 & 6.0 & 24.0 & 27.9\end{array}$
$\begin{array}{lllll}0.3 & 13.0 & 25.0 & 29.3\end{array}$
$0.311 .0 \quad 25.0 \quad 29.5$
$0.4 \quad 24.0 \quad 30.0$
$0.3 \quad 14.0 \quad 26.0 \quad 31.0$
$\begin{array}{lllll}0.3 & 10.3 & 16.0 & 21.9\end{array}$
$\begin{array}{llll}0.2 & 9.4 & 14.9 & 20.1\end{array}$
$\begin{array}{llll}0.3 & 8.7 & 14.7 & 18.9\end{array}$
$\begin{array}{llll}0.3 & 9.7 & 13.9 & 18.6\end{array}$
$\begin{array}{lllll}0.2 & 9.1 & 14.8 & 19.6\end{array}$
$\begin{array}{lllll}0.1 & 9.8 & 12.0 & 17.2\end{array}$
$\begin{array}{llll}0.2 & 10.9 & 14.9 & 19.4\end{array}$
$\begin{array}{llll}0.1 & 9.7 & 14.1 & 18.7\end{array}$
$\begin{array}{llll}0.2 & 9.5 & 12.2 & 17.6\end{array}$
$\begin{array}{lllll}0.4 & 8.6 & 16.4 & 21.6\end{array}$
$\begin{array}{llll}0.2 & 9.8 & 12.9 & 18.3\end{array}$
$\begin{array}{lllll}0.2 & 11.3 & 15.7 & 20.6\end{array}$
$\begin{array}{lllll}0.1 & 10.6 & 14.5 & 19.1\end{array}$
$\begin{array}{lllll}0.2 & 8.3 & 16.6 & 21.9\end{array}$
$\begin{array}{lllll}0.1 & 10.4 & 13.4 & 19.4\end{array}$
$\begin{array}{llll}0.2 & 9.4 & 15.0 & 19.8\end{array}$
$\begin{array}{lllll}0.2 & 10.6 & 13.7 & 19.2\end{array}$
$\begin{array}{lllllll}0.3 & 10.1 & 17.0 & 20.7\end{array}$

Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num

| DFS2 | 1 | 22 | DF | 19.017 .8 | 16.015 .09 .5 |  | 0.2 | 8.6 | 12.7 | 16.8 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DFS2 | 3 | 23 | DF | 25.022 .2 | 20.518 .011 .5 | 0.5 | 0.2 | 7.3 | 14.3 | 18.1 |
| DFS2 | 4 | 24 | DF | 26.022 .4 | 21.018 .510 .0 |  | 0.2 | 8.5 | 13.5 | 17.4 |
| DFS2 | 1 | 25 | DF | 21.017 .5 | 16.515 .510 .0 | 0.5 | 0.2 | 8.6 | 13.2 | 18.6 |
| DFS2 | 3 | 26 | DF | 25.520 .8 | 19.518 .511 .0 | 1.5 | 0.2 | 8.1 | 13.6 | 18.7 |
| DFS2 | 2 | 27 | DF | 21.519 .3 | 17.015 .59 .0 | 0.5 | 0.2 | 9.0 | 13.2 | 18.3 |
| DFS2 | 1 | 28 | DF | 17.516 .1 | 14.513 .58 .0 |  | 0.2 | 10.3 | 12.3 | 17.5 |
| DFS2 | 4 | 29 | DF | 27.024 .5 | 22.020 .012 .5 | 5.0 | 0.3 | 8.7 | 16.1 | 22.1 |
| DFS2 | 4 | 30 | DF | 30.527 .2 | 25.024 .015 .0 | 5.5 | 0.3 | 6.7 | 16.6 | 20.7 |
| DFS3 | 4 | 1 | DF | 24.524 .4 | 24.022 .515 .0 | 3.5 | 0.3 | 8.8 | 16.1 | 19.7 |
| DFS3 | 2 | 2 | DF | 18.518 .0 | 16.014 .09 .5 |  | 0.2 | 8.3 | 13.2 | 18.6 |
| DFS3 | 1 | 3 | DF | 17.515 .2 | 13.513 .08 .0 | 0.5 | 0.1 | 9.4 |  | 18.3 |
| DFS3 | 1 | 4 | DF | 20.517 .3 | 16.514 .58 .5 | 1.0 | 0.1 | 5.8 | 12.3 | 18.3 |
| DFS3 | 1 | 5 | DF | 14.012 .4 | 11.09 .54 .5 |  | 0.1 | 9.0 | 9.0 | 15.9 |
| DFS3 | 4 | 6 | DF | 28.025 .1 | 24.522 .513 .0 | 2.5 | 0.3 | 8.3 | 15.0 | 19.6 |
| DFS3 | 4 | 7 | DF | 28.024 .6 | 23.022 .516 .0 | 4.5 | 0.3 | 9.2 | 16.4 | 20.6 |
| DFS3 | 1 | 8 | DF | 14.513 .1 | 12.09 .53 .0 |  | 0.1 | 8.3 | 8.5 | 14.1 |
| DFS3 | 3 | 9 | DF | 26.521 .9 | 21.019 .012 .5 | 2.0 | 0.3 | 6.8 | 15.0 | 20.0 |
| DFS3 | 2 | 10 | DF | 23.518 .6 | 17.516 .011 .0 |  | 0.2 | 9.8 | 13.7 | 19.1 |
| DFS3 | 4 | 11 | DF | 28.525 .1 | 23.521 .014 .0 | 4.0 | 0.2 | 10.4 | 15.5 | 20.8 |
| DFS3 | 1 | 12 | DF | 8.07 .1 | $6.0 \quad 5.0$ |  | 0.1 | 6.1 | 0.1 | 10.5 |
| DFS3 | 1 | 13 | DF | 18.015 .2 | 14.513 .57 .0 |  | 0.2 | 9.1 | 11.8 | 16.7 |
| DFS3 | 1 | 14 | DF | 14.513 .8 | 10.510 .04 .5 |  | 0.2 | 8.3 | 9.1 | 15.9 |
| DFS3 | 3 | 15 | DF | 25.020 .6 | 20.518 .013 .5 | 4.0 | 0.1 | 8.6 | 15.1 | 19.9 |
| DFS3 | 1 | 16 | DF | 17.016 .5 | 15.513 .08 .0 |  | 0.2 | 8.8 | 12.0 | 17.4 |
| DFS3 | 3 | 17 | DF | 25.522 .0 | 21.019 .012 .5 | 3.0 | 0.2 | 9.8 | 15.3 | 20.4 |
| DFS3 | 1 | 18 | DF | 17.515 .8 | 15.012 .58 .0 |  | 0.2 | 8.8 | 12.0 | 17.5 |
| DFS3 | 1 | 19 | DF | 19.016 .6 | 15.513 .08 .0 |  | 0.2 | 7.9 | 12.0 | 18.0 |
| DFS3 | 2 | 20 | DF | 21.520 .1 | 19.517 .012 .0 |  | 0.2 | 8.7 | 14.7 | 19.6 |
| DFS3 | 3 | 21 | DF | 23.020 .8 | 18.017 .011 .5 | 2.0 | 0.2 | 9.2 | 14.6 | 19.7 |
| DFS3 | 1 | 22 | DF | 15.514 .1 | 13.011 .57 .5 |  | 0.2 | 7.5 | 10.4 | 16.6 |
| DFS3 | 3 | 23 | DF | 26.021 .8 | 21.019 .512 .5 | 2.5 | 0.2 | 10.2 | 14.9 | 19.9 |
| DFS3 | 2 | 24 | DF | 23.019 .6 | 19.017 .011 .0 | 1.5 | 0.2 | 9.8 | 14.6 | 18.9 |
| DFS3 | 1 | 25 | DF | 19.517 .8 | 16.515 .09 .5 |  | 0.2 | 9.8 | 12.7 | 17.5 |
| DFS3 | 2 | 26 | DF | 23.520 .1 | 19.017 .513 .5 | 3.0 | 0.2 | 10.2 | 15.4 | 19.7 |

Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num

| DFS4 | 2 | 20 | DF | 24.520 .72 | 20.017 .511 .5 | 1.5 | 0.2 | 8.8 | 13.6 | 18.2 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DFS4 | 4 | 21 | DF | 29.524 .02 | 21.520 .013 .0 | 4.0 | 0.2 | 8.1 | 15.7 | 20.7 |
| DFS4 | 3 | 22 | DF | 26.523 .12 | 21.019 .014 .0 | 6.0 | 0.2 | 9.3 | 15.9 | 21.8 |
| DFS4 | 1 | 23 | DF | 21.518 .817 | 17.516 .59 .0 | 1.0 | 0.1 | 9.8 | 12.8 | 18.2 |
| DFS4 | 2 | 24 | DF | 26.521 .32 | 21.020 .013 .0 | 3.0 | 0.2 | 10.1 | 15.1 | 20.2 |
| DFS4 | 2 | 25 | DF | 22.520 .71 | 19.016 .510 .0 | 1.0 | 0.2 | 8.6 | 13.8 | 18.5 |
| DFS4 | 1 | 26 | DF | 19.517 .717 | 17.015 .07 .5 |  | 0.2 | 8.4 | 11.6 | 17.4 |
| DFS4 | 1 | 27 | DF | 21.518 .317 | 17.015 .010 .0 |  | 0.2 | 8.9 | 13.6 | 18.9 |
| DFS4 | 2 | 28 | DF | 25.521 .51 | 19.017 .511 .5 | 3.5 | 0.3 | 9.7 | 14.5 | 19.7 |
| DFS4 | 4 | 29 | DF | 29.024 .12 | 23.020 .514 .0 | 4.5 | 0.2 | 9.3 | 16.0 | 21.6 |
| DFS4 | 2 | 30 | DF | 22.519 .71 | 19.017 .511 .5 | 3.0 | 0.2 | 10.5 | 14.5 | 19.8 |
| DFS4 | 1 | 31 | DF | 18.016 .71 | 15.514 .58 .5 | 0.5 | 0.2 | 8.9 | 12.5 | 18.1 |
| DFS4 | 2 | 32 | DF | 25.521 .82 | 21.518 .514 .5 | 6.0 | 0.1 | 10.4 | 16.3 | 20.7 |
| DFS4 | 3 | 33 | DF | 27.022 .32 | 21.520 .013 .0 | 4.5 | 0.2 | 6.9 | 15.6 | 20.8 |
| DFS4 | 4 | 34 | DF | 27.524 .3 | 24.023 .015 .5 | 4.5 | 0.3 | 8.2 | 16.3 | 21.1 |
| DFS4 | 3 | 35 | DF | 24.022 .41 | 19.518 .012 .5 | 3.0 | 0.2 | 8.8 | 15.4 | 19.6 |
| DFS4 | 4 | 36 | DF | 26.024 .5 | 21.020 .014 .0 | 3.0 | 0.2 | 9.4 | 15.8 | 20.0 |
| DFS4 | 4 | 37 | DF | 29.525 .3 | 23.521 .012 .0 | 2.5 | 0.2 | 9.1 | 14.2 | 19.9 |
| DFS4 | 1 | 38 | DF | 21.017 .31 | 16.515 .09 .0 |  | 0.3 | 6.7 | 12.5 | 17.4 |
| DFS5 | 3 | 1 | DF | 31.024 .5 | 25.021 .516 .0 | 6.0 | 0.3 | 10.2 | 15.7 | 21.7 |
| DFS5 | 4 | 2 | DF | 32.025 .62 | 24.022 .016 .5 | 7.0 | 0.2 | 9.3 | 17.1 | 22.5 |
| DFS5 | 1 | 3 | DF | 23.020 .11 | 19.016 .511 .5 | 2.5 | 0.2 | 9.7 | 14.4 | 19.6 |
| DFS5 | 1 | 4 | DF | 18.015 .51 | 14.011 .56 .0 |  | 0.2 | 7.7 | 9.9 | 16.2 |
| DFS5 | 2 | 5 | DF | 22.020 .62 | 20.018 .010 .5 | 1.5 | 0.2 | 8.8 | 14.2 | 19.0 |
| DFS5 | 1 | 6 | DF | 22.519 .41 | 18.017 .012 .0 | 3.0 | 0.3 | 8.3 | 14.9 | 20.4 |
| DFS5 | 1 | 7 | DF | 22.519 .21 | 19.017 .512 .0 | 3.5 | 0.2 | 9.2 | 14.7 | 20.1 |
| DFS5 | 1 | 8 | DF | 23.519 .01 | 19.517 .011 .0 | 2.0 | 0.2 | 7.5 | 14.3 | 19.3 |
| DFS5 | 4 | 9 | DF | 30.526 .12 | 26.524 .017 .0 | 6.5 | 0.2 | 9.7 | 17.4 | 21.9 |
| DFS5 | 1 | 10 | DF | 20.518 .717 | 17.516 .511 .0 | 2.5 | 0.2 | 9.3 | 14.3 | 19.5 |
| DFS5 | 4 | 11 | DF | 31.027 .82 | 26.525 .518 .5 | 9.0 | 0.2 | 9.4 | 18.6 | 23.1 |
| DFS5 | 3 | 12 | DF | 25.523 .2 | 21.019 .513 .0 | 6.0 | 0.2 | 9.8 | 15.1 | 19.8 |
| DFS5 | 1 | 13 | DF | 24.020 .11 | 17.516 .010 .0 | 2.5 | 0.2 | 9.8 | 14.0 | 19.6 |
| DFS5 | 3 | 14 | DF | 27.523 .92 | 23.020 .514 .5 | 4.5 | 0.2 | 8.9 | 16.7 | 20.9 |
| DFS5 | 3 | 15 | DF | 28.023 .92 | 23.521 .515 .0 | 6.0 | 0.3 | 8.9 | 15.1 | 21.1 |
| DFS5 | 4 | 16 | DF | 31.024 .523 | 23.021 .015 .5 | 6.0 | 0.2 | 10.6 | 16.8 | 21.5 |

Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num

| MCL4 | 1 | 31 | WF | 10.5 | 11.0 | 9.0 | 6.0 |  |  | 0.3 | 3.2 | 3.8 | 9.2 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MCL4 | 4 | 32 | PP | 71.5 | 66.0 | 55.5 | 50.042 .0 | 35.020 .5 | 9.0 | 0.2 | 15.3 | 30.3 | 32.7 |
| MCL4 | 1 | 33 | WF | 17.5 | 16.0 | 14.0 | 10.51 .0 |  |  | 0.3 | 2.2 | 7.7 | 12.4 |
| MCL4 | 1 | 34 | IC | 17.5 | 15.0 | 11.0 | 8.0 |  |  | 0.2 | 3.1 | 6.0 | 10.2 |
| MCL4 | 1 | 35 | IC | 13.5 | 10.5 | 6.5 | 0.5 |  |  | 0.2 | 2.6 | 2.4 | 6.1 |
| MCL4 | 3 | 37 | PP | 68.5 | 59.0 | 52.0 | 50.043 .0 | 36.018 .5 | 9.0 | 0.3 | 13.9 | 30.6 | 33.3 |
| MCL4 | 2 | 39 | PP | 46.0 | 41.5 | 35.0 | 31.528 .0 | 20.011 .0 |  | 0.4 | 15.2 | 25.9 | 29.1 |
| MCL4 | 1 | 40 | WF | 16.0 | 14.5 | 11.0 | 9.02 .0 |  |  | 0.3 | 3.1 | 8.5 | 13.3 |
| MCL4 | 1 | 41 | WF | 24.5 | 22.5 | 19.5 | 16.08 .0 |  |  | 0.3 | 2.5 | 12.0 | 17.2 |
| MCL4 | 3 | 42 | PP | 65.0 | 55.5 | 47.0 | 43.537 .5 | 28.520 .0 | 7.0 | 0.2 | 12.1 | 29.5 | 32.2 |
| MCL4 | 1 | 43 | WF | 13.0 | 11.5 | 10.5 | 7.5 |  |  | 0.2 | 4.1 | 5.4 | 11.3 |
| MCL4 | 1 | 44 | WF | 13.0 | 11.5 | 10.5 | 6.5 |  |  | 0.2 | 2.0 | 5.1 | 10.9 |
| MCL4 | 1 | 45 | IC | 12.5 | 10.0 | 7.0 | 1.0 |  |  | 0.2 | 2.7 | 2.5 | 6.6 |
| MCL4 | 3 | 37B | PP |  |  |  |  | 20.5 | 8.0 | 22.4 | N/A | 30.0 | 33.3 |
| $\begin{gathered} \text { MCM } \\ 1 \end{gathered}$ | 2 | 1 | WF | 28.5 | 24.1 | 23.0 | 21.514 .0 |  |  | 0.2 | 8.2 | 15.5 | 19.0 |
| $\begin{gathered} \text { MCM } \\ 1 \end{gathered}$ | 1 | 3 | IC | 12.5 | 12.0 | 8.0 | 3.0 |  |  | 0.1 | 4.1 | 3.0 | 7.5 |
| MCM <br> 1 | 2 | 4 | IC | 23.0 | 21.0 | 20.0 | 16.05 .0 |  |  | 0.2 | 7.9 | 10.3 | 13.8 |
| $\begin{gathered} \text { MCM } \\ 1 \end{gathered}$ | 1 | 5 | WF | 16.5 | 14.0 | 12.0 | 9.0 |  |  | 0.2 | 4.6 | 6.7 | 11.2 |
| $\begin{gathered} \text { MCM } \\ 1 \end{gathered}$ | 1 | 6 | OAK | 17.5 | 17.0 | 11.0 | $7.0 \quad 0.5$ |  |  | 0.2 | 3.1 | 3.2 | 12.7 |
| $\begin{gathered} \text { MCM } \\ 1 \end{gathered}$ | 1 | 7 | WF | 15.5 | 14.5 | 12.0 | 9.0 |  |  | 0.1 | 4.4 | 6.9 | 10.9 |
| $\begin{gathered} \text { MCM } \\ 1 \end{gathered}$ | 1 | 8 | IC | 10.0 | 10.5 | 5.0 |  |  |  | 0.1 | 2.7 | 9.3 | 5.6 |
| $\begin{gathered} \mathrm{MCM} \\ 1 \end{gathered}$ | 2 | 9 | WF | 28.5 | 26.0 | 24.5 | 20.512 .0 |  |  | 0.3 | 8.2 | 14.2 | 18.2 |
| $\begin{gathered} \text { MCM } \\ 1 \end{gathered}$ | 1 | 10 | IC | 12.0 | 11.5 | 7.0 | 0.5 |  |  | 0.3 | 4.1 | 2.4 | 6.5 |
| $\begin{gathered} \text { MCM } \\ 1 \end{gathered}$ | 1 | 11 | IC | 8.0 | 8.5 | 3.5 |  |  |  |  | dead | 0.0 | 5.0 |
| MCM | 1 | 12 | IC | 9.0 | 8.5 | 4.5 |  |  |  | 0.3 | dead | 0.7 | 3.6 |

Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num

| MCM | 1 | 30 | WF | 16.0 | 13.5 | 12.010 .51 .5 |  | 0.1 | 5.5 | 9.0 | 13.2 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 31 | IC | 8.5 | 7.0 | 3.0 |  | 0.0 | 2.0 | 0.1 | 4.1 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 32 | IC | 12.5 | 6.5 | 1.0 |  | 0.1 | 3.7 | 0.2 | 4.3 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 33 | WF | 7.0 | 5.5 | 3.5 |  | 0.0 | 2.3 | NA | 5.1 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 34 | WF | 19.0 | 15.5 | 14.011 .06 .0 |  | 0.2 | 6.8 | 10.5 | 15.7 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 2 | 35 | IC | 24.5 | 22.0 | 19.013 .0 |  | 0.2 | 5.4 | 8.4 | 11.8 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 2 | 36 | IC | 29.5 | 26.0 | 22.020 .013 .52 .0 |  | 0.2 | 7.5 | 14.8 | 18.7 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 37 | IC | 14.5 | 12.0 | 9.05 .0 |  | 0.1 | dead | 3.6 | 7.5 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 2 | 38 | IC | 27.0 | 20.0 | 17.516 .08 .5 |  | 0.2 | 7.9 | 12.7 | 17.1 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 39 | IC | 9.5 | 9.0 | 4.5 |  | 0.1 | dead | 0.8 | 5.4 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 2 | 40 | IC | 26.0 | 22.5 | 19.017 .59 .5 |  | 0.2 | 7.0 | 13.3 | 17.3 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 41 | IC | 17.5 | 17.5 | 13.59 .0 |  | 0.2 | 5.3 | 6.4 | 10.3 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 42 | IC | 9.5 | 9.0 | 6.0 |  | 0.1 | dead | 0.6 | 6.0 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 43 | IC | 6.5 | 6.5 | 3.0 |  | 0.1 | dead | NA | 4.1 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 4 | 44 | WF | 60.0 | 58.5 | 49.045 .037 .026 .0 | 8.5 | 0.5 | 9.1 | 24.6 | 27.6 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 45 | IC | 15.0 | 10.5 | 5.0 |  | 0.3 | dead | 1.5 | 4.7 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 3 | 46 | IC | 35.5 | 33.5 | 29.026 .015 .1 |  | 0.4 | 8.0 | 14.0 | 17.6 |
| 1 |  |  |  |  |  |  |  |  |  |  |  |
| MCM | 1 | 48 | IC | 11.0 | 7.5 | 3.5 |  | 0.1 | dead | 0.6 | 4.7 |

Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num

1


1
$\begin{array}{ccccccccccccc}\text { MCM } & 1 & 93 & \text { IC } & 14.0 & 9.5 & 8.5 & 5.5 & 0.1 & 6.1 & 3.3 & 8.6 \\ 1 & & & & & 21 & 17.5 & 13.0 & 5.0 & 0.2 & 9.1 & 9.8 & 14.2\end{array}$
1
$\begin{array}{lllllllllllllllll}\text { MCM } & 2 & 96 & \text { IC } & 27.0 & 24.5 & 22.0 & 19.5 & 12.0 & 1.0 & 0.2 & 6.8 & 14.6 & 18.9\end{array}$
1
$\begin{array}{llllllllllllllllllll}\text { MCM } & 1 & 97 & \text { IC } & 9.0 & 7.5 & 3.5 & 0.1 & \text { dead } & 0.5 & 4.3\end{array}$
1
$\begin{array}{llllllllllll}\text { MCM } & 1 & 98 & \text { IC } & 9.5 & 8.0 & 4.5 & 0.2 & 3.8 & 1.0 & 5.8\end{array}$
1

1
$\begin{array}{llllllllll}\text { MCM } & 1 & 100 & \text { WF } & 4.5 & 4.0 & 3.0 & 0.0 & 4.8 & \text { NA } \\ 5.8\end{array}$
1

| $\begin{array}{c}\text { MCM } \\ 1\end{array}$ | 1 | 101 | IC | 11.0 | 10.5 | 7.5 | 2.0 | 0.3 | 4.9 | 2.7 | 8.9 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MCM | 4 | 102 | WF | 53.5 | 47.5 | 40.5 | 38.5 | 32.5 | 22.5 | 12.0 | 0.2 | 9.3 | 1

Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp , Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)


Table A. 1 (Continued)
Plot Qt. Tree Sp , Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp , Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num


Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num

| MCS3 | 2 | 4 | PP | 34.030 | 30.522 .017 .5 |  | 0.3 | 1.0 | 8.0 | 11.5 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MCS3 | 1 | 5 | PP | 31.028 .0 | 8.023 .014 .0 | 2.5 | 0.3 | 4.6 | 9.2 | 12.6 |
| MCS3 | 2 | 6 | PP | 34.029 .0 | 29.021 .014 .5 | 4.0 | 0.3 | 3.8 | 10.4 | 13.0 |
| MCS3 | 1 | 7 | PP | 29.027 | 27.022 .017 .0 | 3.0 | 0.2 | 3.4 | 10.3 | 12.5 |
| MCS3 | 4 | 8 | PP | 39.034 | 34.529 .023 .0 | 7.0 | 0.3 | 3.6 | 11.7 | 14.2 |
| MCS3 | 3 | 9 | PP | 36.032 | 32.524 .018 .5 | 4.0 | 0.2 | 2.6 | 10.1 | 12.9 |
| MCS3 | 4 | 10 | PP | 36.033 | 33.024 .020 .5 | 5.5 | 0.3 | 3.9 | 10.9 | 13.9 |
| MCS3 | 2 | 11 | PP | 33.028 | 8.524 .519 .5 | 5.5 | 0.3 | 2.5 | 11.3 | 13.5 |
| MCS3 | 1 | 12 | PP | 25.524 | 24.020 .017 .0 | 0.0 | 0.3 | 3.4 | 9.4 | 12.0 |
| MCS3 | 3 | 13 | PP | 32.031 .0 | 31.024 .520 .0 | 9.5 | 0.2 | 5.1 | 12.6 | 15.7 |
| MCS3 | 3 | 14 | PP | 36.532 | 32.524 .019 .0 | 6.0 | 0.3 | 3.6 | 11.0 | 13.5 |
| MCS3 | 4 | 15 | PP | 38.533 | 33.026 .522 .5 | 8.0 | 0.3 | 2.7 | 12.0 | 14.6 |
| MCS3 | 3 | 16 | PP | 37.032 | 32.528 .025 .0 | 12.5 | 0.3 | 3.6 | 14.0 | 16.5 |
| MCS3 | 2 | 17 | PP | 33.029 | 29.526 .019 .0 | 4.0 | 0.3 | 3.4 | 11.2 | 12.7 |
| MCS3 | 1 | 18 | PP | 28.025 | 25.519 .515 .5 | 4.0 | 0.4 | 2.7 | 10.3 | 12.9 |
| MCS3 | 1 | 19 | PP | 29.525 | 25.520 .014 .5 |  | 0.3 | 2.2 | 8.6 | 11.6 |
| MCS3 | 1 | 20 | PP | 28.026 | 26.019 .515 .0 |  | 0.3 | 2.1 | 8.8 | 11.6 |
| MCS3 | 1 | 5B | PP |  | 15.5 | 5.5 | 6.0 | NA | 10.5 | 13.5 |
| MCS4 | 2 | 1 | PP | 38.533 | 33.528 .525 .0 | 14.5 | 0.3 | 4.1 | 13.6 | 16.4 |
| MCS4 | 3 | 2 | PP | 40.034 | 34.535 .026 .5 | 13.0 | 0.3 | 3.5 | 14.1 | 16.2 |
| MCS4 | 4 | 3 | PP | 50.544 | 44.538 .034 .5 | 12.0 | 0.4 | 1.3 | 13.2 | 16.3 |
| MCS4 | 1 | 4 | PP | 33.029 | 29.023 .519 .0 | 6.0 | 0.2 | 1.8 | 10.9 | 13.6 |
| MCS4 | 1 | 5 | PP | 21.019 | 9.515 .09 .5 |  | 0.2 | 2.8 | 6.6 | 9.7 |
| MCS4 | 1 | 6 | PP | 31.027 .0 | 27.021 .013 .5 |  | 0.2 | 1.9 | 8.4 | 11.4 |
| MCS4 | 1 | 7 | PP | 28.5 | 24.018 .013 .5 |  | 0.3 | 2.7 | 8.8 | 11.9 |
| MCS4 | 2 | 8 | PP | 41.032 | 32.529 .025 .5 | 12.5 | 0.3 | 4.0 | 13.4 | 15.6 |
| MCS4 | 4 | 9 | PP | 48.540 | 40.536 .034 .0 | 17.5 | 0.3 | 3.3 | 14.4 | 17.3 |
| MCS4 | 3 | 10 | PP | 39.034 | 34.029 .024 .0 | 10.0 | 0.3 | 2.5 | 13.0 | 14.7 |
| MCS4 | 3 | 11 | PP | 38.533 | 33.529 .023 .5 | 9.0 | 0.2 | 4.4 | 12.6 | 15.3 |
| MCS4 | 2 | 12 | PP | 38.033 | 33.028 .021 .0 | 9.0 | 0.3 | 3.5 | 12.8 | 15.2 |
| MCS4 | 2 | 13 | PP | 36.032 | 32.027 .524 .0 | 10.5 | 0.3 | 3.1 | 12.8 | 15.0 |
| MCS4 | 3 | 14 | PP | 38.534 | 34.027 .524 .0 | 8.5 | 0.3 | 2.8 | 13.0 | 15.2 |
| MCS4 | 1 | 15 | PP | 33.031 | 31.527 .022 .5 | 11.0 | 0.5 | 1.3 | 12.8 | 15.2 |
| MCS5 | 2 | 1 | PP | 32.028 .0 | 28.024 .021 .0 | 5.5 | 0.4 | 3.7 | 11.1 | 13.7 |
| MCS5 | 1 | 3 | IC | 12.011 | 11.05 .5 |  | 0.2 | 0.5 | 1.9 | 5.0 |

Table A. 1 (Continued)
Plot Qt. Tree Sp, Butt DBH 3 m 6 m 12 m 18 m 24 m 30 m 36 m 42 m St GC 8CT TH Num

| MCS5 | 2 | 4 | PP | 35.029 .5 | 24.519 .0 |  | 0.3 | 1.5 | 11.4 | 14.1 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MCS5 | 3 | 5 | PP | 36.030 .0 | 25.523 .0 | 10.5 | 0.3 | 4.4 | 13.0 | 15.4 |
| MCS5 | 1 | 6 | PP | 24.020 .5 | 16.010 .0 |  | 0.2 | 3.3 | 7.4 | 10.8 |
| MCS5 | 2 | 7 | PP | 33.528 .0 | 24.020 .0 | 7.0 | 0.3 | 2.8 | 11.8 | 14.6 |
| MCS5 | 3 | 8 | PP | 38.532 .0 | 35.521 .0 | 9.0 | 0.3 | 3.5 | 12.5 | 15.4 |
| MCS5 | 1 | 9 | PP | 28.025 .0 | 19.517 .0 | 4.5 | 0.3 | 2.8 | 10.5 | 13.2 |
| MCS5 | 3 | 10 | PP | 36.531 .0 | 27.522 .5 | 8.5 | 0.3 | 5.0 | 12.3 | 14.8 |
| MCS5 | 1 | 11 | PP | 32.026 .5 | 23.019 .5 | 7.5 | 0.2 | 3.6 | 11.9 | 14.7 |
| MCS5 | 2 | 12 | PP | 33.029 .5 | 23.520 .5 | 8.0 | 0.3 | 4.4 | 12.0 | 14.6 |
| MCS5 | 4 | 13 | PP | 46.541 .0 | 34.027 .5 | 13.5 | 0.3 | 2.1 | 13.8 | 16.7 |
| MCS5 | 4 | 14 | PP | 36.533 .5 | 27.018 .5 | 6.0 | 0.3 | 2.7 | 11.1 | 14.1 |
| MCS5 | 1 | 15 | PP | 27.023 .0 | 19.013 .5 | 2.0 | 0.3 | 2.0 | 8.7 | 12.2 |
| MCS5 | 3 | 17 | PP | 37.030 .0 | 28.026 .0 | 12.5 | 0.4 | 4.3 | 13.5 | 16.0 |
| MCS5 | 4 | 18 | PP | 41.538 .0 | 32.527 .5 | 15.0 | 0.3 | 3.7 | 14.6 | 17.8 |
| MCS5 | 1 | 19 | IC | 14.012 .5 | 8.53 .0 |  | 0.2 | 1.2 | 3.3 | 7.6 |
| MCS5 | 1 | 20 | PP | 30.526 .0 | 22.518 .5 | 5.5 | 0.3 | 3.0 | 10.6 | 13.2 |
| MCS5 | 1 | 21 | PP | 19.018 .0 | 13.58 .5 |  | 0.2 | 1.1 | 6.3 | 9.2 |
| MCS5 | 4 | 14B | PP |  | 16.5 | 4.5 | 5.2 | dead | 10.3 | 13.5 |

Table B. 1 (Continued)

| PloTree <br> t <br> Num. Qu Species | Disk | Height | DOB | DUB Heartw | Dry Wt | "Wet" | Density |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $(\mathrm{m})$ | $(\mathrm{cm})$ | $(\mathrm{cm})$ | ood | $(\mathrm{kg})$ | Wt | $(\mathrm{kg} / \mathrm{L})$ |

## APPENDIX B: TREE SECTIONS TAKEN FOR BOLE DENSITY ESTIMATES FROM SELECT TREES, EACH PLOT

Plot, Species, and Quartile are the same as from Appendix A.
Disks were taken from the tree at the bottom of each merchantable log, as well as the top of the topmost merchantable log, where applicable.

Key:
Disk 0 is taken from the bottom of the butt log, increasing numbers indicate disks taken from increasing tree heights.
DOB, DUB, and Heartwood measurements were taken after disks were oven dried.
Disks were weighed after drying (Dry Wt), then submerged in water and weighed again ("Wet" Wt).. Using water displacement, the volume of the disk was estimated. At that point, density was estimated.

Table B.1. Bole Section Measurements

| $\underset{\mathrm{t}}{\mathrm{Plo}}$ | Tree Num. | Qu art, | Species | Disk | Height (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | $\begin{gathered} \text { " Wet" } \\ \text { Wt } \\ (\mathrm{kg}) \end{gathered}$ | Density $(\mathrm{kg} / \mathrm{L})$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 2 | 4 | DF | 0 | 0.0 | 64.0 | 55.0 | 21.0 | 2.149 | 3.697 | 0.581 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 4 | DF | 1 | 12.5 | 44.5 | 42.0 | 20.5 | 2.101 | 4.168 | 0.504 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 4 | DF | 2 | 22.1 | 34.5 | 32.5 | 17.5 | 1.233 | 2.639 | 0.467 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 4 | DF | 3 | 25.4 | 27.5 | 29.5 | 12.5 | 0.63 | 1.345 | 0.468 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 4 | DF | 4 | 30.4 | 14.2 | 12.5 | 3.0 | 0.245 | 0.496 | 0.494 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 3 | DF | 0 | 0.0 | 60.0 | 52.0 | 40.0 | 1.443 | 2.573 | 0.561 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 3 | DF | 1 | 15.0 | 40.0 | 36.0 | 31.0 | 1.189 | 2.096 | 0.567 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 3 | DF | 2 | 27.3 | 32.5 | 29.2 | 19.0 | 1.478 | 2.752 | 0.537 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 3 | DF | 3 | 28.5 | 14.5 | 13.0 | 3.0 | 0.37 | 0.654 | 0.566 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 3 | DF | 4 | 29.5 | 11.5 | 10.5 | 2.2 | 0.064 | 0.135 | 0.474 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 2 | DF | 0 | 0.0 | 52.0 | 45.0 | 33.0 | 2.527 | 3.997 | 0.632 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 2 | DF | 1 | 12.5 | 33.8 | 30.4 | 20.7 | 1.114 | 2.012 | 0.554 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 2 | DF | 2 | 25.0 | 19.5 | 17.0 | 8.0 | 0.483 | 0.930 | 0.519 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 2 | DF | 3 | 29.6 | 10.6 | 9.3 | 2.2 | 0.115 | 0.222 | 0.518 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 2 | DF | 0 | 0.0 | 44.0 | 38.0 | 27.0 | 1.832 | 3.505 | 0.523 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 2 | DF | 1 | 12.5 | 26.8 | 24.7 | 15.4 | 0.988 | 1.913 | 0.516 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \mathrm{t} \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | " Wet" Wt <br> (kg) | $\begin{aligned} & \text { Density } \\ & \text { (kg/L) } \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 10 | 2 | DF | 2 | 19.6 | 21.5 | 19.7 | 9.3 | 0.475 | 0.852 | 0.558 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 2 | DF | 3 | 26.1 | 10.7 | 9.5 | 3.0 | 0.106 | 0.212 | 0.500 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 2 | DF | 0 | 0.0 | 39.5 | 34.0 | 25.0 | 1.785 | 2.979 | 0.599 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 2 | DF | 1 | 1.8 | 29.5 | 26.0 | 18.0 | 0.884 | 1.511 | 0.585 |
| L1 11 1  <br> 1    |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 2 | DF | 2 | 14.4 | 19.5 | 17.0 | 12.5 | 0.355 | 0.692 | 0.513 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 2 | DF | 3 | 23.2 | 10.5 | 9.0 | 3.8 | 0.175 | 0.349 | 0.501 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 3 | DF | 0 | 0.0 | 68.0 | 60.0 | 44.0 | 2.74 | 4.041 | 0.678 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 3 | DF | 1 | 12.5 | 37.0 | 34.5 | 24.0 | 1.931 | 4.771 | 0.405 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 3 | DF | 2 | 24.0 | 27.0 | 23.5 | 11.5 | 0.69 | 0.421 | 1.639 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 3 | DF | 3 | 28.0 | 17.0 | 15.5 | 5.5 | 0.31 | 0.625 | 0.496 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 3 | DF | 4 | 29.9 | 11.5 | 10.2 | 2.2 | 0.16 | 0.333 | 0.480 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 4 | DF | 0 | 0.0 | 58.0 | 53.0 | 45.0 | 2.893 | 5.335 | 0.542 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 4 | DF | 1 | 12.5 | 50.0 | 46.5 | 37.5 | 1.625 | 3.404 | 0.477 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 4 | DF | 2 | 25.1 | 33.5 | 31.0 | 20.5 | 1.304 | 2.764 | 0.472 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 14 | 1 | DF | 0 | 0.0 | 31.5 | 26.0 | 14.5 | 1.489 | 2.513 | 0.593 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 14 | 1 | DF | 1 | 11.2 | 13.6 | 12.0 | 6.0 | 0.175 | 0.307 | 0.570 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 14 | 1 | DF | 2 | 14.3 | 10.2 | 9.8 | 1.5 | 0.136 | 0.243 | 0.560 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 1 | 2 | DF | 0 | 0.0 | 47.0 | 39.0 | 30.0 | 1.246 | 1.972 | 0.632 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 1 | 2 | DF | 1 | 12.5 | 31.6 | 29.2 | 21.3 | 1.532 | 2.705 | 0.566 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 1 | 2 | DF | 2 | 24.9 | 15.3 | 13.6 | 6.4 | 0.359 | 0.625 | 0.574 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 1 | 2 | DF | 3 | 26.2 | 10.6 | 9.2 | 3.5 | 0.242 | 0.398 | 0.608 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 4 | DF | 0 | 0.0 | 68.0 | 59.0 | 44.0 | 2.049 | 3.846 | 0.533 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 4 | DF | 1 | 12.5 | 52.0 | 48.0 | 36.0 | 1.041 | 2.196 | 0.474 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 4 | DF | 2 | 23.7 | 40.0 | 37.0 | 22.0 | 1.585 | 3.633 | 0.436 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 4 | DF | 3 | 29.0 | 29.0 | 25.5 | 12.0 | 0.964 | 2.147 | 0.449 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| Plo | Tree Num. | Qu art, | Species | Disk | Height <br> (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 2 | 4 | DF | 4 | 35.8 | 8.5 | 7.5 | 2.0 | 0.069 | 0.135 | 0.511 |
| D |  |  |  |  |  |  |  |  |  |  |  |
|  | 3 | 2 | DF | 0 | 0.0 | 38.0 | 33.5 | 24.0 | 1.508 | 2.852 | 0.529 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 2 | DF | 1 | 12.5 | 25.0 | 23.0 | 18.0 | 0.577 | 1.184 | 0.487 |
| L |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 2 | DF | 2 | 24.9 | 18.0 | 16.0 | 9.5 | 0.254 | 0.526 | 0.483 |
| L |  |  |  |  |  |  |  |  |  |  |  |
|  | 3 | 2 | DF | 3 | 29.3 | 12.0 | 10.5 | 3.1 | 0.118 | 0.272 | 0.434 |
| L |  |  |  |  |  |  |  |  |  |  |  |
|  | 4 | 3 | DF | 0 | 0.0 | 60.0 | 25.5 | 23.0 | 0.823 | 1.502 | 0.548 |
| L |  |  |  |  |  |  |  |  |  |  |  |
|  | 4 | 3 | DF | 1 | 12.5 | 37.0 | 34.0 | 17.0 | 0.994 | 2.079 | 0.478 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| $\begin{aligned} & \mathrm{L2} \\ & \text { DF } \end{aligned}$ | 4 | 3 | DF | 2 | 25.0 | 25.5 | 23.0 | 14.0 | 0.656 | 1.429 | 0.459 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| L | 4 | 3 | DF | 3 | 30.7 | 13.5 | 12.0 | 4.5 | 0.181 | 0.382 | 0.474 |
| L |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 3 | DF | 4 | 31.7 | 11.5 | 10.0 | 2.5 | 0.128 | 0.259 | 0.494 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 3 | DF | 0 | 0.0 | 54.0 | 50.0 | 46.0 | 0.123 | 2.342 | 0.053 |
| L |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 3 | DF | 1 | 12.5 | 33.5 | 30.5 | 20.0 | 1.148 | 2.370 | 0.484 |
| L |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 3 | DF | 2 | 25.0 | 24.0 | 22.0 | 12.0 | 0.31 | 0.639 | 0.485 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| L2 | 5 | 3 | DF | 3 | 32.7 | 10.2 | 9.0 | 1.2 | 0.082 | 0.163 | 0.503 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 1 | DF | 0 | 0.9 | 25.0 | 21.0 | 14.0 | 0.437 | 0.845 | 0.517 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 1 | DF | 1 | 2.7 | 19.0 | 18.0 | 12.0 | 0.332 | 0.602 | 0.551 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| D | 7 | 1 | DF | 2 | 15.2 | 12.5 | 11.8 | 8.0 | 0.187 | 0.392 | 0.477 |
| L |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 1 | DF | 3 | 17.8 | 11.3 | 10.2 | 6.0 | 0.11 | 0.230 | 0.478 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 3 | DF | 0 | 0.0 | 64.0 | 58.0 | 42.0 | 3.108 | 4.961 | 0.626 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| D | 2 | 3 | DF | 1 | 12.5 | 42.0 | 39.5 | 28.0 | 2.682 | 4.792 | 0.560 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 3 | DF | 2 | 25.2 | 27.5 | 25.0 | 13.5 | 0.807 | 1.545 | 0.522 |
| L |  |  |  |  |  |  |  |  |  |  |  |
|  | 2 | 3 | DF | 3 | 31.5 | 14.5 | 13.0 | 5.0 | 0.124 | 0.241 | 0.515 |
| L |  |  |  |  |  |  |  |  |  |  |  |
|  | 2 | 3 | DF | 4 | 34.2 | 11.5 | 10.0 | 2.5 | 0.165 | 0.330 | 0.500 |
| L |  |  |  |  |  |  |  |  |  |  |  |
|  | 3 | 1 | DF | 0 | 0.0 | 38.0 | 36.0 | 27.0 | 2.006 | 3.794 | 0.529 |
| D |  |  |  |  |  |  |  |  |  |  |  |
| L | 3 | 1 | DF | 1 | 12.5 | 24.0 | 22.2 | 13.0 | 0.607 | 1.155 | 0.526 |
| DF |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\underset{\mathrm{t}}{\mathrm{Plo}}$ | Tree Num. | Qu art, | Species | Disk | Height (m) | DOB | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | $\begin{gathered} \text { " Wet" } \\ \text { Wt } \\ (\mathrm{kg}) \end{gathered}$ | $\begin{gathered} \text { Density } \\ (\mathrm{kg} / \mathrm{L}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 3 | 1 | DF | 2 | 19.6 | 17.3 | 15.6 | 5.5 | 0.261 | 0.542 | 0.482 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 1 | DF | 3 | 23.6 | 11.5 | 10.2 | 2.2 | 0.135 | 0.292 | 0.462 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 2 | BM | 0 | 0.0 | 23.0 | 21.5 | 11.0 | 0.867 | 1.512 | 0.573 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 2 | BM | 1 | 13.1 | 27.5 | 26.0 | 12.0 | 1.219 | 2.271 | 0.537 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 2 | BM | 2 | 18.8 | 13.2 | 11.7 | 2.0 | 0.15 | 0.267 | 0.562 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 4 | DF | 0 | 0.0 | 76.0 | 62.0 | 51.0 | 2.1 | 4.631 | 0.453 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 4 | DF | 1 | 2.5 | 61.0 | 53.0 | 41.0 | 1.702 | 2.896 | 0.588 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 4 | DF | 2 | 15.0 | 45.5 | 42.5 | 32.5 | 3.042 | 5.921 | 0.514 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 4 | DF | 3 | 26.4 | 33.0 | 30.0 | 19.5 | 0.885 | 1.879 | 0.471 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 4 | DF | 4 | 35.9 | 13.2 | 11.5 | 3.2 | 0.125 | 0.264 | 0.473 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 4 | DF | 5 | 36.8 | 10.2 | 9.1 | 2.2 | 0.103 | 0.211 | 0.488 |
| $\begin{array}{llllllllllllllllllll}\text { L3 } & \\ \text { L }\end{array}$ |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 4 | DF | 0 | 0.0 | 66.0 | 54.0 | 38.0 | 2.386 | 4.337 | 0.550 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 4 | DF | 1 | 12.5 | 42.0 | 39.5 | 28.0 | 1.789 | 3.675 | 0.487 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 4 | DF | 2 | 25.2 | 28.0 | 26.0 | 13.5 | 0.858 | 1.673 | 0.513 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 4 | DF | 3 | 30.4 | 14.8 | 13.5 | 4.5 | 0.24 | 0.479 | 0.501 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 4 | DF | 4 | 31.9 | 11.6 | 10.4 | 3.0 | 0.164 | 0.338 | 0.485 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 1 | DF | 0 | 0.0 | 20.5 | 18.0 | 14.5 | 0.467 | 0.855 | 0.546 |
| L3 12 1  |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 1 | DF | 1 | 6.4 | 13.2 | 12.0 | 9.0 | 0.192 | 0.355 | 0.541 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 1 | DF | 2 | 10.0 | 11.0 | 10.0 | 7.0 | 0.09 | 0.173 | 0.520 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 3 | DF | 0 | 0.0 | 52.0 | 44.0 | 34.0 | 2.03 | 3.696 | 0.549 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 3 | DF | 1 | 12.5 | 41.0 | 37.0 | 24.5 | 2.376 | 4.998 | 0.475 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 3 | DF | 2 | 25.1 | 28.0 | 26.0 | 12.0 | 0.964 | 2.015 | 0.478 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 3 | DF | 3 | 31.9 | 13.0 | 11.5 | 2.5 | 0.241 | 0.437 | 0.551 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 3 | DF | 4 | 33.1 | 11.0 | 9.5 | 2.0 | 0.193 | 0.369 | 0.523 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 2 | DF | 0 | 0.3 | 59.0 | 54.0 | 44.0 | 2.154 | 3.950 | 0.545 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)
$\left.\begin{array}{cccccccccccc}\text { Plo } & \text { Tree } & \text { Qu } & \text { Species } & \text { Disk } & \begin{array}{c}\text { Height } \\ \text { t }\end{array} & \begin{array}{c}\text { Num. } \\ \text { art, }\end{array} & & & & \begin{array}{c}\text { DOB } \\ (\mathrm{cm})\end{array} & \begin{array}{c}\text { DUB } \\ (\mathrm{cm})\end{array} \\ & & & & & & & \text { Heartw } \\ \text { ood } \\ (\mathrm{cm})\end{array}\right)$

Table B. 1 (Continued)

| Plo | Tree Num. | Qu art, | Species | Disk | Height <br> (m) | DOB | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 8 | 2 | DF | 2 | 25.0 | 23.2 | 21.5 | 14.2 | 0.638 | 1.214 | 0.526 |
| L5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 8 | 2 | DF | 3 | 35.5 | 10.5 | 9.4 | 2.5 | 0.092 | 0.180 | 0.511 |
| L5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 2 | DF | 0 | 0.4 | 45.0 | 42.2 | 32.5 | 0.53 | 1.058 | 0.501 |
| L5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 2 | DF | 1 | 12.4 | 32.0 | 29.5 | 21.0 | 1.183 | 2.294 | 0.516 |
| L5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 2 | DF | 2 | 17.4 | 29.0 | 21.5 | 13.0 | 0.424 | 0.893 | 0.475 |
| L5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 2 | DF | 3 | 36.5 | 11.5 | 10.4 | 3.0 | N/A | N/A | N/A |
| L5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 4 | DF | 0 | 0.0 | 56.0 | 44.0 | 36.0 | 1.165 | 1.981 | 0.588 |
| L5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 4 | DF | 1 | 12.5 | 41.0 | 36.0 | 28.0 | 0.805 | 1.457 | 0.553 |
| L5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 4 | DF | 2 | 25.1 | 31.0 | 28.0 | 20.0 | 1.047 | 2.031 | 0.516 |
| L5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 4 | DF | 3 | 38.0 | 11.0 | 9.5 | 2.0 | 0.094 | 0.188 | 0.500 |
| L5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 1 | 4 | DF | 0 | 0.0 | 45.0 | 37.8 | 27.0 | 2.93 | 6.722 | 0.436 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 1 | 4 | DF | 1 | 12.5 | 28.0 | 26.2 | 17.5 | 0.476 | 1.166 | 0.408 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 1 | 4 | DF | 2 | 19.4 | 18.0 | 16.5 | 7.5 | 0.321 | 0.743 | 0.432 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 1 | 4 | DF | 3 | 22.4 | 11.1 | 10.0 | 2.0 | 0.089 | 0.216 | 0.412 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 0 | 0.0 | 44.0 | 36.5 | 26.0 | 1.491 | 3.020 | 0.494 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 1 | 12.7 | 25.0 | 23.0 | 18.0 | 0.821 | 1.973 | 0.416 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 2 | 18.5 | 17.0 | 15.5 | 8.0 | 0.274 | 0.676 | 0.405 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 3 | 21.2 | 12.5 | 11.5 | 4.0 | 0.141 | 0.346 | 0.408 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 9 | 1 | DF | 0 | 0.0 | 32.5 | 27.5 | 19.0 | 0.716 | 1.307 | 0.548 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 9 | 1 | DF | 1 | 12.6 | 20.5 | 19.0 | 9.0 | 0.237 | 0.512 | 0.463 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 9 | 1 | DF | 2 | 18.4 | 14.0 | 12.5 | 4.0 | 0.154 | 0.343 | 0.449 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 9 | 1 | DF | 3 | 20.1 | 11.5 | 10.2 | 2.3 | 0.122 | 0.272 | 0.449 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 3 | DF | 0 | 0.0 | 36.0 | 32.0 | 24.0 | 0.925 | 2.118 | 0.437 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 3 | DF | 1 | 12.5 | 21.5 | 20.5 | 13.0 | 0.425 | 0.902 | 0.471 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 3 | DF | 2 | 17.8 | 14.5 | 13.0 | 7.0 | 0.132 | 0.301 | 0.439 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \text { t } \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height <br> (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & \text { (cm) } \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 13 | 3 | DF | 3 | 18.8 | 11.5 | 10.5 | 3.0 | 0.154 | 0.305 | 0.505 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 19 | 3 | DF | 0 | 0.0 | 34.0 | 28.5 | 22.5 | 1.549 | 2.845 | 0.544 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 19 | 3 | DF | 1 | 12.5 | 23.5 | 21.5 | 12.5 | 0.562 | 1.249 | 0.450 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 19 | 3 | DF | 2 | 20.8 | 13.4 | 10.2 | 2.5 | 0.129 | 0.294 | 0.439 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| DF | 19 | 3 | DF | 3 | 22.4 | 10.3 | 9.2 | 1.2 | 0.065 | 0.146 | 0.445 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 1 | DF | 0 | 0.0 | 28.0 | 24.5 | 20.5 | 0.522 | 1.093 | 0.478 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 1 | DF | 1 | 3.9 | 21.5 | 19.5 | 15.0 | 0.272 | 0.585 | 0.465 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 1 | DF | 2 | 15.2 | 14.0 | 13.0 | 6.0 | 0.099 | 0.253 | 0.391 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 1 | DF | 3 | 17.8 | 12.0 | 10.8 | 2.5 | 0.089 | 0.182 | 0.489 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 3 | DF | 0 | 0.0 | 50.0 | 43.0 | 34.0 | 0.717 | 1.517 | 0.473 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 3 | DF | 1 | 12.5 | 28.5 | 26.0 | 16.5 | 0.317 | 0.722 | 0.439 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 2 | 3 | DF | 2 | 21.3 | 14.5 | 13.5 | 5.0 | 0.105 | 0.243 | 0.432 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 4 | DF | 0 | 0.0 | 47.0 | 41.0 | 32.0 | 0.763 | 1.620 | 0.471 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 4 | DF | 1 | 12.5 | 29.5 | 27.0 | 17.0 | 0.673 | 1.406 | 0.479 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 4 | DF | 2 | 20.2 | 16.7 | 15.4 | 6.5 | 0.188 | 0.500 | 0.376 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 4 | DF | 3 | 23.0 | 11.0 | 9.7 | 2.0 | 0.044 | 0.161 | 0.273 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 1 | DF | 0 | 0.0 | 29.5 | 26.0 | 16.0 | 0.385 | 0.738 | 0.522 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 1 | DF | 1 | 12.5 | 20.2 | 18.4 | 10.4 | 0.172 | 0.362 | 0.475 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 1 | DF | 2 | 19.0 | 14.0 | 13.0 | 4.0 | 0.095 | 0.207 | 0.459 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 1 | DF | 3 | 21.0 | 11.5 | 10.5 | 0.5 | 0.065 | 0.147 | 0.442 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 1 | DF | 0 | 0.0 | 37.5 | 32.5 | 24.5 | 1.205 | 2.320 | 0.519 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 1 | DF | 1 | 12.5 | 25.0 | 23.5 | 13.0 | 0.332 | 0.709 | 0.468 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 1 | DF | 2 | 21.8 | 13.5 | 12.0 | 2.2 | 0.119 | 0.254 | 0.469 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 1 | DF | 3 | 22.6 | 10.5 | 9.7 | 2.0 | 0.048 | 0.112 | 0.429 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\underset{\mathrm{t}}{\mathrm{Plo}}$ | Tree Num. | Qu art, | Species | Disk | Height (m) | $\begin{gathered} \text { DOB } \\ (\mathrm{cm}) \end{gathered}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" <br> (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 12 | 2 | DF | 0 | 0.0 | 39.0 | 35.0 | 27.0 | 0.889 | 1.756 | 0.506 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 2 | DF | 1 | 12.5 | 30.5 | 28.0 | 18.0 | 0.805 | 1.387 | 0.580 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 2 | DF | 2 | 22.7 | 15.5 | 14.5 | 5.0 | 0.185 | 0.374 | 0.495 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 2 | DF | 3 | 24.5 | 10.5 | 9.7 | 2.5 | 0.071 | 0.150 | 0.473 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 14 | 1 | DF | 0 | 0.0 | 43.0 | 36.5 | 25.5 | 2.323 | 4.323 | 0.537 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 14 | 1 | DF | 1 | 12.5 | 25.1 | 23.8 | 14.5 | 0.338 | 0.709 | 0.477 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 14 | 1 | DF | 2 | 20.8 | 14.2 | 12.7 | 3.0 | 0.077 | 0.169 | 0.456 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 14 | 1 | DF | 3 | 22.8 | 11.0 | 9.9 | 1.5 | 0.087 | 0.188 | 0.463 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 0 | 0.0 | 41.0 | 34.0 | 27.0 | 1.755 | 3.639 | 0.482 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 1 | 12.5 | 36.0 | 33.5 | 26.0 | 0.337 | 0.739 | 0.456 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 2 | 18.6 | 23.5 | 21.2 | 13.0 | 0.127 | 0.281 | 0.452 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 3 | 21.1 | 14.8 | 13.1 | 5.5 | 0.089 | 0.185 | 0.481 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 4 | 22.1 | 11.2 | 9.8 | 5.0 |  |  |  |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 8 | 4 | DF | 0 | 0.0 | 35.0 | 29.0 | 22.0 | 0.538 | 1.131 | 0.476 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 8 | 4 | DF | 1 | 12.5 | 23.5 | 21.5 | 13.5 | 0.262 | 0.617 | 0.425 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 8 | 4 | DF | 2 | 20.0 | 14.0 | 12.5 | 4.0 | 0.138 | 0.308 | 0.448 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 8 | 4 | DF | 3 | 22.2 | 10.5 | 9.6 | 3.0 | 0.082 | 0.185 | 0.443 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 4 | DF | 0 | 0.0 | 40.0 | 35.0 | 26.0 | 0.752 | 0.799 | 0.941 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 4 | DF | 1 | 12.5 | 26.0 | 24.0 | 12.0 | 0.374 | 0.842 | 0.444 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 4 | DF | 2 | 19.0 | 15.5 | 14.0 | 3.5 | 0.149 | 0.358 | 0.416 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 4 | DF | 3 | 20.3 | 10.5 | 9.3 | 1.0 | 0.053 | 0.115 | 0.461 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 1 | DF | 0 | 0.0 | 26.0 | 21.5 | 18.0 | 0.493 | 0.998 | 0.494 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 1 | DF | 1 | 11.2 | 16.0 | 14.5 | 10.0 | 0.212 | 0.513 | 0.413 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 1 | DF | 2 | 16.1 | 11.5 | 9.7 | 3.5 | 0.05 | 0.102 | 0.490 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 20 | 3 | DF | 0 | 0.0 | 33.0 | 29.0 | 24.0 | 0.446 | 0.857 | 0.520 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| Plo | Tree Num. | Qu art, | Species | Disk | Height <br> (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 20 | 3 | DF | 1 | 11.2 | 20.5 | 19.0 | 10.5 | 0.279 | 0.630 | 0.443 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 20 | 3 | DF | 2 | 16.5 | 14.4 | 13.0 | 4.0 | 0.148 | 0.342 | 0.433 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 20 | 3 | DF | 3 | 19.6 | 9.6 | 8.5 | 0.7 | 0.04 | 0.087 | 0.460 |
| M3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 4 | DF | 0 | 0.0 | 50.0 | 43.0 | 31.0 | 0.404 | 0.920 | 0.439 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 4 | DF | 1 | 12.4 | 29.4 | 27.6 | 18.0 | 0.798 | 1.918 | 0.416 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 4 | DF | 2 | 21.8 | 15.4 | 13.5 | 5.0 | 0.118 | 0.262 | 0.450 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 4 | DF | 3 | 24.4 | 11.0 | 9.5 | 2.3 | 0.098 | 0.218 | 0.450 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 4 | DF | 0 | 0.0 | 54.0 | 46.8 | 34.0 | 0.629 | 1.440 | 0.437 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 4 | DF | 1 | 12.5 | 26.5 | 25.0 | 15.0 | 0.593 | 1.404 | 0.422 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 4 | DF | 2 | 20.8 | 14.5 | 13.4 | 5.0 | 0.151 | 0.426 | 0.354 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 4 | DF | 3 | 23.8 | 9.0 | 8.0 | 2.0 | N/A | N/A | N/A |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 3 | DF | 0 | 0.0 | 22.0 | 19.5 | 14.5 | 0.776 | 1.555 | 0.499 |
| M4 ${ }^{\text {d }}$ |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 3 | DF | 1 | 12.5 | 25.5 | 24.2 | 16.7 | 0.52 | 1.150 | 0.452 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 3 | DF | 2 | 20.8 | 14.3 | 13.3 | 3.6 | 0.154 | 0.337 | 0.457 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 13 | 3 | DF | 3 | 23.2 | 10.3 | 9.3 | 1.4 | 0.062 | 0.134 | 0.463 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 1 | DF | 0 | 0.0 | 31.0 | 26.5 | 19.2 | 0.536 | 1.145 | 0.468 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 1 | DF | 1 | 12.6 | 19.5 | 17.5 | 10.2 | 0.211 | 0.472 | 0.447 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 1 | DF | 2 | 19.0 | 13.6 | 12.7 | 4.0 | 0.053 | 0.122 | 0.434 |
| $\begin{array}{lllllllllllllllllll}\text { M4 } & \\ \end{array}$ |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 1 | DF | 3 | 21.7 | 9.5 | 8.4 | 2.0 | 0.104 | 0.224 | 0.464 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 18 | 1 | DF | 0 | 0.0 | 38.0 | 35.5 | 28.0 | 0.47 | 0.911 | 0.516 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 18 | 1 | DF | 1 | 12.5 | 21.0 | 20.0 | 11.5 | 0.452 | 0.981 | 0.461 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 18 | 1 | DF | 2 | 19.0 | 13.8 | 12.8 | 5.4 | 0.2 | 0.402 | 0.498 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 18 | 1 | DF | 3 | 21.2 | 9.9 | 8.9 | 3.2 | 0.023 | 0.047 | 0.489 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| DF | 21 | 4 | DF | 0 | 0.0 | 28.5 | 26.0 | 20.5 | 0.725 | 1.691 | 0.429 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 21 | 4 | DF | 1 | 12.4 | 31.5 | 29.7 | 18.6 | 0.75 | 1.749 | 0.429 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \text { t } \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height <br> (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & \text { (cm) } \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 21 | 4 | DF | 2 | 19.4 | 21.1 | 19.6 | 7.5 | 0.303 | 0.638 | 0.475 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 21 | 4 | DF | 3 | 24.3 | 9.8 | 9.0 | 1.9 | 0.06 | 0.121 | 0.496 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 23 | 2 | DF | 0 | 0.0 | 41.0 | 36.0 | 26.5 | 0.954 | 1.804 | 0.529 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 23 | 2 | DF | 1 | 12.5 | 25.4 | 23.5 | 13.0 | 0.64 | 1.299 | 0.493 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 23 | 2 | DF | 2 | 20.8 | 14.5 | 13.2 | 2.8 | 0.144 | 0.321 | 0.449 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 23 | 2 | DF | 3 | 23.2 | 9.7 | 8.6 | 1.5 | 0.018 | 0.038 | 0.474 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 1 | DF | 0 | 0.0 | 26.3 | 22.5 | 18.5 | 0.434 | 0.842 | 0.515 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 1 | DF | 1 | 11.3 | 13.8 | 13.3 | 9.0 | 0.161 | 0.325 | 0.495 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 1 | DF | 2 | 16.4 | 10.8 | 9.7 | 4.4 | 0.098 | 0.201 | 0.488 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 3 | DF | 0 | 0.0 | 46.4 | 41.4 | 30.0 | 0.637 | 1.191 | 0.535 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 3 | DF | 1 | 12.5 | 30.5 | 28.0 | 18.3 | 1.095 | 1.984 | 0.552 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 3 | DF | 2 | 20.8 | 19.4 | 17.7 | 7.3 | 0.358 | 0.764 | 0.469 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 3 | DF | 3 | 25.9 | 10.3 | 9.2 | 2.0 | 0.065 | 0.137 | 0.474 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 2 | DF | 0 | 0.0 | 48.0 | 44.0 | 27.0 | 1.317 | 2.647 | 0.498 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 2 | DF | 1 | 12.5 | 24.5 | 23.0 | 9.8 | 0.538 | 1.093 | 0.492 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 2 | DF | 2 | 21.0 | 14.2 | 13.5 | 2.6 | 0.195 | 0.382 | 0.510 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 2 | DF | 3 | 23.5 | 9.4 | 8.6 | 1.7 | 0.055 | 0.117 | 0.470 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 1 | DF | 0 | 0.0 | 33.0 | 26.5 | 20.0 | 0.877 | 1.543 | 0.568 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 1 | DF | 1 | 12.5 | 21.0 | 19.5 | 12.3 | 0.378 | 0.779 | 0.485 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 1 | DF | 2 | 19.0 | 15.0 | 14.0 | 5.0 | 0.127 | 0.286 | 0.444 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 10 | 1 | DF | 3 | 21.5 | 11.0 | 10.3 | 3.3 | 0.044 | 0.095 | 0.463 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 4 | DF | 0 | 0.0 | 52.0 | 44.0 | 31.0 | 0.67 | 1.288 | 0.520 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 4 | DF | 1 | 12.4 | 34.0 | 31.0 | 20.0 | 0.864 | 1.811 | 0.477 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 4 | DF | 2 | 23.7 | 14.6 | 13.5 | 5.0 | 0.139 | 0.304 | 0.457 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 4 | DF | 3 | 26.5 | 9.4 | 8.4 | 2.0 | 0.059 | 0.124 | 0.476 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \mathrm{t} \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height <br> (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 22 | 4 | DF | 0 | 0.0 | 51.0 | 43.0 | 32.0 | 1.016 | 2.038 | 0.499 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 4 | DF | 1 | 12.5 | 31.0 | 28.5 | 15.5 | 0.4 | 0.780 | 0.513 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 4 | DF | 2 | 23.7 | 14.5 | 12.5 | 5.0 | 0.11 | 0.233 | 0.472 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 4 | DF | 3 | 26.0 | 9.0 | 8.2 | 1.8 | 0.043 | 0.086 | 0.500 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 1 | DF | 0 | 0.0 | 30.5 | 27.4 | 14.5 | 0.703 | 1.389 | 0.506 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 1 | DF | 1 | 1.3 | 24.5 | 22.5 | 12.5 | 0.689 | 1.423 | 0.484 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 1 | DF | 2 | 12.0 | 13.0 | 12.0 | 3.5 | 0.165 | 0.351 | 0.470 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 3 | 1 | DF | 3 | 13.5 | 10.0 | 9.2 | 2.0 | 0.123 | 0.248 | 0.496 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 4 | DF | 0 | 0.0 | 26.0 | 23.5 | 16.0 | 0.958 | 2.004 | 0.478 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 4 | DF | 1 | 7.3 | 20.5 | 19.0 | 11.0 | 0.217 | 0.598 | 0.363 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 4 | DF | 2 | 12.5 | 13.0 | 11.8 | 3.5 | 0.155 | 0.391 | 0.396 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 12 | 4 | DF | 3 | 14.5 | 11.5 | 10.0 | 2.2 | 0.112 | 0.208 | 0.538 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 19 | 1 | DF | 0 | 0.0 | 15.0 | 13.2 | 6.0 | 0.19 | 0.393 | 0.483 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 19 | 1 | DF | 1 | 5.2 | 12.5 | 11.5 | 5.0 | 0.13 | 0.284 | 0.458 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 19 | 1 | DF | 2 | 8.6 | 10.8 | 10.0 | 2.0 | 0.09 | 0.208 | 0.433 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 19 | 1 | DF | 3 | 10.5 | 10.0 | 9.0 | 0.8 | 0.094 | 0.193 | 0.487 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 23 | 3 | DF | 0 | 0.0 | 24.0 | 21.0 | 12.3 | 0.59 | 1.176 | 0.502 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 23 | 3 | DF | 1 | 11.3 | 15.2 | 14.4 | 4.7 | 0.142 | 0.339 | 0.419 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 23 | 3 | DF | 2 | 14.3 | 11.6 | 10.6 | 1.9 | 0.144 | 0.334 | 0.431 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 24 | 3 | DF | 0 | 0.0 | 27.0 | 25.5 | 12.5 | 0.839 | 1.713 | 0.490 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 24 | 3 | DF | 1 | 11.2 | 16.0 | 15.0 | 5.0 | 0.434 | 0.900 | 0.482 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 24 | 3 | DF | 2 | 14.1 | 11.5 | 10.4 | 2.0 | 0.149 | 0.352 | 0.423 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 28 | 2 | DF | 0 | 0.0 | 23.0 | 20.0 | 13.0 | 0.559 | 1.204 | 0.464 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 28 | 2 | DF | 1 | 8.1 | 14.4 | 13.0 | 7.0 | 0.18 | 0.419 | 0.430 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 28 | 2 | DF | 2 | 11.7 | 11.0 | 9.8 | 4.0 | 0.071 | 0.160 | 0.444 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\underset{\mathrm{t}}{\mathrm{Plo}}$ | Tree Num. | Qu art, | Species | Disk | Height (m) | DOB | $\begin{aligned} & \text { DUB } \\ & \text { (cm) } \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | $\begin{gathered} \text { " Wet" } \\ \text { Wt } \\ (\mathrm{kg}) \end{gathered}$ | $\begin{gathered} \text { Density } \\ (\mathrm{kg} / \mathrm{L}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 29 | 2 | DF | 0 | 0.0 | 24.5 | 21.7 | 12.3 | 0.694 | 1.399 | 0.496 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 29 | 2 | DF | 1 | 8.9 | 15.3 | 14.1 | 3.0 | 0.179 | 0.369 | 0.485 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 29 | 2 | DF | 2 | 13.0 | 10.8 | 9.8 | 1.3 | 0.096 | 0.191 | 0.503 |
| S1 20 ${ }^{\text {d }}$ |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 3 | DF | 0 | 0.0 | 26.5 | 22.5 | 11.5 | 0.771 | 1.475 | 0.523 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 3 | DF | 1 | 10.0 | 14.5 | 13.7 | 5.0 | 0.125 | 0.261 | 0.479 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 3 | DF | 2 | 13.6 | 9.8 | 9.0 | 1.7 | 0.092 | 0.200 | 0.460 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 2 | DF | 0 | 0.0 | 21.8 | 19.5 | 10.5 | 0.507 | 1.031 | 0.492 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 2 | DF | 1 | 7.6 | 13.8 | 12.9 | 5.3 | 0.152 | 0.339 | 0.448 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 2 | DF | 2 | 10.8 | 10.3 | 9.7 | 2.7 | 0.074 | 0.166 | 0.446 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 4 | DF | 0 | 0.0 | 26.0 | 23.8 | 12.0 | 0.729 | 1.515 | 0.481 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 4 | DF | 1 | 11.3 | 14.2 | 13.2 | 4.5 | 0.12 | 0.275 | 0.436 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 4 | DF | 2 | 13.4 | 10.9 | 10.0 | 1.6 | 0.08 | 0.183 | 0.437 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 24 | 4 | DF | 0 | 0.0 | 26.5 | 23.5 | 15.0 | 0.759 | 1.646 | 0.461 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 24 | 4 | DF | 1 | 9.4 | 14.5 | 13.5 | 6.0 | 0.158 | 0.401 | 0.394 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 24 | 4 | DF | 2 | 12.0 | 10.5 | 9.5 | 2.0 | 0.113 | 0.289 | 0.391 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 28 | 1 | DF | 0 | 0.0 | 18.5 | 16.8 | 8.2 | 0.35 | 0.722 | 0.485 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 28 | 1 | DF | 1 | 7.6 | 13.0 | 12.0 | 3.5 | 0.253 | 0.585 | 0.432 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 28 | 1 | DF | 2 | 10.4 | 10.7 | 10.0 | 1.8 | 0.105 | 0.252 | 0.417 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 30 | 4 | DF | 0 | 0.0 | 30.0 | 27.0 | 16.5 | 0.968 | 2.039 | 0.475 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 30 | 4 | DF | 1 | 8.8 | 20.5 | 19.5 | 8.0 | 0.243 | 0.611 | 0.398 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 30 | 4 | DF | 2 | 13.1 | 14.5 | 13.2 | 4.0 | 0.142 | 0.368 | 0.386 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 30 | 4 | DF | 3 | 15.1 | 11.5 | 10.5 | 2.0 | 0.113 | 0.279 | 0.405 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 0 | 0.0 | 29.0 | 25.5 | 12.0 | 1.329 | 2.565 | 0.518 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 1 | 11.3 | 15.0 | 14.0 | 3.0 | 0.257 | 0.614 | 0.419 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 6 | 4 | DF | 2 | 13.7 | 11.0 | 9.8 | 1.0 | 0.093 | 0.220 | 0.423 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \mathrm{t} \end{gathered}$ | Tree <br> Num. | Qu art, | Species | Disk | Height <br> (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 12 | 1 | DF | 0 | 0.0 | 9.0 | 7.8 | 3.0 | 0.079 | 0.141 | 0.560 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 3 | DF | 0 | 0.0 | 25.5 | 22.5 | 7.5 | 0.429 | 0.882 | 0.486 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 3 | DF | 1 | 10.6 | 14.3 | 13.5 | 4.8 | 0.18 | 0.422 | 0.427 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 15 | 3 | DF | 2 | 13.4 | 10.7 | 9.8 | 2.0 | 0.136 | 0.308 | 0.442 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 18 | 1 | DF | 0 | 0.0 | 17.5 | 16.0 | 6.8 | 0.331 | 0.643 | 0.515 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 18 | 1 | DF | 1 | 5.3 | 14.4 | 13.5 | 4.0 | 0.219 | 0.431 | 0.508 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 18 | 1 | DF | 2 | 9.5 | 11.2 | 10.3 | 1.3 | 0.085 | 0.196 | 0.434 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 31 | 3 | DF | 0 | 0.0 | 26.5 | 24.0 | 13.8 | 0.831 | 1.776 | 0.468 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 31 | 3 | DF | 1 | 11.3 | 14.5 | 13.5 | 4.5 | 0.206 | 0.509 | 0.405 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 32 | 4 | DF | 0 | 0.0 | 13.6 | 12.5 | 8.0 | 0.471 | 1.055 | 0.446 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 32 | 4 | DF | 1 | 11.3 | 14.4 | 13.4 | 4.2 | 0.142 | 0.335 | 0.424 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 32 | 4 | DF | 2 | 13.4 | 11.2 | 10.3 | 2.2 | 0.163 | 0.386 | 0.422 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 40 | 2 | DF | 0 | 0.0 | 21.5 | 18.0 | 8.5 | 0.784 | 1.541 | 0.509 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 40 | 2 | DF | 1 | 10.0 | 14.0 | 13.0 | 4.0 | 0.112 | 0.256 | 0.438 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 40 | 2 | DF | 2 | 12.6 | 10.5 | 9.5 | 1.2 | 0.066 | 0.151 | 0.437 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 2 | DF | 0 | 0.0 | 21.5 | 19.0 | 9.0 | 0.391 | 0.810 | 0.483 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 2 | DF | 1 | 11.3 | 13.0 | 12.3 | 5.0 | 0.316 | 0.632 | 0.500 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 7 | 2 | DF | 2 | 13.8 | 10.5 | 9.8 | 2.0 | 0.1 | 0.237 | 0.422 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 4 | DF | 0 | 0.0 | 29.5 | 25.5 | 15.2 | 1.004 | 2.161 | 0.465 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 4 | DF | 1 | 11.3 | 16.1 | 14.8 | 5.1 | 0.217 | 0.517 | 0.420 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 11 | 4 | DF | 2 | 13.2 | 12.0 | 11.0 | 2.2 | 0.104 | 0.255 | 0.408 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 1 | DF | 0 | 0.0 | 14.6 | 13.5 | 6.2 | 0.123 | 0.285 | 0.432 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 1 | DF | 1 | 6.4 | 11.7 | 10.7 | 3.8 | 0.146 | 0.345 | 0.423 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 17 | 1 | DF | 2 | 9.5 | 10.2 | 9.3 | 2.7 | 0.076 | 0.171 | 0.444 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 20 | 2 | DF | 0 | 0.0 | 25.1 | 21.8 | 12.4 | 0.634 | 1.376 | 0.461 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \text { t } \end{gathered}$ | Tree Num. | Qu <br> art, | Species | Disk | Height <br> (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & \text { (cm) } \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 20 | 2 | DF | 1 | 10.1 | 14.1 | 12.9 | 4.0 | 0.166 | 0.392 | 0.423 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 20 | 2 | DF | 2 | 12.3 | 11.0 | 10.1 | 2.2 | 0.097 | 0.236 | 0.411 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 3 | DF | 0 | 0.0 | 27.2 | 24.5 | 13.5 | 0.697 | 1.385 | 0.503 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 3 | DF | 1 | 11.3 | 15.5 | 14.2 | 5.6 | 0.148 | 0.326 | 0.454 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 3 | DF | 2 | 13.5 | 13.0 | 11.7 | 3.0 | 0.201 | 0.451 | 0.446 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 22 | 3 | DF | 3 | 15.2 | 9.8 | 8.8 | 1.3 | 0.114 | 0.257 | 0.444 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 32 | 2 | DF | 0 | 0.0 | 26.5 | 23.0 | 13.5 | 0.613 | 1.170 | 0.524 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 32 | 2 | DF | 1 | 12.5 | 15.3 | 14.2 | 4.8 | 0.257 | 0.543 | 0.473 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 32 | 2 | DF | 2 | 16.1 | 10.6 | 9.9 | 1.7 | 0.13 | 0.280 | 0.464 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 1 | DF | 0 | 0.0 | 18.6 | 15.7 | 8.5 | 0.231 | 0.473 | 0.488 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 1 | DF | 1 | 4.5 | 13.1 | 12.1 | 6.8 | 0.161 | 0.364 | 0.442 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 4 | 1 | DF | 2 | 7.3 | 10.9 | 10.1 | 4.3 | 0.09 | 0.209 | 0.431 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 2 | DF | 0 | 0.0 | 22.2 | 19.5 | 11.2 | 0.423 | 0.943 | 0.449 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 2 | DF | 1 | 7.7 | 16.5 | 15.3 | 7.9 | 0.229 | 0.504 | 0.454 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 5 | 2 | DF | 2 | 11.1 | 12.0 | 11.2 | 2.5 | 0.143 | 0.350 | 0.409 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 8 | 1 | DF | 0 | 0.0 | 24.2 | 21.5 | 11.0 | 0.382 | 0.822 | 0.465 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 8 | 1 | DF | 1 | 8.9 | 14.9 | 13.5 | 6.6 | 0.226 | 0.524 | 0.431 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 8 | 1 | DF | 2 | 12.4 | 12.0 | 10.8 | 3.5 | 0.213 | 0.437 | 0.487 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 14 | 3 | DF | 0 | 0.0 | 28.0 | 24.5 | 13.5 | 1.043 | 2.001 | 0.521 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 14 | 3 | DF | 1 | 12.5 | 14.0 | 13.0 | 3.2 | 0.223 | 0.481 | 0.464 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 14 | 3 | DF | 2 | 15.1 | 11.0 | 10.0 | 1.5 | 0.094 | 0.198 | 0.475 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 20 | 4 | DF | 0 | 0.0 | 29.5 | 25.0 | 16.0 | 0.71 | 1.368 | 0.519 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 20 | 4 | DF | 1 | 12.5 | 15.4 | 14.1 | 2.7 | 0.176 | 0.377 | 0.467 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 20 | 4 | DF | 2 | 15.4 | 11.4 | 10.3 | 1.2 | 0.127 | 0.265 | 0.479 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 31 | 3 | DF | 0 | 0.0 | 26.0 | 23.0 | 12.0 | 0.671 | 1.506 | 0.446 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \mathrm{t} \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood <br> (cm) | Dry Wt <br> (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| DF | 31 | 3 | DF | 1 | 10.1 | 14.9 | 13.8 | 3.7 | 0.289 | 0.658 | 0.439 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| DF | 31 | 3 | DF | 2 | 13.5 | 11.0 | 10.0 | 2.5 | 0.098 | 0.226 | 0.434 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 2 | 1 | WF | 0 | 0.0 | 18.4 | 14.8 | 3.0 | 0.29 | 0.694 | 0.418 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 2 | 1 | WF | 1 | 6.0 | 10.0 | 9.2 | 2.6 | 0.069 | 0.191 | 0.361 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 1 | IC | 0 | 0.0 | 7.5 | 6.0 | 1.7 | 0.054 | 0.115 | 0.470 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 1 | IC | 1 | 2.1 | N/A | N/A | N/A | N/A | N/A | N/A |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 27 | 2 | DF | 0 | 0.0 | 31.0 | 25.0 | 14.0 | 1.311 | 2.696 | 0.486 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 27 | 2 | DF | 1 | 10.7 | 16.0 | 15.5 | 7.0 | 0.228 | 0.526 | 0.433 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 27 | 2 | DF | 2 | 14.8 | 9.5 | 8.5 | 2.5 | 0.071 | 0.163 | 0.436 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 34 | 1 | PP | 0 | 0.0 | 42.0 | 33.4 | N/A | 0.267 | 0.584 | 0.457 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 34 | 1 | PP | 1 | 7.0 | 20.7 | 19.3 | N/A | 0.413 | 0.939 | 0.440 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 34 | 1 | PP | 2 | 10.7 | 14.3 | 13.7 | N/A | 0.105 | 0.242 | 0.434 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 34 | 1 | PP | 3 | 16.2 | 10.1 | 9.7 | N/A | 0.098 | 0.210 | 0.467 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 35 | 1 | PP | 0 | 0.0 | 28.0 | 25.0 | 5.0 | 0.551 | 1.039 | 0.530 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 35 | 1 | PP | 1 | 10.6 | 19.0 | 16.0 | 4.5 | 0.331 | 0.724 | 0.457 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 35 | 1 | PP | 2 | 20.9 | 10.0 | 8.5 | 0.4 | 0.09 | 0.191 | 0.471 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 35 | 1 | PP | 3 | 23.7 | N/A | N/A | N/A | N/A | N/A | N/A |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 36 | 1 | PP | 0 | 0.0 | 13.5 | 9.2 | 1.2 | 0.141 | 0.348 | 0.405 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 36 | 1 | PP | 1 | 3.5 | 7.5 | 6.4 | 1.5 | 0.042 | 0.079 | 0.532 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 37 | 1 | WF | 0 | 0.0 | 13.8 | 12.1 | 4.0 | 0.18 | 0.412 | 0.437 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 37 | 1 | WF | 1 | 5.9 | 8.8 | 8.5 | 1.6 | 0.039 | 0.108 | 0.361 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 38 | 1 | IC | 0 | 0.0 | 15.0 | 13.0 | 3.5 | 0.152 | 0.367 | 0.414 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 38 | 1 | IC | 1 | 3.7 | 8.0 | 7.0 | N/A | 0.047 | 0.112 | 0.420 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 42 | 1 | IC | 0 | 0.0 | 11.0 | 10.5 | 3.0 | 0.165 | 0.362 | 0.456 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 42 | 1 | IC | 1 | 2.7 | 6.2 | 5.5 | 0.0 | 0.032 | 0.168 | 0.190 |
| L1 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \mathrm{t} \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height <br> (m) | DOB | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MC | 45 | 1 | WF | 0 | 0.0 | 21.6 | 19.3 | 6.3 | 0.331 | 0.825 | 0.401 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| MC | 45 | 1 | WF | 1 | 5.4 | 15.1 | 14.4 | 6.2 | 0.205 | 0.540 | 0.380 |
| L | 45 | 1 | WF | 2 | 11.8 | 8.9 | 8.3 | 2.0 | 0.05 | 0.142 | 0.352 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| $\begin{aligned} & \mathrm{L} 1 \\ & \text { MC } \end{aligned}$ | 1 | 1 | PP | 0 | 0.0 | 25.0 | 20.5 | N/A | 0.474 | 1.174 | 0.404 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| L2 | 1 | 1 | PP | 1 | 7.8 | 8.0 | 7.4 | N/A | 0.046 | 0.129 | 0.357 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 1 | WF | 0 | 0.0 | 13.5 | 11.0 | 4.0 | 0.17 | 0.331 | 0.514 |
| L |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 1 | WF | 1 | 4.3 | 8.5 | 8.0 | 3.8 | 0.08 | 0.179 | 0.447 |
|  |  |  |  |  |  |  |  |  |  |  |  |
|  | 6 | 4 | PP | 0 | 0.0 | 37.5 | 28.2 | N/A | 3.65 | 7.201 | 0.507 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
|  | 6 | 4 | PP | 1 | 10.1 | 24.1 | 21.1 | N/A | 0.929 | 2.129 | 0.436 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| MC | 6 | 4 | PP | 2 | 20.8 | 29.8 | 28.4 | N/A | 1.014 | 2.405 | 0.422 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 6 | 4 | PP | 3 | 25.7 | 19.9 | 19.3 | N/A | 0.354 | 0.833 | 0.425 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| $\begin{aligned} & \mathrm{MC} \\ & \mathrm{~L} \end{aligned}$ | 6 | 4 | PP | 4 | 29.6 | 8.7 | 7.9 | N/A | 0.084 | 0.184 | 0.457 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| $\begin{aligned} & \mathrm{L2} \\ & \mathrm{MC} \end{aligned}$ | 13 | 1 | WF | 0 | 0.0 | 22.0 | 17.0 | 4.0 | 0.522 | 1.149 | 0.454 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 13 | 1 | WF | 1 | 8.1 | 10.0 | 9.2 | 2.0 | 0.069 | 0.189 | 0.365 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| $\begin{aligned} & \mathrm{L} 2 \\ & \mathrm{MC} \end{aligned}$ | 16 | 2 | WF | 0 | 0.0 | 35.3 | 29.9 | 13.3 | 0.81 | 1.659 | 0.488 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| L | 16 | 2 | WF | 1 | 3.8 | 20.1 | 18.5 | 6.2 | 0.39 | 0.903 | 0.432 |
| L |  |  |  |  |  |  |  |  |  |  |  |
| MC | 16 | 2 | WF | 2 | 9.4 | 10.4 | 9.6 | 1.8 | 0.088 | 0.221 | 0.398 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 18 | 1 | WF | 0 | 0.0 | 19.0 | 16.5 | 3.5 | 0.246 | 0.558 | 0.441 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 18 | 1 | WF | 1 | 5.9 | 9.8 | 9.2 | 0.3 | 0.09 | 0.229 | 0.393 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 23 | 1 | IC | 0 | 0.0 | 16.8 | 13.3 | 8.4 | 0.19 | 0.496 | 0.383 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 23 | 1 | IC | 1 | 3.2 | 9.2 | 8.2 | 5.8 | 0.057 | 0.113 | 0.504 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| M | 25 | 2 | IC | 0 | 0.0 | 29.8 | 24.9 | 14.7 | 1.482 | 3.723 | 0.398 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 25 | 2 | IC | 1 | 7.7 | 8.3 | 7.5 | 1.1 | 0.057 | 0.150 | 0.380 |
| $\stackrel{L}{\text { M }}$ |  |  |  |  |  |  |  |  |  |  |  |
|  | 27 | 2 | IC | 0 | 0.0 | 25.6 | 22.9 | 15.0 | 1.442 | 4.254 | 0.339 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| MC | 27 | 2 | IC | 1 | 5.5 | 19.4 | 18.1 | 7.3 | 0.297 | 0.833 | 0.357 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \mathrm{t} \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height <br> (m) | DOB | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MC | 27 | 2 | IC | 2 | 12.6 | 10.6 | 10.1 | 2.2 | 0.92 | 2.248 | 0.409 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 28 | 1 | WF | 0 | 0.0 | 25.4 | 22.5 | 10.0 | 0.65 | 1.337 | 0.486 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 28 | 1 | WF | 1 | 5.4 | 18.4 | 17.3 | 6.3 | 0.255 | 0.644 | 0.396 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 28 | 1 | WF | 2 | 12.3 | 9.7 | 9.1 | 1.5 | 0.067 | 0.166 | 0.404 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 30 | 1 | IC | 0 | 0.0 | 17.8 | 16.4 | 4.5 | 0.257 | 0.756 | 0.340 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 30 | 1 | IC | 1 | 5.1 | 9.2 | 7.8 | 0.3 | 0.056 | 0.170 | 0.329 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 33 | 1 | IC | 0 | 0.0 | 28.0 | 23.5 | 11.4 | 0.505 | 1.378 | 0.366 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 33 | 1 | IC | 1 | 5.3 | 9.5 | 8.5 | 2.0 | 0.07 | 0.202 | 0.347 |
| L2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 10 | 1 | IC | 0 | 0.0 | 12.6 | 10.7 | 8.8 | 0.135 | 0.337 | 0.401 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 10 | 1 | IC | 1 | 2.4 | 8.1 | 7.3 | 5.7 | 0.037 | 0.089 | 0.416 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 23 | 1 | WF | 0 | 0.0 | 32.8 | 26.8 | 15.5 | 1.675 | 3.585 | 0.467 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 23 | 1 | WF | 1 | 13.6 | 20.5 | 19.3 | 6.8 | 0.286 | 0.773 | 0.370 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 23 | 1 | WF | 2 | 23.5 | 8.8 | 8.4 | 1.9 | 0.06 | 0.165 | 0.364 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 29 | 1 | WF | 0 | 0.0 | 15.8 | 14.3 | 3.4 | 0.095 | 0.240 | 0.396 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 29 | 1 | WF | 1 | 6.3 | 8.1 | 7.7 | 1.8 | 0.058 | 0.147 | 0.395 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 35 | 2 | PP | 0 | 0.0 | 63.0 | 53.0 | N/A | 2.658 | 5.350 | 0.497 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 35 | 2 | PP | 1 | 10.7 | 34.0 | 32.0 | N/A | 1.029 | 2.642 | 0.389 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 35 | 2 | PP | 2 | 18.8 | 25.0 | 22.0 | N/A | 0.478 | 1.225 | 0.390 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 35 | 2 | PP | 3 | 27.6 | 9.5 | 8.5 | N/A | 0.07 | 0.156 | 0.449 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 44 | 1 | IC | 0 | 0.0 | 16.5 | 13.8 | 6.1 | 0.202 | 0.492 | 0.411 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 44 | 1 | IC | 1 | 3.8 | 8.5 | 7.5 | 1.7 | 0.069 | 0.172 | 0.401 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 47 | 2 | PP | 0 | 0.0 | 48.0 | 40.5 | N/A | 2.4 | 4.383 | 0.548 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 47 | 2 | PP | 1 | 10.7 | 23.0 | 22.0 | N/A | 0.597 | 1.519 | 0.393 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 47 | 2 | PP | 2 | 16.2 | 17.0 | 15.0 | N/A | 0.199 | 0.518 | 0.384 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 47 | 2 | PP | 3 | 20.9 | 9.0 | 8.5 | N/A | 0.079 | 0.188 | 0.420 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \text { t } \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height <br> (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MC | 48 | 1 | WF | 0 | 0.0 | 23.1 | 20.7 | 6.6 | 0.822 | 1.732 | 0.475 |
| MC | 48 | 1 | WF | 1 | 13.2 | 9.9 | 9.3 | 2.3 | 0.09 | 0.224 | 0.402 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 55 | 1 | IC | 0 | 0.0 | 30.5 | 25.0 | 14.0 | 1.164 | 3.684 | 0.316 |
| L3 | 55 | 1 | IC | 1 | 5.7 | 18.5 | 16.0 | 7.5 | 0.237 | 0.721 | 0.329 |
| L |  |  |  |  |  |  |  |  |  |  |  |
| MC | 55 | 1 | IC | 2 | 12.5 | 10.0 | 9.5 | 0.4 | 0.061 | 0.186 | 0.328 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| L | 60 | 1 | IC | 0 | 0.0 | 22.0 | 18.5 | 8.5 | 0.482 | 1.261 | 0.382 |
| MC |  |  |  |  |  |  |  |  |  |  |  |
| L3 | 60 | 1 | IC | 1 | 5.9 | 9.0 | 8.2 | 3.0 | 0.052 | 0.143 | 0.364 |
| L |  |  |  |  |  |  |  |  |  |  |  |
|  | 62 | 1 | WF | 0 | 0.0 | 21.0 | 17.0 | 4.0 | 0.406 | 0.943 | 0.431 |
| MC |  |  |  |  |  |  |  |  |  |  |  |
| L3 MC | 62 | 1 | WF | 1 | 10.9 | 9.5 | 9.1 | 1.5 | 0.071 | 0.205 | 0.346 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 64 | 2 | IC | 0 | 0.0 | 46.5 | 39.0 | 24.0 | 2.259 | 7.740 | 0.292 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 64 | 2 | IC | 1 | 5.6 | 21.0 | 19.0 | 6.0 | 0.28 | 0.865 | 0.324 |
| L3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 64 | 2 | IC | 2 | 12.7 | 9.5 | 9.0 | N/A | 0.046 | 0.145 | 0.317 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| L | 3 | 1 | IC | 0 | 0.0 | 22.7 | 19.3 | 9.8 | 0.552 | 1.358 | 0.406 |
| MC |  |  |  |  |  |  |  |  |  |  |  |
| MC | 3 | 1 | IC | 1 | 8.3 | 9.8 | 8.8 | 2.1 | 0.045 | 0.134 | 0.336 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| L | 4 | 2 | PP | 0 | 0.0 | 33.0 | 27.0 | N/A | 1.531 | 3.344 | 0.458 |
| L |  |  |  |  |  |  |  |  |  |  |  |
| MC | 4 | 2 | PP | 1 | 12.3 | 9.5 | 8.5 | N/A | 0.058 | 0.146 | 0.397 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| M | 8 | 1 | WF | 0 | 0.0 | 11.0 | 8.8 | 3.3 | 0.087 | 0.229 | 0.380 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| MC | 14 | 2 | IC | 0 | 0.0 | 33.0 | 27.0 | 10.0 | 0.894 | 2.834 | 0.315 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| L | 14 | 2 | IC | 1 | 3.8 | 18.0 | 16.0 | 3.0 | 0.107 | 0.360 | 0.297 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| M | 14 | 2 | IC | 2 | 7.9 | 10.0 | 8.5 | 3.0 | 0.086 | 0.239 | 0.360 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 15 | 1 | IC | 0 | 0.0 | 5.8 | 5.1 | 1.8 | 0.033 | 0.063 | 0.524 |
| L |  |  |  |  |  |  |  |  |  |  |  |
| M | 20 | 1 | WF | 0 | 0.0 | 15.4 | 13.2 | 5.8 | 0.197 | 0.392 | 0.503 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| LLL | 20 | 1 | WF | 1 | 4.2 | 8.9 | 8.2 | 2.6 | 0.067 | 0.145 | 0.462 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| LML | 22 | 1 | IC | 0 | 0.0 | 19.0 | 15.0 | 5.5 | 0.277 | 0.813 | 0.341 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| M | 22 | 1 | IC | 1 | 5.8 | 8.5 | 7.5 | 0.4 | 0.062 | 0.189 | 0.328 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \text { t } \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | DUB <br> (cm) | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MC | 25 | 2 | PP | 0 | 0.0 | 53.0 | 46.0 | N/A | 3.154 | 5.880 | 0.536 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 25 | 2 | PP | 1 | 10.6 | 28.5 | 25.5 | N/A | 0.958 | 2.684 | 0.357 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 25 | 2 | PP | 2 | 18.8 | 16.0 | 14.0 | N/A | 0.138 | 0.343 | 0.402 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 25 | 2 | PP | 3 | 23.8 | 9.0 | 8.0 | N/A | 0.086 | 0.193 | 0.446 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 26 | 1 | WF | 0 | 0.0 | 22.5 | 18.5 | 4.5 | 0.69 | 1.604 | 0.430 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 26 | 1 | WF | 1 | 9.2 | 10.0 | 9.5 | 1.0 | 0.067 | 0.193 | 0.347 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 33 | 1 | WF | 0 | 0.0 | 18.0 | 15.5 | 4.0 | 0.358 | 0.779 | 0.460 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 33 | 1 | WF | 1 | 7.6 | 8.5 | 8.0 | 0.4 | 0.04 | 0.112 | 0.357 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 41 | 1 | WF | 0 | 0.0 | 24.0 | 20.5 | N/A | 0.488 | 1.129 | 0.432 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 41 | 1 | WF | 1 | 12.1 | 8.5 | 8.0 | N/A | 0.045 | 0.117 | 0.385 |
| L4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 16 | 2 | WF | 0 | 0.0 | 22.1 | 19.2 | 8.5 | 0.511 | 1.098 | 0.465 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 16 | 2 | WF | 1 | 11.1 | 10.2 | 9.6 | 3.6 | 0.068 | 0.163 | 0.417 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 34 | 1 | WF | 0 | 0.0 | 18.7 | 17.1 | 5.7 | 0.454 | 1.000 | 0.454 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 34 | 1 | WF | 1 | 8.5 | 9.8 | 8.9 | 3.2 | 0.053 | 0.130 | 0.408 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 96 | 2 | IC | 0 | 0.0 | 28.0 | 22.0 | 7.0 | 0.903 | 2.628 | 0.344 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 96 | 2 | IC | 1 | 12.7 | 11.0 | 10.5 | N/A | 0.09 | 0.265 | 0.340 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 99 | 3 | PP | 0 | 0.0 | 46.0 | 40.0 | N/A | 2.183 | 4.686 | 0.466 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 99 | 3 | PP | 1 | 10.2 | 30.0 | 28.0 | N/A | 0.423 | 1.027 | 0.412 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 99 | 3 | PP | 2 | 22.4 | 10.5 | 10.0 | N/A | 0.064 | 0.162 | 0.395 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 102 | 4 | WF | 0 | 0.0 | 56.0 | 50.0 | N/A | 1.066 | 2.269 | 0.470 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 102 | 4 | WF | 1 | 10.6 | 33.1 | 31.0 | N/A | 0.415 | 0.993 | 0.418 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 102 | 4 | WF | 2 | 24.3 | 11.0 | 9.5 | N/A | 0.074 | 0.162 | 0.457 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 106 | 1 | IC | 0 | 0.0 | 8.9 | 7.2 | 1.9 | 0.118 | 0.303 | 0.389 |
| M1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 36 | 1 | IC | 0 | 0.0 | 17.5 | 15.7 | 9.2 | 0.349 | 0.805 | 0.434 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 36 | 1 | IC | 1 | 2.7 | 9.8 | 8.6 | 5.5 | 0.07 | 0.181 | 0.387 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \text { t } \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | DUB <br> (cm) | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MC | 47 | 3 | PP | 0 | 0.0 | 40.0 | 35.5 | N/A | 1.214 | 2.637 | 0.460 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 47 | 3 | PP | 1 | 13.2 | 21.0 | 20.0 | N/A | 0.457 | 1.135 | 0.403 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 47 | 3 | PP | 2 | 21.6 | 12.0 | 10.5 | N/A | 0.105 | 0.234 | 0.449 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 51 | 1 | WF | 0 | 0.0 | 17.7 | 15.2 | 4.7 | 0.406 | 0.796 | 0.510 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 51 | 1 | WF | 1 | 9.1 | 9.8 | 9.4 | 3.8 | 0.057 | 0.134 | 0.425 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 57 | 3 | WF | 0 | 0.0 | 36.0 | 31.0 | 7.5 | 1.634 | 3.486 | 0.469 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 57 | 3 | WF | 1 | 10.7 | 20.5 | 19.5 | 7.0 | 0.438 | 1.126 | 0.389 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 57 | 3 | WF | 2 | 17.5 | 10.5 | 9.0 | 1.5 | 0.07 | 0.184 | 0.380 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 62 | 3 | IC | 0 | 0.0 | 35.5 | 27.0 | 13.0 | 0.873 | 2.811 | 0.311 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 62 | 3 | IC | 1 | 11.1 | 10.0 | 9.0 | N/A | 0.095 | 0.251 | 0.378 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 108 | 2 | PP | 0 | 0.0 | 23.4 | 20.2 | N/A | 0.575 | 1.009 | 0.570 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 108 | 2 | PP | 1 | 12.9 | 9.6 | 8.8 | N/A | 0.04 | 0.100 | 0.400 |
| M2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 1 | 1 | IC | 0 | 0.0 | 12.9 | 10.8 | 3.3 | 0.105 | 0.258 | 0.407 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 1 | 1 | IC | 1 | 2.2 | 8.4 | 7.5 | 1.7 | 0.05 | 0.121 | 0.413 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 3 | 1 | PP | 0 | 0.0 | N/A | N/A | N/A | N/A | N/A | N/A |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 3 | 1 | PP | 1 | 5.5 | N/A | N/A | N/A | N/A | N/A | N/A |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 2 | PP | 0 | 0.0 | 23.3 | 18.7 | 7.0 | 0.402 | 0.853 | 0.471 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 2 | PP | 1 | 2.7 | 16.9 | 14.6 | 4.2 | 0.113 | 0.256 | 0.441 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 2 | PP | 2 | 8.5 | 8.9 | 8.2 | N/A | 0.068 | 0.170 | 0.400 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 7 | 3 | PP | 0 | 0.0 | 20.2 | 17.5 | N/A | 1.034 | 2.185 | 0.473 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 7 | 3 | PP | 1 | 13.3 | 22.2 | 21.1 | N/A | 0.455 | 1.169 | 0.389 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 7 | 3 | PP | 2 | 20.2 | 10.0 | 8.9 | N/A | 0.078 | 0.189 | 0.413 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 9 | 1 | IC | 0 | 0.0 | 21.1 | 16.6 | 10.3 | 0.387 | 1.051 | 0.368 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 9 | 1 | IC | 1 | 3.7 | 8.8 | 7.6 | 1.2 | 0.053 | 0.135 | 0.393 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 20 | 4 | IC | 0 | 0.0 | 45.0 | 36.0 | 20.0 | 1.985 | 6.460 | 0.307 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| Plo | Tree Num. | Qu art, | Species | Disk | Height (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MC | 20 | 4 | IC | 1 | 7.6 | 23.0 | 21.5 | 6.0 | 0.322 | 0.998 | 0.323 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 20 | 4 | IC | 2 | 12.4 | 11.5 | 10.5 | 2.0 | 0.046 | 0.143 | 0.322 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 23 | 2 | IC | 0 | 0.0 | 25.6 | 20.7 | 7.4 | 0.611 | 1.804 | 0.339 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 23 | 2 | IC | 1 | 6.1 | 8.5 | 7.3 | 1.2 | 0.093 | 0.214 | 0.435 |
| M4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 3 | 1 | WF | 0 | 0.0 | 25.0 | 19.0 | 5.5 | 0.726 | 1.504 | 0.483 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| M5  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
| MC | 4 | 1 | WF | 0 | 0.0 | 25.7 | 21.6 | 5.0 | 0.648 | 1.487 | 0.436 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 4 | 1 | WF | 1 | 6.5 | 8.8 | 7.9 | 1.2 | 0.047 | 0.120 | 0.392 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 1 | IC | 0 | 0.0 | 27.0 | 23.0 | 9.5 | 0.698 | 1.753 | 0.398 |
|  |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 1 | IC | 1 | 5.8 | 9.0 | 8.2 | 3.0 | 0.046 | 0.118 | 0.390 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 6 | 1 | PP | 0 | 0.0 | 24.4 | 18.1 | 3.0 | 0.867 | 1.930 | 0.449 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
| MC | 7 | 2 | IC | 0 | 0.0 | 49.0 | 40.0 | 18.0 | 3.015 | 8.793 | 0.343 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 7 | 2 | IC | 1 | 5.6 | 9.0 | 7.5 | N/A | 0.07 | 0.156 | 0.449 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 9 | 4 | PP | 0 | 0.0 | 62.8 | 54.9 | N/A | 3.501 | 7.695 | 0.455 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 9 | 4 | PP | 1 | 10.6 | 40.2 | 38.1 | N/A | 1.633 | 3.884 | 0.420 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 9 | 4 | PP | 2 | 13.6 | 15.2 | 14.4 | N/A | 0.173 | 0.476 | 0.363 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 9 | 4 | PP | 3 | 20.2 | 8.8 | 7.8 | N/A | 0.059 | 0.153 | 0.386 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 9 | 4 | PP | 4 | 23.1 | 9.0 | 8.0 | N/A | 0.058 | 0.155 | 0.374 |
| M5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 1 | 4 | PP | 0 | 0.0 | 43.0 | 39.0 | N/A | 1.055 | 2.254 | 0.468 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 1 | 4 | PP | 1 | 10.6 | 19.0 | 17.0 | N/A | 0.223 | 0.568 | 0.393 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 1 | 4 | PP | 2 | 12.4 | 10.0 | 9.0 | N/A | 0.086 | 0.193 | 0.446 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 4 | 1 | PP | 0 | 0.0 | 41.0 | 37.0 | N/A | 0.842 | 1.741 | 0.484 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 4 | 1 | PP | 1 | 5.6 | 27.0 | 24.5 | N/A | 0.607 | 1.128 | 0.538 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 4 | 1 | PP | 2 | 7.9 | 15.5 | 13.5 | N/A | 0.25 | 0.612 | 0.408 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\begin{gathered} \text { Plo } \\ \mathrm{t} \end{gathered}$ | Tree Num. | Qu art, | Species | Disk | Height <br> (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MC | 4 | 1 | PP | 3 | 8.3 | 10.0 | 9.0 | N/A | 0.075 | 0.177 | 0.424 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 6 | 3 | PP | 0 | 0.0 | 39.4 | 38.2 | N/A | 1.041 | 2.056 | 0.506 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 6 | 3 | PP | 1 | 8.2 | 16.7 | 15.2 | N/A | 0.224 | 0.602 | 0.372 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 6 | 3 | PP | 2 | 10.9 | 8.6 | 7.6 | N/A | 0.053 | 0.140 | 0.379 |
| S1 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 1 | 3 | PP | 0 | 0.0 | 34.0 | 31.9 | N/A | 2.15 | 4.080 | 0.527 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 1 | 3 | PP | 1 | 5.5 | 18.9 | 17.4 | N/A | 0.323 | 0.753 | 0.429 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 1 | 3 | PP | 2 | 8.7 | 9.7 | 8.8 | N/A | 0.078 | 0.168 | 0.464 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 2 | 2 | PP | 0 | 0.0 | 34.8 | 32.2 | N/A | 0.51 | 1.153 | 0.442 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 2 | 2 | PP | 1 | 5.5 | 16.4 | 15.1 | N/A | 0.209 | 0.554 | 0.377 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 2 | 2 | PP | 2 | 7.6 | 9.6 | 8.5 | N/A | 0.074 | 0.185 | 0.400 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 6 | 1 | PP | 0 | 0.0 | 32.0 | 30.0 | N/A | 1.785 | 3.569 | 0.500 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 6 | 1 | PP | 1 | 5.5 | 15.0 | 13.5 | N/A | 0.285 | 0.576 | 0.495 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 6 | 1 | PP | 2 | 6.9 | 11.0 | 10.0 | N/A | 0.088 | 0.204 | 0.431 |
| S2 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 1 | PP | 0 | 0.0 | 31.0 | 27.0 | N/A | 1.03 | 1.966 | 0.524 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 1 | PP | 1 | 5.5 | 22.0 | 20.0 | N/A | 0.31 | 0.776 | 0.399 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 1 | PP | 2 | 8.5 | 11.1 | 10.5 | N/A | 0.055 | 0.132 | 0.417 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 5 | 1 | PP | 3 | 8.8 | 10.0 | 8.5 | N/A | 0.13 | 0.317 | 0.410 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 13 | 3 | PP | 0 | 0.0 | 35.0 | 31.0 | N/A | 1.38 | 3.006 | 0.459 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 13 | 3 | PP | 1 | 8.3 | 17.0 | 15.0 | N/A | 0.2 | 0.501 | 0.399 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 13 | 3 | PP | 2 | 11.0 | 11.0 | 10.0 | N/A | 0.078 | 0.198 | 0.394 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 20 | 1 | PP | 0 | 0.0 | 30.2 | 26.3 | N/A | 1.083 | 2.415 | 0.448 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 20 | 1 | PP | 1 | 5.5 | 16.4 | 15.6 | N/A | 0.2 | 0.556 | 0.360 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 20 | 1 | PP | 2 | 8.6 | 9.8 | 8.9 | N/A | 0.056 | 0.148 | 0.378 |
| S3 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 3 | 4 | PP | 0 | 0.0 | 48.4 | 45.8 | N/A | 0.97 | 2.140 | 0.453 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 3 | 4 | PP | 1 | 10.6 | 18.1 | 16.4 | N/A | 0.176 | 0.481 | 0.366 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |

Table B. 1 (Continued)

| $\underset{\mathrm{t}}{\mathrm{Plo}}$ | Tree Num. | Qu art, | Species | Disk | Height (m) | $\begin{aligned} & \text { DOB } \\ & (\mathrm{cm}) \end{aligned}$ | $\begin{aligned} & \text { DUB } \\ & (\mathrm{cm}) \end{aligned}$ | Heartw ood (cm) | Dry Wt <br> (kg) | "Wet" Wt (kg) | Density (kg/L) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MC | 3 | 4 | PP | 2 | 12.5 | 10.9 | 9.8 | N/A | 0.116 | 0.261 | 0.444 |
| MC | 7 | 1 | PP | 0 | 0.0 | 30.0 | 23.0 | 2.0 | 0.662 | 1.416 | 0.468 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 7 | 1 | PP | 1 | 5.4 | 16.0 | 15.0 | 1.5 | 0.251 | 0.489 | 0.513 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 7 | 1 | PP | 2 | 7.9 | 9.5 | 9.0 | 1.0 | 0.072 | 0.187 | 0.385 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 15 | 1 | PP | 0 | 0.0 | 33.3 | 29.6 | N/A | 1.175 | 2.705 | 0.434 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 15 | 1 | PP | 1 | 8.2 | 19.1 | 17.7 | N/A | 0.285 | 0.764 | 0.373 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 15 | 1 | PP | 2 | 11.8 | 10.4 | 9.4 | N/A | 0.104 | 0.278 | 0.374 |
| S4 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 3 | 1 | IC | 0 | 0.0 | 13.0 | 11.5 | 1.0 | 0.103 | 0.287 | 0.359 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 3 | 1 | IC | 1 | 1.9 | 8.5 | 7.5 | 0.5 | 0.053 | 0.135 | 0.393 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 9 | 1 | PP | 0 | 0.0 | 28.0 | 25.0 | N/A | 0.62 | 1.203 | 0.515 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 9 | 1 | PP | 1 | 5.5 | 18.0 | 16.0 | N/A | 0.202 | 0.507 | 0.398 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 9 | 1 | PP | 2 | 9.4 | 10.0 | 9.2 | N/A | 0.087 | 0.193 | 0.451 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 14 | 4 | PP | 0 | 0.0 | 37.0 | 33.5 | N/A | 0.874 | 2.043 | 0.428 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 14 | 4 | PP | 1 | 2.8 | 28.0 | 26.0 | N/A | 0.628 | 1.288 | 0.488 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 14 | 4 | PP | 2 | 10.2 | 10.0 | 8.5 | N/A | 0.082 | 0.210 | 0.390 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 21 | 1 | PP | 0 | 0.0 | 20.0 | 17.0 | N/A | 0.329 | 0.721 | 0.456 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 21 | 1 | PP | 1 | 5.5 | 9.0 | 8.0 | N/A | 0.066 | 0.169 | 0.391 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |
| MC | 14B | 4 | PP | 0 | N/A | N/A | N/A | N/A | 0.056 | 0.142 | 0.394 |
| S5 |  |  |  |  |  |  |  |  |  |  |  |

## APPENDIX C: BOLE BIOMASS ESTIMATES BASED ON VOLUME AND DENSITY ESTIMATES

Once the volume and density of tree boles were estimated from Appendices $A$ and $B$, in-house software was used to estimate the biomass of all trees greater than 8 cm DBH from all plots. Trees are broken into plot and quartile. All biomass estimates are in kg.

Table C.1: Bole Biomass Estimates from Plots near Molalla, OR

| Tree Number | DFL1 |  |  |  | DFL2 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 1 |  | 460.5 |  |  |  | 1056.3 |  |  |
| 2 |  |  |  | 2180.8 |  |  |  | 2814.9 |
| 3 | 206.8 |  |  |  |  | 674.0 |  |  |
| 4 |  |  | 1335.4 |  |  |  | 1620.2 |  |
| 5 |  | 1216.5 |  |  |  |  | 1258.3 |  |
| 6 | 114.6 |  |  |  |  | 559.2 |  |  |
| 7 | 114.6 |  |  |  | 194.5 |  |  |  |
| 8 |  |  | 389.7 |  | 114.6 |  |  |  |
| 9 | 389.7 |  |  |  |  |  |  |  |
| 10 |  | 745.7 |  |  |  |  |  |  |
| 11 |  | 462.9 |  |  |  |  |  |  |
| 12 |  |  | 1585.5 |  |  |  |  |  |
| 13 |  |  |  | 2978.0 |  |  |  |  |
| 14 | 216.6 |  |  |  |  |  |  |  |
| 15 |  |  |  |  |  |  |  |  |
| 16 |  |  |  |  |  |  |  |  |

$\left.\begin{array}{|c|cccc|}\hline \begin{array}{c}\text { Tree } \\ \text { Number }\end{array} & & & & \\ \hline & & & & \\ & & & \text { DFL3 }\end{array}\right]$

Table C. 1 (Continued)

| Tree Number | DFL4 |  |  |  | DFL5 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 1 | 155.9 |  |  |  |  |  |  | 2080.9 |
| 2 |  | 706.1 |  |  |  | 1220.4 |  |  |
| 3 | 407.5 |  |  |  | 541.3 |  |  |  |
| 4 | 607.0 |  |  |  |  |  | 1797.3 |  |
| 5 |  |  | 2087.4 |  | 586.6 |  |  |  |
| 6 |  |  | 1639.0 |  | 1055.5 |  |  |  |
| 7 | 7.1 |  |  |  |  |  | 1343.3 |  |
| 8 |  |  |  | 2179.7 |  | 1307.7 |  |  |
| 9 | 509.9 |  |  |  | 509.9 |  |  |  |
| 10 |  | 964.0 |  |  |  | 1227.5 |  |  |
| 11 |  | 987.5 |  |  |  |  | 2052.5 |  |
| 12 | 278.0 |  |  |  | 94.0 |  |  |  |
| 13 | 805.9 |  |  |  |  |  |  | 1975.0 |
| 14 |  |  | 1904.9 |  |  | 581.2 |  |  |
| 15 |  |  |  | 1973.2 |  |  |  |  |
| 16 |  |  |  |  |  |  |  |  |
| 17 |  |  |  |  |  |  |  |  |
| 18 |  |  |  |  |  |  |  |  |
| 19 |  |  |  |  |  |  |  |  |
| 20 |  |  |  |  |  |  |  |  |
| 21 |  |  |  |  |  |  |  |  |
| 22 |  |  |  |  |  |  |  |  |

Table C. 1 (Continued)

| Tree Number | DFM1 |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 |
| 1 |  |  |  | 718.1 |
| 2 |  |  |  | 563.0 |
| 3 |  |  | 443.4 |  |
| 4 |  | 501.1 |  |  |
| 5 |  |  |  | 737.0 |
| 6 |  |  |  | 611.7 |
| 7 | 141.6 |  |  |  |
| 8 | 383.0 |  |  |  |
| 9 | 370.2 |  |  |  |
| 10 | 233.2 |  |  |  |
| 11 |  |  | 476.6 |  |
| 12 |  | 450.9 |  |  |
| 13 |  |  | 440.9 |  |
| 14 |  |  | 452.2 |  |
| 15 |  | 437.5 |  |  |
| 16 | 379.2 |  |  |  |
| 17 | 284.9 |  |  |  |
| 18 |  | 469.1 |  |  |
| 19 |  |  | 499.1 |  |
| 20 |  | 368.5 |  |  |
| 21 |  | 372.9 |  |  |
| 22 | 247.9 |  |  |  |

Table C. 1 (Continued)

| Tree Number | DFM2 |  |  |  | DFM3 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 1 | 618.1 |  |  |  |  | 254.7 |  |  |
| 2 |  |  | 851.3 |  |  |  |  | 468.8 |
| 3 |  |  |  | 981.1 |  |  | 426.4 |  |
| 4 |  |  | 991.6 |  | 277.9 |  |  |  |
| 5 |  | 595.2 |  |  |  | 297.9 |  |  |
| 6 |  | 462.4 |  |  |  |  |  | 501.1 |
| 7 | 359.0 |  |  |  | 166.3 |  |  |  |
| 8 |  |  | 784.4 |  |  |  |  | 502.1 |
| 9 |  |  |  | 1055.0 |  |  | 448.2 |  |
| 10 |  |  |  | 1013.6 |  |  |  | 608.0 |
| 11 | 515.5 |  |  |  |  | 316.7 |  |  |
| 12 |  | 808.7 |  |  |  |  | 280.1 |  |
| 13 | 381.7 |  |  |  |  |  | 382.6 |  |
| 14 | 598.9 |  |  |  | 284.4 |  |  |  |
| 15 |  |  |  |  | 233.4 |  |  |  |
| 16 |  |  |  |  |  |  | 322.9 |  |
| 17 |  |  |  |  | 213.2 |  |  |  |
| 18 |  |  |  |  | 245.5 |  |  |  |
| 19 |  |  |  |  |  | 353.8 |  |  |
| 20 |  |  |  |  |  |  | 320.2 |  |
| 21 |  |  |  |  |  | 285.6 |  |  |
| 22 |  |  |  |  | 213.5 |  |  |  |
| 23 |  |  |  |  |  | 281.0 |  |  |

Table C. 1 (Continued)
$\left.\begin{array}{|c|cccc|}\hline \begin{array}{c}\text { Tree } \\ \text { Number }\end{array} & & & \text { DFM4 }\end{array}\right]$


Table C. 1 (Continued)

| Tree <br> Number |  | DFM5 |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |  |  |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 1 |  |  | 1002.1 |  |  |  | 222.6 |  |
| 2 |  |  |  | 873.5 |  |  | 152.1 |  |
| 3 | 178.9 |  |  |  | 224.6 |  |  |  |
| 4 |  |  | 932.8 |  | 139.7 |  |  |  |
| 5 | 453.5 |  |  |  |  | 161.0 |  |  |
| 6 |  | 539.9 |  |  | 70.0 |  |  |  |
| 7 |  | 577.9 |  |  |  | 173.9 |  |  |
| 8 |  | 602.4 |  |  | 120.7 |  |  |  |
| 9 | 232.6 |  |  |  | 98.0 |  |  | 239.2 |
| 10 | 414.8 |  |  |  |  | 96.9 |  |  |
| 11 | 191.9 |  |  |  |  |  |  |  |

$\left.\begin{array}{|c|cccc|}\hline \begin{array}{c}\text { Tree } \\ \text { Number }\end{array} & & & \text { DFS2 }\end{array}\right]$

Table C. 1 (Continued)

| Tree Number | DFM2 |  |  |  | DFM3 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 12 | 336.1 |  |  |  |  |  |  | 212.7 |
| 13 | 340.1 |  |  |  | 131.5 |  |  |  |
| 14 | 379.9 |  |  |  |  |  |  | 244.9 |
| 15 |  |  |  | 1148.3 | 101.7 |  |  |  |
| 16 |  |  | 628.6 |  |  | 143.2 |  |  |
| 17 | 427.9 |  |  |  |  | 125.9 |  |  |
| 18 |  |  | 797.5 |  |  |  |  | 293.8 |
| 19 |  | 644.2 |  |  | 70.2 |  |  |  |
| 20 |  | 623.4 |  |  | 99.6 |  |  |  |
| 21 |  |  |  | 898.6 |  |  | 181.7 |  |
| 22 |  |  |  | 960.9 |  |  | 202.7 |  |
| 23 |  |  |  |  |  |  | 187.3 |  |
| 24 |  |  |  |  |  |  | 213.7 |  |
| 25 |  |  |  |  |  | 134.5 |  |  |
| 26 |  |  |  |  | 94.0 |  |  |  |
| 27 |  |  |  |  |  |  |  | 183.4 |
| 28 |  |  |  |  |  | 125.0 |  |  |
| 29 |  |  |  |  |  | 151.4 |  |  |
| 30 |  |  |  |  |  | 144.4 |  |  |
| 31 |  |  |  |  |  |  | 194.7 |  |
| 32 |  |  |  |  |  |  |  | 281.8 |

Table C. 1 (Continued)

| Tree <br> Number |  |  | DFM4 |  |
| :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |
|  | Q1 | Q2 | Q3 | Q4 |
| 12 |  | 151.8 |  |  |
| 13 |  |  | 143.3 |  |
| 14 |  |  |  | 204.6 |
| 15 |  | 106.3 |  |  |
| 16 |  | 117.0 |  | 197.8 |
| 17 |  |  |  |  |
| 18 |  | 146.8 |  |  |
| 19 | 86.3 |  |  |  |
| 20 |  | 113.3 |  |  |
| 21 |  | 129.1 |  |  |
| 22 | 98.5 |  |  | 163.4 |
| 23 |  |  | 158.9 |  |
| 24 |  |  |  | 151.0 |
| 25 | 107.0 |  |  |  |
| 26 |  |  |  |  |
| 27 |  | 110.0 |  |  |
| 28 | 81.1 |  |  |  |
| 29 |  |  |  |  |
| 30 |  |  |  |  |

Table C. 1 (Continued)

| Tree <br> Number | DFS3 |  |  |  | DFS4 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 1 |  |  |  | 235.5 |  |  | 180.5 |  |
| 2 |  | 95.2 |  |  |  | 188.0 |  |  |
| 3 | 70.3 |  |  |  | 123.0 |  |  |  |
| 4 | 93.5 |  |  |  |  |  | 197.6 |  |
| 5 | 36.8 |  |  |  |  |  | 212.7 |  |
| 6 |  |  |  | 239.3 | 151.6 |  |  |  |
| 7 |  |  |  | 245.0 |  | 141.1 |  |  |
| 8 | 39.0 |  |  |  |  |  | 188.5 |  |
| 9 |  |  | 177.2 |  |  | 156.7 |  |  |
| 10 |  | 122.8 |  |  | 118.3 |  |  |  |
| 11 |  |  |  | 220.1 |  |  |  | 252.4 |
| 12 | 0.2 |  |  |  | 83.1 |  |  |  |
| 13 | 76.3 |  |  |  | 68.0 |  |  |  |
| 14 | 40.4 |  |  |  |  |  |  | 296.7 |
| 15 |  |  | 165.1 |  | 58.7 |  |  |  |
| 16 | 78.3 |  |  |  |  | 162.0 |  |  |
| 17 |  |  | 175.0 |  | 92.7 |  |  |  |
| 18 | 79.4 |  |  |  | 68.4 |  |  |  |
| 19 | 80.6 |  |  |  |  |  | 187.8 |  |
| 20 |  | 143.1 |  |  |  | 150.4 |  |  |
| 21 |  |  | 139.0 |  |  |  |  | 199.1 |
| 22 | 55.1 |  |  |  |  |  | 194.2 |  |
| 23 |  |  | 176.8 |  | 113.0 |  |  |  |

Table C. 1 (Continued)
$\left.\begin{array}{|c|cccc|}\hline \begin{array}{c}\text { Tree } \\ \text { Number }\end{array} & & & \text { DFS5 }\end{array}\right]$

Table C. 1 (Continued)


Table C. 1 (Continued)

| Tree <br> Number |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |
|  | Q1 | Q2 | Q3 | Q4 |
| 24 | 130.2 |  |  |  |
| 25 | 81.7 |  |  |  |
| 26 |  | 122.2 |  |  |
| 27 |  |  | 205.2 |  |
| 28 |  |  | 212.9 |  |
| 29 | 173.2 |  |  |  |
| 30 | 185.3 |  |  |  |
| 31 |  | 174.5 |  |  |

Table C.2.: Bole Biomass Estimates from Plots near Hambone, CA

| Tree Number | MCL1 |  |  |  | MCL2 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 1 |  |  |  |  | 77.40 |  |  |  |
| 2 | 53.40 |  |  |  |  |  |  |  |
| 3 |  |  |  |  | 9.85 |  |  |  |
| 4 |  |  |  | 1115.35 | 9.31 |  |  |  |
| 5 |  |  |  |  | 20.30 |  |  |  |
| 6 | 38.36 |  |  |  |  |  |  | 2100.00 |
| 7 |  |  |  | 1154.16 |  |  |  | 931.12 |
| 8 |  |  |  |  |  |  |  |  |
| 9 | 15.25 |  |  |  | 8.59 |  |  |  |
| 10 |  | 649.56 |  |  |  |  |  |  |
| 11 |  |  |  |  |  |  |  |  |
| 12 | 289.65 |  |  |  |  |  |  |  |
| 13 |  |  | 943.23 |  | 72.47 |  |  |  |
| 14 |  |  |  |  | 34.31 |  |  |  |
| 15 |  |  |  |  | 19.26 |  |  |  |
| 16 |  |  |  |  |  | 151.49 |  |  |
| 17 | 43.97 |  |  |  |  |  |  |  |
| 18 |  |  |  |  | 44.89 |  |  |  |
| 19 |  | 742.01 |  |  |  |  | 991.8 |  |

Table C. 2 (Continued)

| Tree <br> Number | MCL3 |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 |
| 1 |  |  |  |  |
| 2 |  |  |  |  |
| 3 | 155.62 |  |  |  |
| 4 |  |  |  |  |
| 5 | 233.33 |  |  |  |
| 6 |  |  |  |  |
| 7 | 23.46 |  |  |  |
| 8 |  |  |  |  |
| 9 |  |  |  |  |
| 10 | 8.82 |  |  |  |
| 11 |  |  |  |  |
| 12 | 12.20 |  |  |  |
| 13 |  |  |  |  |
| 14 |  |  |  |  |
| 15 |  |  |  |  |
| 16 |  |  |  |  |
| 17 |  |  |  |  |
| 19 |  |  |  |  |
| 19 |  |  |  |  |

Table C. 2 (Continued)


Table C. 2 (Continued)


Table C. 2 (Continued)


Table C. 2 (Continued)

| Tree Number | MCL3 |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 |
| 45 | 79.86 |  |  |  |
| 46 |  |  |  |  |
| 47 |  | 543.64 |  |  |
| 48 | 125.47 |  |  |  |
| 49 | 10.09 |  |  |  |
| 51 |  |  |  |  |
| 52 |  |  |  | 1793.17 |
| 53 | 16.37 |  |  |  |
| 54 | 7.75 |  |  |  |
| 55 | 179.42 |  |  |  |
| 56 | 201.23 |  |  |  |
| 58 | 26.44 |  |  |  |
| 59 | 14.90 |  |  |  |
| 60 | 54.67 |  |  |  |
| 62 | 93.30 |  |  |  |
| 63 |  | 702.99 |  |  |
| 64 |  | 283.91 |  |  |
| 31B |  |  |  |  |
| 44B |  |  |  |  |
| 7B |  |  |  |  |
| 30B |  |  |  | 833.63 |
| 31B |  |  | 48.71 |  |
| 41B |  | 352.78 |  |  |


| Tree <br> Number | MCL3 |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 |
| $43 B$ |  |  | 286.98 |  |
| 8B |  |  |  | 45.34 |

Table C. 2 (Continued)

| Tree Number | MCL4 |  |  |  | MCM1 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 1 | 20.48 |  |  |  |  | 203.78 |  |  |
| 2 | 79.43 |  |  |  |  |  |  |  |
| 3 | 78.00 |  |  |  | 13.35 |  |  |  |
| 4 |  | 223.77 |  |  |  | 106.96 |  |  |
| 5 | 29.13 |  |  |  | 35.86 |  |  |  |
| 6 |  | 133.80 |  |  | 28.27 |  |  |  |
| 7 |  |  |  |  | 35.35 |  |  |  |
| 8 | 2.08 |  |  |  |  |  |  |  |
| 9 | 100.89 |  |  |  |  | 197.33 |  |  |
| 10 |  |  |  |  | 11.44 |  |  |  |
| 11 | 105.62 |  |  |  |  |  |  |  |
| 12 |  |  |  |  |  |  |  |  |
| 13 |  |  |  |  | 9.92 |  |  |  |
| 14 |  | 129.84 |  |  | 33.41 |  |  |  |
| 15 | 5.22 |  |  |  | 91.79 |  |  |  |
| 16 |  |  |  |  |  | 91.79 |  |  |


| Tree <br> Number |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 |
| 1 |  |  |  |  |
| 2 |  |  |  |  |
| 3 |  |  |  |  |
| 4 | 4.23 |  |  |  |
| 5 | 35.64 |  |  |  |
| 6 | 25.46 |  |  |  |
| 7 |  |  |  |  |
| 8 |  |  | 253.65 |  |
| 9 |  |  |  |  |
| 10 |  |  |  |  |
| 11 | 17.52 |  |  |  |
| 12 |  |  |  |  |
| 13 | 28.86 |  |  |  |
| 14 |  | 77.42 |  |  |
| 15 | 8.24 |  |  |  |
| 16 |  |  |  |  |

Table C. 2 (Continued)


Table C. 2 (Continued)


Table C. 2 (Continued)


Table C. 2 (Continued)

| Tree Number | MCM2 |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 |
| 40 | 24.78 |  |  |  |
| 41 |  |  | 319.11 |  |
| 42 |  |  | 309.27 |  |
| 43 |  |  | 159.59 |  |
| 44 |  |  |  | 727.93 |
| 45 |  | 53.71 |  |  |
| 46 |  |  |  |  |
| 47 |  |  | 383.51 |  |
| 48 |  | 65.66 |  |  |
| 49 |  | 14.23 |  |  |
| 50 | 25.57 |  |  |  |
| 51 | 46.27 |  |  |  |
| 52 |  |  |  |  |
| 53 |  |  |  |  |
| 54 |  |  |  |  |
| 55 |  |  |  |  |
| 56 | 9.67 |  |  |  |
| 57 |  |  | 298.81 |  |
| 58 | 10.20 |  |  |  |
| 59 | 23.13 |  |  |  |
| 60 |  |  |  |  |
| 61 |  |  | 280.15 |  |
| 62 |  |  | 154.03 |  |

Table C. 2 (Continued)


Table C. 2 (Continued)

| Tree Number | MCM2 |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 |
| 63 |  |  | 186.99 |  |
| 64 | 58.01 |  |  |  |
| 65 |  |  | 461.41 |  |
| 66 |  |  |  |  |
| 67 |  | 48.47 |  |  |
| 68 |  |  | 197.56 |  |
| 69 | 20.42 |  |  |  |
| 70 |  |  |  |  |
| 71 |  |  |  |  |
| 72 |  |  |  |  |
| 73 |  |  |  |  |
| 74 |  |  |  |  |
| 75 |  | 41.48 |  |  |
| 76 |  |  |  |  |
| 77 |  |  |  | 1416.90 |
| 78 |  |  |  | 199.11 |
| 79 | 8.72 |  |  |  |
| 80 |  | 118.56 |  |  |
| 81 |  |  |  |  |
| 82 |  | 68.34 |  |  |
| 83 |  |  | 193.59 |  |
| 84 |  |  | 45.82 |  |
| 85 | 31.66 |  |  |  |

Table C. 2 (Continued)
$\left.\begin{array}{|c|cccc|}\hline \begin{array}{c}\text { Tree } \\ \text { Number }\end{array} & & & & \text { MCM1 }\end{array}\right]$

Table C. 2 (Continued)

| Tree Number | MCM2 |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 |
| 86 | 55.57 |  |  |  |
| 87 |  | 76.99 |  |  |
| 88 |  | 129.37 |  |  |
| 89 | 10.15 |  |  |  |
| 90 |  | 116.26 |  |  |
| 91 |  | 134.88 |  |  |
| 92 |  | 317.02 |  |  |
| 93 |  | 104.13 |  |  |
| 94 | 20.90 |  |  |  |
| 95 |  |  |  |  |
| 96 | 21.20 |  |  |  |
| 97 |  | 67.27 |  |  |
| 99 |  |  |  |  |
| 100 | 27.98 |  |  |  |
| 101 |  |  |  |  |
| 102 |  |  |  |  |
| 103 | 36.10 |  |  |  |
| 104 | 8.71 |  |  |  |
| 105 |  |  |  |  |
| 106 | 61.02 |  |  |  |
| 107 |  | 90.93 |  |  |
| 108 |  | 83.67 |  |  |
| 109 |  |  |  | 629.71 |

Table C. 2 (Continued)

| Tree Number | MCL4 |  |  |  | MCM1 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 111 | 68.64 |  |  |  | 13.28 | 387.45 |  |  |
| 112 |  |  |  |  | 9.42 |  |  |  |
| 113 |  |  |  |  | 42.14 |  |  |  |
| 114 |  |  |  |  |  |  |  |  |
| 115 |  |  |  |  |  |  |  |  |
| 37B |  |  |  |  |  |  |  |  |
| 77B |  |  |  |  |  |  |  |  |


| Tree Number | MCM2 |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 |
| 111 |  |  |  |  |
| 112 |  |  |  |  |
| 113 |  |  |  |  |
| 114 |  |  |  |  |
| 115 |  |  |  |  |
| 37B |  |  |  |  |
| 77B |  |  |  | 412.60 |



Table C. 2 (Continued)

| Tree <br> Number |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | MCS1 |  |
| 1 |  |  |  | 404.09 |
| 2 | 184.33 |  |  |  |
| 3 |  | 232.63 |  |  |
| 4 | 122.63 |  |  |  |
| 5 |  |  | 245.45 |  |
| 6 |  |  | 261.28 |  |
| 7 |  |  |  |  |
| 8 |  |  |  |  |
| 9 |  |  |  |  |
| 10 |  |  |  |  |
| 11 |  |  |  |  |


| Tree Number | MCM4 |  |  |  | MCM5 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 12 | 74.15 |  |  |  |  |  |  |  |
| 13 |  |  |  |  |  |  |  |  |
| 14 | 9.11 |  |  |  |  |  |  |  |
| 15 |  |  | 178.06 |  |  |  |  |  |
| 20 |  |  |  | 425.26 |  |  |  |  |
| 21 | 46.86 |  |  |  |  |  |  |  |
| 22 | 55.25 |  |  |  |  |  |  |  |
| 23 |  | 64.48 |  |  |  |  |  |  |
| 24 | 17.12 |  |  |  |  |  |  |  |
| 25 |  | 185.89 |  |  |  |  |  |  |
| 26 |  | 85.61 |  |  |  |  |  |  |
| 9 B 1 |  |  |  |  |  |  |  | 55.53 |
| 9B2 |  |  |  |  |  |  |  | 21.50 |

Table C. 2 (Continued)

| Tree Number | MCS2 |  |  |  | MCS3 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 1 |  |  | 165.35 |  | 80.18 |  |  |  |
| 2 |  | 146.58 |  |  |  | 150.98 |  |  |
| 3 |  |  |  | 266.51 |  |  |  | 316.95 |
| 4 |  |  | 230.38 |  |  | 153.31 |  |  |
| 5 | 164.84 |  |  |  | 154.15 |  |  |  |
| 6 | 118.41 |  |  |  |  | 147.80 |  |  |
| 7 |  |  |  |  | 141.54 |  |  |  |
| 8 |  |  |  |  |  |  |  | 259.60 |
| 9 |  |  |  |  |  |  | 183.81 |  |
| 10 |  |  |  |  |  |  |  | 204.87 |
| 11 |  |  |  |  |  | 183.84 |  |  |
| 12 |  |  |  |  | 118.53 |  |  |  |
| 13 |  |  |  |  |  |  | 208.92 |  |
| 14 |  |  |  |  |  |  | 142.22 |  |
| 15 |  |  |  |  |  |  |  | 241.46 |
| 16 |  |  |  |  |  |  | 280.73 |  |
| 17 |  |  |  |  |  | 189.66 |  |  |
| 18 |  |  |  |  | 317.97 |  |  |  |
| 19 |  |  |  |  | 117.43 |  |  |  |
| 20 |  |  |  |  | 119.29 |  |  |  |
| 5B |  |  |  |  | 22.39 |  |  |  |

Table C. 2 (Continued)

| Tree <br> Number | MCS4 |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q 1 | Q 2 | Q 3 | Q 4 |
| 1 |  | 297.16 |  |  |
| 2 |  |  | 343.87 |  |
| 3 |  |  |  | 506.82 |
| 4 | 172.49 |  |  |  |
| 5 | 56.95 |  |  |  |
| 6 | 120.70 |  |  |  |
| 7 | 106.08 |  |  |  |
| 8 |  | 296.62 |  |  |
| 9 |  |  |  | 487.29 |
| 10 |  |  | 275.71 |  |
| 11 |  |  | 259.90 |  |
| 12 |  | 242.39 |  |  |
| 13 |  | 255.88 |  |  |
| 14 |  |  | 262.66 |  |
| 15 | 242.08 |  |  |  |
| 16 |  |  |  |  |
| 17 |  |  |  |  |
| 18 |  |  |  |  |
| 19 |  |  |  |  |
| 20 |  |  |  |  |

Table C. 2 (Continued)

| Tree Number | MCS5 |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Q1 | Q2 | Q3 | Q4 |
| 1 |  | 188.20 |  |  |
| 2 |  |  |  |  |
| 3 | 8.59 |  |  |  |
| 4 |  | 189.37 |  |  |
| 5 |  |  | 234.78 |  |
| 6 | 68.30 |  |  |  |
| 7 |  | 187.69 |  |  |
| 8 |  |  | 275.71 |  |
| 9 | 131.22 |  |  |  |
| 10 |  |  | 236.43 |  |
| 11 | 170.89 |  |  |  |
| 12 |  | 193.41 |  |  |
| 13 |  |  |  | 391.15 |
| 14 |  |  |  | 211.74 |
| 15 | 101.23 |  |  |  |
| 16 |  |  |  |  |
| 17 |  |  | 282.60 |  |
| 18 |  |  |  | 365.98 |
| 19 | 16.65 |  |  |  |
| 20 | 154.62 |  |  |  |
| 21 | 44.33 |  |  |  |
| 14B |  |  |  | 30.98 |

## APPENDIX D: CROWN WEIGHT CONVERSIONS

Bags of chips were collected and combined from each quartile for each plot. One bag of chips was collected for each plot. The bags were immediately weighed on site to obtain the green weight. Bags were stored and later oven-dried, and then weighed again to obtain an estimate for converting green chip weights to bone dry weight.
When there were multiple species present within the same plot, a separate bag of chips was collected for each species.

Table D.1. Chip Weights for Plots near Molalla, OR

| Plot <br> ID | Species | Green Weight <br> (kg) | Dry Weight <br> (kg) | Conversion for <br> Dry/Green <br> Weights |
| :---: | :--- | ---: | ---: | ---: |
|  | DF | 17.23 | 9.72 | 0.565 |
| DFS2 | DF | 21.31 | 9.83 | 0.462 |
| DFS3 | DF | 20.40 | 10.25 | 0.502 |
| DFS4 | DF | 19.95 | 9.18 | 0.460 |
| DF55 | DF | 20.85 | 10.58 | 0.507 |
| DFM1 | DF | 21.76 | 9.25 | 0.425 |
| DFM2 | DF | 21.76 | 12.34 | 0.567 |
| DFM3 | DF | 19.04 | 10.50 | 0.552 |
| DFM4 | DF | 21.76 | 12.39 | 0.569 |
| DFM5 | DF | 19.95 | 11.23 | 0.563 |
| DFL1 | DF | 24.00 | 13.34 | 0.556 |
| DFL2 | DF | 19.70 | 10.39 | 0.527 |
| DFL3 | DF | 21.70 | 13.44 | 0.619 |
| DFL4 | DF | 24.50 | 11.37 | 0.464 |
| DFL5 | DF | 18.00 | 9.22 | 0.512 |

Table D.2. Chip Weights for Plots near Hambone, CA

| Plot ID | Species | Green Weight (kg) | $\begin{gathered} \text { Dry Weight } \\ (\mathrm{kg}) \end{gathered}$ | Conversion for Dry/Green Weights |
| :---: | :---: | :---: | :---: | :---: |
| MCS1 | PP | 8.61 | 4.61 | 0.535 |
| MCS2 | PP | 8.61 | 4.56 | 0.529 |
| MCS3 | PP | 10.88 | 5.93 | 0.545 |
| MCS4 | PP | 9.97 | 5.12 | 0.513 |
| MCS5 | PP | 9.52 | 4.88 | 0.513 |
| MCS5 | IC | 6.35 | 2.81 | 0.442 |
| MCM1 | PP | 5.70 | 2.99 | 0.524 |
| MCM1 | WF | 7.60 | 4.28 | 0.563 |
| MCM1 | IC | 14.00 | 3.23 | 0.231 |
| MCM2 | PP | 6.00 | 3.22 | 0.537 |
| MCM2 | WF | 14.00 | 6.97 | 0.498 |
| MCM2 | IC | 10.70 | 5.57 | 0.521 |
| MCM4 | PP | 14.40 | 6.31 | 0.438 |
| MCM4 | WF | 12.10 | 5.43 | 0.449 |
| MCM4 | IC | 12.20 | 6.55 | 0.537 |
| MCM5 | PP | 13.10 | 7.32 | 0.559 |
| MCM5 | WF | 4.40 | 2.34 | 0.532 |
| MCM5 | IC | 13.30 | 6.70 | 0.504 |
| MCM5 | DF | 4.40 | 1.46 | 0.333 |
| MCL1 | PP | 15.10 | 9.63 | 0.637 |
| MCL1 | IC | 4.10 | 1.98 | 0.483 |
| MCL2 | PP | 5.89 | 3.70 | 0.628 |
| MCL2 | WF | 9.97 | 5.26 | 0.527 |
| MCL2 | IC | 8.61 | 4.55 | 0.528 |
| MCL2 | DF | 4.53 | 2.28 | 0.503 |
| MCL3 | PP | 11.79 | 3.70 | 0.314 |
| MCL3 | WF | 3.00 | 1.98 | 0.660 |
| MCL3 | IC | 11.00 | 3.30 | 0.300 |
| MCL4 | PP | 13.80 | 8.76 | 0.634 |
| MCL4 | WF | 3.00 | 1.67 | 0.558 |
| MCL4 | IC | 11.00 | 5.28 | 0.480 |

## APPENDIX E: DRY CROWN WEIGHT ESTIMATES FOR SELECT TREES

For a select number of trees, the crown weight was individually weighed for that tree. The total dry biomass (kg) is shown in the table below.

Table E.1. Dry Crown Weight Estimates

| Plot <br> ID | Tree | $\begin{array}{\|l} \hline \begin{array}{l} \text { Total } \\ (\mathrm{kg}) \end{array} \\ \hline \end{array}$ | $\begin{aligned} & \text { Plot } \\ & \text { ID } \\ & \hline \end{aligned}$ | Tree ID | $\begin{array}{\|l} \hline \begin{array}{l} \text { Total } \\ (\mathrm{kg}) \end{array} \\ \hline \end{array}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| DFL1 | 1 | 157.5 | DFL4 | 2 | 114.9 |
|  | 2 | 558.5 |  | 5 | 524.1 |
|  | 4 | 338.2 |  | 14 | 359.9 |
|  | 5 | 275.2 |  | 15 | 518.8 |
|  | 8 | 116.9 | DFL5 | 1 | 176.6 |
|  | 10 | 151.2 |  | 6 | 93.7 |
|  | 11 | 62.3 |  | 8 | 153.4 |
|  | 12 | 463.3 |  | 10 | 220.5 |
|  | 13 | 506.2 |  | 13 | 220.8 |
|  | 14 | 123.5 | DFM1 | 1 | 226.3 |
| DFL2 | 1 | 382.2 |  | 6 | 223.6 |
|  | 2 | 739.7 |  | 9 | 156.9 |
|  | 3 | 47.4 |  | 13 | 126.1 |
|  | 4 | 247.2 |  | 19 | 159.7 |
|  | 5 | 167.6 |  | 22 | 92.1 |
|  | 7 | 41.8 | DFM2 | 2 | 274.9 |
| DFL3 | 2 | 652.1 |  | 3 | 503.0 |
|  | 3 | 141.8 |  | 7 | 112.5 |
|  | 4 | 433.8 |  | 11 | 303.5 |
|  | 7 | 519.4 |  | 12 | 290.8 |
|  | 8 | 425.3 |  | 14 | 230.4 |
|  | 10 | 559.8 | DFM3 | 6 | 162.8 |
|  | 11 | 27.4 |  | 8 | 145.2 |
|  | 12 | 34.0 |  | 10 | 167.4 |
|  | 13 | 77.9 |  | 17 | 61.7 |
|  | 14 | 42.2 |  | 20 | 79.8 |
|  | 15 | 553.9 |  |  |  |
|  | 16 | 120.7 |  |  |  |


| Plot ID | Tree <br> ID | Total (kg) |
| :---: | :---: | :---: |
| DFM4 | 3 | 160.6 |
|  | 12 | 160.6 |
|  | 13 | 181.4 |
|  | 17 | 106.6 |
|  | 18 | 152.4 |
|  | 21 | 353.8 |
|  | 23 | 205.5 |
| DFM5 | 3 | 86.9 |
|  | 4 | 254.9 |
|  | 7 | 193.1 |
|  | 10 | 118.8 |
|  | 15 | 352.4 |
|  | 22 | 241.8 |
| DFS1 | 3 | 200.0 |
|  | 8 | 76.2 |
|  | 12 | 95.3 |
|  | 13 | 59.1 |
|  | 19 | 63.5 |
|  | 23 | 103.0 |
|  | 24 | 121.1 |
|  | 28 | 59.4 |
|  | 29 | 111.6 |
| DFS2 | 5 | 127.0 |
|  | 15 | 72.1 |
|  | 17 | 125.2 |
|  | 24 | 71.7 |
|  | 28 | 65.8 |
|  | 30 | 174.6 |

Table E.1, Continued.

| Plot | Tree | Total <br> $(\mathrm{kg})$ |
| :--- | ---: | ---: |
| DFS3 | 6 | 167.8 |
|  | 12 | 20.9 |
|  | 15 | 112.0 |
|  | 18 | 45.4 |
|  | 31 | 86.2 |
|  | 32 | 116.6 |
|  | 40 | 97.5 |
| DFS4 | 7 | 81.6 |
|  | 11 | 137.9 |
|  | 17 | 73.0 |
|  | 20 | 105.2 |
|  | 22 | 121.6 |
|  | 32 | 116.1 |
| DFS5 | 4 | 56.2 |
|  | 5 | 80.7 |
|  | 8 | 117.9 |
|  | 14 | 147.4 |
|  | 20 | 152.9 |
|  | 31 | 123.8 |
| MCL1 | 2 | 59.1 |
|  | 5 | 9.1 |
|  | 27 | 179.9 |
|  | 34 | 84.8 |
|  | 35 | 55.3 |
|  | 36 | 19.8 |
|  | 37 | 48.3 |
|  | 38 | 20.4 |
|  | 42 | 24.7 |
|  | 61.7 |  |


| Plot <br> ID | Tree <br> ID | Total <br> $(\mathrm{kg})$ |
| :--- | ---: | ---: |
| MCL2 | 1 | 16.3 |
|  | 5 | 33.6 |
|  | 6 | 1154.0 |
|  | 7 | 501.7 |
|  | 13 | 69.9 |
|  | 16 | 150.6 |
|  | 18 | 65.3 |
|  | 19 | 560.2 |
|  | 23 | 26.8 |
|  | 25 | 54.4 |
|  | 26 | 60.3 |
|  | 27 | 93.9 |
|  | 28 | 115.2 |
|  | 30 | 35.8 |
|  | 33 | 39.9 |
|  | 34 | 84.8 |
| MCL3 | 10 | 21.6 |
|  | 23 | 202.8 |
|  | 29 | 46.9 |
|  | 35 | 212.0 |
|  | 44 | 25.3 |
|  | 47 | 107.6 |
|  | 48 | 97.7 |
|  | 51 | 8.7 |
|  | 55 | 60.9 |
|  | 60 | 30.9 |
|  | 62 | 60.5 |
|  |  | 138.2 |


| Plot ID | Tree ID | $\begin{array}{\|l} \hline \begin{array}{l} \text { Total } \\ (\mathrm{kg}) \end{array} \\ \hline \end{array}$ |
| :---: | :---: | :---: |
| MCL4 | 3 | 39.9 |
|  | 4 | 99.1 |
|  | 6 | 48.4 |
|  | 8 | 10.2 |
|  | 11 | 17.9 |
|  | 14 | 83.3 |
|  | 15 | 20.1 |
|  | 20 | 40.7 |
|  | 22 | 25.3 |
|  | 25 | 195.3 |
|  | 26 | 70.5 |
|  | 32 | 373.5 |
|  | 33 | 58.4 |
|  | 39 | 169.7 |
|  | 41 | 118.9 |
| MCM1 | 16 | 52.3 |
|  | 34 | 42.2 |
|  | 102 | 359.1 |
|  | 106 | 11.8 |
| MCM2 | 17 | 49.8 |
|  | 36 | 20.5 |
|  | 44 | 353.6 |
|  | 47 | 106.8 |
|  | 49 | 40.2 |
|  | 51 | 46.0 |
|  | 57 | 181.4 |
|  | 62 | 53.5 |
|  | 66 | 56.1 |
|  | 78 | 114.3 |
|  | 108 | 47.5 |

Table E.1, Continued.

| Plot | Tree | Total <br> $(\mathrm{kg})$ |
| :--- | ---: | ---: |
| MCM4 | 1 | 21.2 |
|  | 3 | 7.9 |
|  | 4 | 128.2 |
|  | 5 | 44.8 |
|  | 7 | 328.0 |
|  | 8 | 65.1 |
|  | 9 | 19.7 |
|  | 15 | 186.9 |
|  | 20 | 243.8 |
|  | 23 | 44.7 |
|  | 26 | 36.5 |
| MCM5 | 1 | 824.7 |
|  | 3 | 63.7 |
|  | 4 | 136.8 |
|  | 5 | 80.6 |
|  | 6 | 30.0 |
|  | 7 | 493.0 |
|  | 9 | 898.9 |


| Plot ID | Tree <br> ID | Total <br> $(\mathrm{kg})$ |
| :--- | ---: | ---: |
| MCS1 | 1 | 432.7 |
|  | 2 | 173.7 |
|  | 3 | 254.9 |
|  | 4 | 166.0 |
|  | 5 | 346.1 |
| MCS2 | 1 | 189.1 |
|  | 2 | 216.8 |
|  | 3 | 264.0 |
|  | 4 | 296.2 |
|  | 5 | 294.8 |
| MCS3 | 5 | 175.5 |
|  | 13 | 142.0 |
|  | 20 | 140.2 |
| MCS4 | 3 | 396.0 |
|  | 7 | 110.7 |
|  | 9 | 402.3 |
|  | 15 | 292.1 |
| MCS5 | 3 | 19.5 |
|  | 9 | 90.7 |
|  | 14 | 171.0 |
|  | 21 | 47.6 |

## APPENDIX F: DISCUSSION OF HEMISPHERICAL PHOTOGRAPHS

While obtaining and analyzing hemispherical photographs, there were many issues and imperfections that were dealt with that affected the accuracy of gap fraction measurements. Several assumptions had to be made, especially given the heterogeneous lighting conditions for many plots, especially in more open plots or if the sun was more directly overhead. Figure F. 1 shows one of the hemispherical photographs with more uniform lighting conditions, which is more ideal for this methodology. However, as seen in several photographs below, these assumptions do not always hold.


Figure F.1: Typical Hemispherical Photograph with Relatively Uniform Lighting

Figure F. 2 shows how lighting within the plot increases as the trees were removed from the plot. This made it more difficult to measure gap fractions for higher quartiles.


Figure F.2: Progression of Q1, Q2, Q3, Q4 Images for MCM1

The photographs below graphically depict issues with photographs from each site.
Molalla, $O R$


Figure F.3: Light Gradient of Sky, Relative Brightness of Tree Boles


Figure F.4: Direct Overhead Sunlight (Not Used in Analysis)


Figure F.5: Sun Blocked to Improve Lighting, Pixels Later Adjusted


Figure F.6: Canopy Lighting, Especially Affecting Uppermost Canopy

Hambone, CA


Figure F.7: Sky Lighting Gradient, Tree Bole Color Differences


Figure F.8: Cloud Cover that Caused Image Analysis Problems


Figure F.9: Extreme Color Differences for Canopy and Bole Pixels

## Pringle Falls, CA



Figure F.10: Relatively Short Trees with Less Biomass


Figure F.11: Relatively Tall Trees with More Biomass


Figure F.12: Plot from Thinning Trial, which had the Most Biomass, but Large Gaps

The following images briefly show graphically some of the techniques used to separate sky and canopy pixels.


Figure F.13: Orthogonal Transformation


Figure F.14: PCA Analysis
Once the classifications were made in ENVI, each classification was divided into either sky or canopy. As seen in Figure F.15, brightly lit tree trunks were still often misclassified, and the only way to properly classify them was to manually manipulate the image.


Figure F.15: Dividing Pixels into Sky and Canopy

## APPENDIX G: FIELD METHODOLOGY AND GENERAL STAND CONDITIONS

All destructive sampling from all plots for the Molalla, OR and Hambone, CA areas were conducting with similar methodology, as outlined in the photographs below. All trees were felled and bucked by chainsaw (Figures G. 11 and G.12). The mobile chipper was placed between plots whenever possible to minimize the number of moves (Figure G.13). Once the trees from a quartile were felled, diameter and height measurements were made for each tree (Figure G.14). Once the measurements were made, the crown and branches were collected and dragged to a mobile chipper (Figure G.15). Branches were then loaded into the mobile chipper (Figure G.16). A custom made chute was created to ensure that chips were directed into a bucket, although the chute frequently clogged (Figure G.17).

A cable rigging was setup between two trees with a pulley system to allow the bucket to be suspended from the ground (Figure G.18). Once the bucket was lifted, a scale was used to measure chip weight, and the bucket weight was subtracted (Figure G.19). The maximum capacity tested with this methodology was about 150 kg , because the bucket had to be manually lifted and dumped. After the trees from a particular quartile were removed, the camera was set up in the plot center and several photographs were taken at different settings, since it was impossible to come back later and photograph again if there were photograph problems. (Figure G.110).


Figure G.1: Trees Hand Felled Directionally to Minimize Crown Damage


Figure G.2: Trees Delimbed, Cookies cut from Select Trees for Density Estimate


Figure G.3: Mobile Chipper Strategically Located to Minimize Relocating


Figure G.4: Diameter Measurements were Made along the Bole with Caliper


Figure G.5: Crown and Limbs Manually Dragged to Mobile Chipper


Figure G.6: Crown and Limbs Chipped With Mobile Chipper


Figure G.7: Primary Productivity Limitation - Clogging from Custom-Made Chute


Figure G.8: Bucket Suspended with Rigging Between Two Trees


Figure G.9: Come-along ratchet Used To Raise and Weigh Chips (Up to ~150kg)


Figure G.10: Camera Setup on Camera Tripod and Self-Leveling Mount

The following figures show typical conditions for different plot types at the three sites.
All photos below were taken from plot centers, where the hemispherical photograph was taken.
Molalla, OR


Figure G.11: Typical 67-year-old Plot Appearance, Molalla OR


Figure G.12: Typical 66-year-old Plot Appearance, Molalla OR


Figure G.13: Typical 39- year-old Plot Appearance, Molalla OR


Figure G.14: Typical 20-year-old Plot Appearance, Molalla OR
Hambone, CA


Figure G.15: Typical Plot Appearance for Older Stands, Hambone CA


Figure G.16: Typical Plot Appearance for Older Plots, Hambone CA


Figure G.17: Typical Plot Appearance for Younger Plots, Hambone CA

Pringle Falls, OR


Figure G.18: Typical Plot Appearance for Thinning Plots, Pringle Falls, OR


Figure G.19: Typical Plot Appearance for Spacing Plots, Pringle Falls, OR


Figure G.20: Typical Plot Appearance for Spacing Plots, Pringle Falls, OR

