![USDA logo] **United States Department of Agriculture**
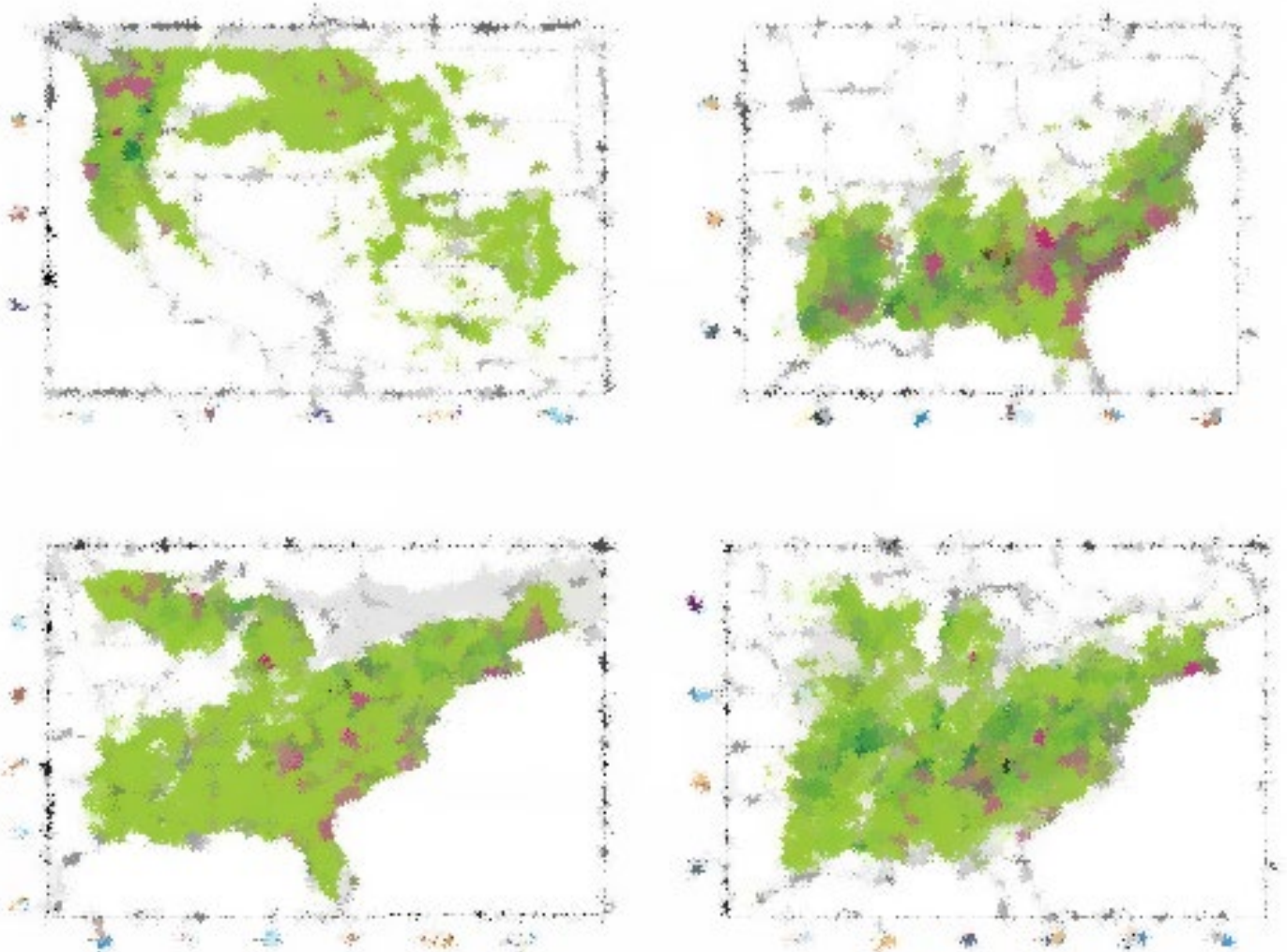
Gaps in Available Data for Modeling Tree Biomass in the United States

Jereme Frank, Aaron Weiskittel, David Walker, James A. Westfall, Philip J. Radtke, David L.R. Affleck, John Coulston, David W. MacFarlane

Abstract

When estimating tree-level biomass and carbon, it is common practice to develop generalized models across numerous species and large spatial extents. However, sampling efforts are generally incomplete and trees are not randomly selected. In this analysis, of the more than 1,000 biomass-related articles that were reviewed, trees were destructively sampled in over 300 studies to estimate biomass in the United States. Studies were summarized and past sampling efforts were explored to illuminate where the largest data gaps occurred in terms of tree components sampled, tree size, tree form, tree species, and location. The most prominent gaps were in large trees, particularly in Douglas-fir trees in the Pacific Northwest. In addition, tree roots were notably undersampled. Lastly, trees of poor or unusual form and low vigor were often not sampled, and this may introduce a systematic bias if not dealt with appropriately. More than 200 species did not have a biomass model or a single data point. The gaps presented here can be viewed as suggestions for future destructive sampling efforts, but the magnitude of a gap for a given model will ultimately depend on the selected modeling framework and the user's objectives.

The Authors

JEREME FRANK is a research assistant with the University of Maine, School of Forest Resources, Orono, ME 04469; jeremem.frank@gmail.com.

AARON WEISKITTEL is a professor of forest biometrics and modeling with the University of Maine, Center for Research on Sustainable Forests, Orono, ME 04469.

DAVID WALKER is a research associate with Virginia Tech, Department of Forest Resources and Environmental Conservation, Blacksburg, VA 24061.

JAMES A. WESTFALL is a research forester with the USDA Forest Service, Northern Research Station, Newtown Square, PA 19703.

PHILIP J. RADTKE is an associate professor of forest biometrics with Virginia Tech, Department of Forest Resources and Environmental Conservation, Blacksburg, VA 24061.

DAVID L.R. AFFLECK is a professor of biometrics with the University of Montana, W.A. Franke College of Forestry and Conservation, Missoula, MT 59812.

JOHN COULSTON is a supervisory research forester with the USDA Forest Service, Southern Research Station, Blacksburg, VA 24060.

DAVID W. MACFARLANE is a professor of forest measurements and modeling with Michigan State University, Department of Forestry, East Lansing, MI 48824.

Cover Art

Cover artwork by D.L.R. Affleck, D.W. MacFarlane, and J. Frank, used with permission.

Gaps in Available Data for Modeling Tree Biomass in the United States

Jereme Frank, Aaron Weiskittel, David Walker, James A. Westfall,
Philip J. Radtke, David L.R. Affleck, John Coulston, David W. MacFarlane

CONTENTS

INTRODUCTION

Rationale

Given increasing interest in accounting for forest biomass and carbon stocks (Aalde et al. 2006, Pan et al. 2011) across the world, and specifically in the United States, there is a need to more closely examine limitations to current tree biomass estimation methods. At a broad level, biomass estimation methods are often categorized as (1) regional biomass conversion/ expansion factors (e.g., Fang and Wang 2001), (2) stand-level biomass models, or (3) tree-level biomass models (Temesgen et al. 2015). In particular, there are two primary factors that influence biomass estimation accuracy: limitations to modeling techniques, and sampling gaps that limit available data and the geographic extent of model applicability. This review explores gaps in previous sampling efforts that limit the available data required to develop tree-level biomass models across the United States. Other important limitations of biomass estimation methods (including modeling techniques) are discussed in Weiskittel et al. (2015).

Generalized Allometric Models

Tree-level biomass models are generally derived by destructively sampling a subset of live trees, drying and weighing the separate tree components (e.g., stems, branches, foliage), and using allometry to relate some easily measured metric (e.g., diameter and sometimes height) to the dry weight of the entire tree or some portion or component of the tree. Destructive sampling is extremely costly and time intensive; thus, most biomass studies sample a relatively small number of trees over a generally small area. In addition, sampling units are difficult to select objectively or at random due to operating restrictions and landowner limitations. Consequently, sampling efforts are often coordinated with ongoing management objectives or otherwise constrained to areas where destructive sampling is feasible. As such, it is difficult to be entirely representative in both site and tree selection.

Variations in wood and bark properties, crown architecture, and stem form can result from different climatic, soil, or management factors (Larson 1963), making it challenging to extrapolate biomass to a different location or larger area. Those seeking to derive stand- and landscape-level biomass and carbon estimates often turn to geographically generalized tree-level allometric models, which use data from multiple studies and locations to refit models to a larger area (e.g., Schmitt and Grigal 1981).

In addition to considering how sites are selected, it is important to consider how individual trees are selected. Standards for sampling trees for volume and yield tables (e.g., Behre et al. 1926), and by extension biomass models, generally exclude trees with abnormalities and defects from model fitting because they detract from a study's ability to identify allometric relationships. This selection effect can result in a significant amount of systematic bias, leading to overestimates, particularly in hardwood biomass (e.g., MacFarlane and Weiskittel 2016).

Previous Tree Biomass Allometric Model Compilations

The plethora of published allometric models and their frequent use in estimating biomass and carbon across various scales has necessitated literature syntheses to understand limitations in both the models and the data used to build them. In Europe, Zianis et al. (2005) summarized the number of biomass models in terms of species by tree component and country. Similar syntheses have summarized models in Australia (Keith et al. 2000), sub-Saharan Africa (Henry et al. 2011), southeast Asia (Yuen et al. 2016), South America (Cifuentes-Jara et al. 2013), and North America (Ter-Mikaelian and Korzukhin 1997). Jenkins et al. (2004)

summarized biomass models from 177 biomass studies for tree species commonly found in the United States. More recently, Chojnacky et al. (2014) updated these models. While most of these compilations focus on developing or comparing models, recent work in the United States has led to a compilation of actual tree-level volume, biomass, and component biomass data (Radtke et al. 2015).

Current Biomass Estimation Approaches for the U.S. Forest Inventory

Perhaps the most widely used standing tree inventory available in the United States is the USDA Forest Service, Forest Inventory and Analysis Database (FIADB) (O'Connell et al. 2016). This database is also considered the best source for estimating biomass and carbon at the landscape level in the United States. For example, the Forest Inventory and Analysis (FIA) program reports its carbon estimates to the United Nations Framework Convention on Climate Change (UNFCCC) (USEPA 2017), and the Department of Energy relies on FIA's estimates of biomass (Aalde et al. 2006). Furthermore, biomass is the basic unit of productivity used in numerous ecological studies (e.g., Clark et al. 2001, Parker and Schneider 1975, Whittaker et al. 1974), and it is clearly important that mean biomass predictions and characterizations of uncertainty are accurate.

To estimate tree-level biomass, FIA uses the Component Ratio Method (CRM) (Woodall et al. 2011b), having switched in 2008 from previously using regionally-specific biomass models (e.g., Wharton and Griffith 1993). CRM uses species-specific regional volume models, deducts cull to estimate sound cubic-foot wood volume, and uses biomass conversion and expansion factors (BCEFs) to estimate total aboveground biomass without foliage. These BCEFs include wood and bark density values (as presented in Miles and Smith 2009) as well as nationally and taxonomically generalized CRM models (as presented in Jenkins et al. 2003). These models are then applied to the tree list in the FIADB to estimate state, regional, and national biomass. Despite this recent switch to the CRM, assessment of the new approach has been minimal (e.g., Domke et al. 2012). A recent analysis using observed tree-level biomass data from the eastern states suggests that the CRM method underestimates biomass by 6-15 percent across the eastern United States (Radtke et al. 2017). Because a fully comprehensive destructive sampling effort to obtain tree biomass data across the United States has not been conducted, it is also important to understand how sampling gaps may influence past and future assessments.

An important underlying assumption of this work is that tree biomass can vary between species, diameter at breast height (d.b.h.) or d.b.h./height, and region even when other factors are held constant. Basic allometry suggests that for a given species within a region, biomass will increase as d.b.h. increases (Jenkins et al. 2003). In addition, for a given tree size, biomass will vary between species within a region due to differences in wood density (Miles and Smith 2009) and tree architecture. Regional differences, however, are more difficult to detect. For instance, Jenkins et al. (2003) found that biomass regressions of the same species varied considerably, but no regional patterns were apparent. This brings up the question as to whether apparent biomass differences should be attributed to regional variation, noise in biomass measurements, or high site-to-site variability.

Objectives and Expectations

The primary objectives for this study were threefold:

1. Report on the number of studies that have been conducted and the number of trees sampled by core component groups to estimate biomass in the United States.

2. Assess the sample sizes and diameter ranges for key species evaluated in previous studies.

3. Characterize the sampling locations of certain species and compare that to the geographic range of the species.

Data collected across these studies will ultimately be used to test the assumptions mentioned in the previous section. Thus, data gaps were considered in terms of (1) how they may affect generalized models and CRM estimators used to assess biomass at various scales across the United States; (2) how the data can serve to validate current models; and (3) how they might restrict future model applicability when using actual data. Ideally, from a validation perspective, the relative representation of data from destructively sampled trees would match the standing tree inventory. However, from a modeling perspective, ensuring sampling across the range of attributes may be preferred (i.e., ensuring some samples of large trees at the tail of size distribution rather than a high number of trees at the peak). To illustrate, the publicly available FIADB was used to compare and formally assess gaps in terms of tree size classes, species, and location.

METHODS

Recording Information for the Gap Analysis

Literature Review

To complete this analysis, an exhaustive search of the literature on tree biomass studies in the United States was conducted. First, previous tree biomass model syntheses and databases (Chojnacky et al. 2014, Jenkins et al. 2004, Ter-Mikaelian and Korzukhin 1997) were examined, and the literature describing the studies cited in these articles were used as a source for additional resources. The literature review leveraged these past works by providing additional details on each study, synthesizing the additional information, and incorporating newer datasets. In addition, this review encompassed a recent (and ongoing) compilation of biomass data from destructively sampled trees (Radtke et al. 2015), hereafter referred to as the "legacy tree database." The data search for the legacy tree database extended beyond the peer-reviewed literature and incorporated a number of unpublished studies. As a matter of accounting and considering the widespread use of the models developed by Jenkins et al. (2004) and Chojnacky et al. (2014) in the United States, it was noted if the reviewed studies appeared in these works. It was also recorded if actual biomass data or only a model could be obtained from each study. For studies that had a model, it was noted if the model contained height as a predictor and if the author reported standard error. The objective was to quantify the number of trees greater than 1 inch d.b.h. within the United States for which at least one tree component was destructively sampled for dry weight. Studies were not included in the analysis if they were located outside of the United States, were compilations, were more theoretical or statistical in nature, measured only external characteristics (without any destructive sampling) on standing trees, sampled only seedlings (i.e., trees less than 1 inch d.b.h.) or shrubs, measured only green weight or volume, or focused on biomass estimates at the stand or regional level rather than the tree level. Exceptions to these rules included studies where both seedlings and larger trees were sampled and the number of each could not be determined. In these cases, the total number of sampled trees included seedlings.

Tree Components

The primary interest of this study was in estimating aboveground biomass (AGB). However, given that other researchers may be interested in the mass of individual tree components, all components sampled were reported. For instance, the CRM and biomass expansion factors (BEFs) in general rely on the relationship between a component (particularly bole biomass) and AGB (without foliage). In addition, recent studies suggest that variations in whole-tree mass are related to differences in the way mass is allocated to tree components (e.g., the crown) (Goodman et al. 2014), and that bole volume is strongly affected by the allocation of wood to branches (MacFarlane and Weiskittel 2016). Filling gaps in tree component data is also important because tree utilization is best understood when the tree is modeled as the sum of its interrelated parts (MacFarlane 2015). Finally, branch and bark models might provide preliminary estimates for bioenergy harvests (Conner and Johnson 2011, USDOE 2011), while foliage estimates are integral for ecosystem process modeling (e.g., Chapin et al. 2002).

The USDA Forest Service National Biomass Estimation Library (Wang 2014), an extension of the Jenkins et al. (2004) database, identified 47 different tree component classes, many of which can be seen as subclasses of other components. For this analysis, gaps in available data were assessed for nine tree component groups: (1) total stem (wood and bark) biomass; (2) branch wood and bark biomass; (3) total above-stump biomass (including foliage); (4) root biomass; (5) stem wood biomass; (6) stem bark biomass; (7) total above-stump wood and bark biomass (excluding foliage); (8) crown (foliage and branch) biomass; and (9) foliage biomass. Studies vary considerably in how they differentiate between size classes of roots or branches, and often models calculate the biomass of the entire component and do not separate by size. In this analysis, a study was considered to have examined root biomass if any portion of the root biomass was measured. For branches (wood and bark), the study had to include at least the live branch component, although for most studies, the branch component included both live and dead branches. There were also differences in how components were separated. For example, in most cases the foliage component was separated from the twig; however, in some cases, foliage was defined as leaf and twig (e.g., Lambert et al. 2005, Whittaker et al. 1974). Finally, studies varied in how they defined the stem, specifically whether it constituted the entire stem or merchantable stem, and how the merchantable stem was delimited (i.e., "topped"). For this analysis, the stem was considered to be sampled if the entire merchantable stem was sampled regardless of where it was delimited.

Tree and Site Selection Criteria

For each reviewed study, the author, year, species, and location were recorded. In addition, for each location by species combination, the sample size; average, minimum, and maximum tree diameter; and tree components sampled were recorded. Each study was then examined to determine if tree-sampling restrictions were imposed as evidenced by avoiding trees of poor form (e.g., low forks, excessive branching, or broken tops) or poor health (e.g., showing signs of low vigor, damage, or disease, and at high risk of mortality). The best available information for site locations was used to estimate latitude and longitude for each study. Frequently, coordinates could be estimated to within 0.05°, although accuracy was much lower for studies that had a location description that was either too general or the extent of the area sampled was too large and little site-specific information was provided. Based on the location data, trees were assigned to one of four FIA regional units: Northern, which was split into Northeast (NE) and North Central (NC); Southeastern (SE); Intermountain West (IMW); and Pacific Northwest (PNW).

The lack of uniformity in recording site characteristics across studies makes it difficult to utilize site factors in the modeling framework. Authors of many articles do not adequately explain how sites are selected and do not describe physiography, landscape, or stand attributes. Some studies utilize classification systems, but groupings often differ across studies or use qualitative descriptors such as poor and good, which makes intra-study comparisons difficult. Site index can be used to classify studies, but in a previous review, site index was recorded in fewer than 10 studies (Ter-Mikaelian and Korzukhin 1997). Instead, in this analysis, data gaps were assessed by location and region, two factors that can be viewed as proxies for variations in climatic conditions, edaphic characteristics (such as soil type or depth), and treatment.

Assessment and Quantification of Data Gaps by Location, Species, and Diameter

This analysis examined available models and actual data (i.e., data available in the legacy tree database) and includes summaries of (1) the total number of trees sampled across all studies; (2) the total number of studies conducted; and (3) the number of trees available in the legacy tree database across all species by components and region. The summaries can be seen as a first assessment of gaps in available data.

As a means to assess gaps in data by tree diameter, diameter distributions for a given species were compared between the FIADB and the legacy tree database. Boxplots showing the maximum, minimum, median, and 25th and 95th quantiles were used to show discrepancies between the distributions of the two datasets and to highlight the limitations in the range of trees sampled in the legacy tree database. Distributions of the data were further examined for species groups and species by proportion of trees and proportion of biomass.

To visualize and assess spatial gaps in data (i.e., do the number of trees sampled represent the biomass across a species' range), maps showing the FIADB-estimated biomass per acre for the 30 species with the most biomass across the continental United States were overlaid with the locations of past biomass studies. Latitudinal and longitudinal biases were depicted by calculating and plotting spherical centroids weighted by FIA plot biomass data and sample size in the legacy tree database. The FIA estimate for total tree biomass was calculated as oven-dry biomass in the merchantable bole + dry biomass of tops and limbs of timber species (DRYBIO_BOLE + DRYBIO_TOP in O'Connell et al. 2016). Percent error was calculated by taking the ratio of the distance between the centroids and the diagonal distance between the minimum and maximum coordinates and then converting this to a percentage.

A goal of this study was to quantify whether past sampling efforts undersampled trees of different sizes and species relative to the amount of biomass reported for trees of the specified sizes and species represented in the U.S. forest carbon inventory. The number of trees for a given species, diameter size class (d.b.h. <5 inches = 1; 5 to <15 inches = 10, 15 to <25 inches = 20, etc.), and FIA region in the legacy tree database and the percentage of the biomass present for the same groups in the FIADB were calculated. Potential gaps were described for illustrative purposes by using a baseline tree sampling objective equal to the FIADB biomass percentage x 10. As a measure of sampling effectiveness, the sampling completeness value (SCV) was calculated as the product of the number of trees in the legacy tree database and the sampling objective. In addition, representation for a biomass pool was calculated as the difference between the percentage of the number of trees in the legacy tree database and the percentage of biomass in the FIADB.

RESULTS

Over 1,060 studies were identified that were potentially related to tree-level biomass estimation. After eliminating studies determined not to contain data relevant to this analysis, 844 studies were further examined. A preliminary review of these 844 studies determined that 351 had actual tree-level aboveground or component biomass (e.g., stem, foliage, roots, or branches) measurements assessed in the United States. Trees were destructively sampled in most of the studies, but in some cases trees were cored and climbed with limited branch sampling (e.g., Sillett et al. 2015). Of the biomass studies that used destructive sampling, 25 were duplicates and were removed, leaving 326 unique studies with a combined total of 47,684 trees in the analysis (see Appendix 1 for a list of all studies). A total of 240 of these studies (74 percent) were not included in Jenkins et al. (2003), which developed generalized models using numerous finer-scale models to generate pseudodata.

Tree and Component Mass

A total of 24,791 trees (52 percent of the 47,684 trees sampled) were identified from 199 studies that employed destructive sampling for above-stump biomass across the United States (Table 1; tables begin on p. 17). Stem biomass was measured for 27,080 trees (57 percent); stem wood biomass estimates were available for 25,618 trees (54 percent); and wood biomass estimates were provided for 20,283 trees (43 percent). Stem measurements generally were taken from a variable stump (generally ≤1 foot) to a variable top, which was almost always reported as a value <4 inches diameter outside bark. Branch, crown, and foliage biomass was estimated for 22,197 (47 percent); 19,154 (40 percent); and 21,262 (45 percent) trees, respectively. Estimates for the stump and root portions of the tree were less common, with root biomass measurements identified for only 2,840 (6 percent) trees.

When considering legacy tree data only, the percentage of known trees measured ranged from 72 percent (14,548 out of 20,283 trees) for stem bark biomass to 13 percent for root biomass (363 out of 2,840 trees). Trees that had both stem and above-stump biomass measured included 11,402 trees from the legacy tree database and 17,251 trees across all studies. In the legacy tree database, above-stump biomass (with or without foliage) was measured for 14,073 trees. This number is slightly higher than the number of trees with above-stump biomass and the number of trees with total wood biomass (Table 1) because it included trees both with and without foliage. For the 30 species with the greatest biomass in the FIADB, subalpine fir[1], Sitka spruce, white fir, and grand fir were lacking in total aboveground estimates. Mountain hemlock and pignut hickory were undersampled for all components and have no known destructively sampled trees. Data for all 148 species that had at least one tree sampled can be found in Table S1 (supplemental files for tables S1-S8 and Appendix S2 are available at https://doi.org/10.2737/NRS-GTR-184.s2).

Tree Selection

Species

Gaps in species data were depicted by tree component (Table 1), study type (Table 2), and region (Table 3). Excluding more general taxonomic groupings and species in the Caribbean and Pacific, 354 unique tree species were identified in the FIADB. Models or legacy tree data were available for 148 of these species (see Appendix S2 in supplemental tables file for list), leaving 206 species for which a published biomass model could not be located. These 206 species, however, accounted for less than 10 percent of the total biomass in the FIADB. The

---

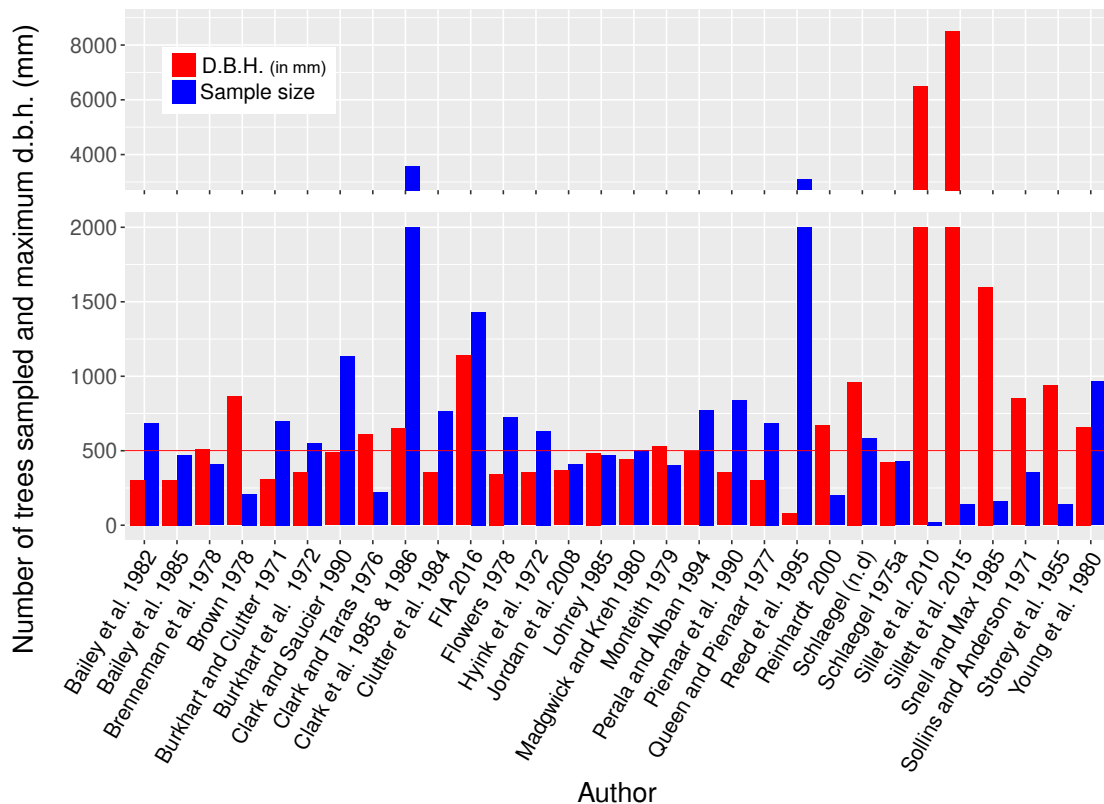[1]Scientific names for all tree species are listed in Appendix 2.

Figure 1.—Sample size and maximum d.b.h. (in mm = inches * 25.4) sampled for the 30 studies with the greatest importance index (simply sample size * maximum d.b.h. (mm) sampled). A threshold of 500 (red line) highlights the studies that sampled a maximum diameter tree greater than 19.7 inches (500 mm) or sampled more than 500 trees. Please note the discontinued scale. (See Appendix 1 for study citations.)

10, 20, and 30 species with the greatest amount of biomass in the FIADB made up 42 percent, 57 percent, and 67 percent, respectively, of the total biomass in the FIADB and 33 percent, 42 percent, and 61 percent, respectively, of the destructively sampled trees in the literature. The species with the greatest number of trees was loblolly pine, with 9,967 trees sampled (Table 2). By comparison, only 1,177 Douglas-fir trees have been sampled for at least one component of tree biomass. Of the 30 species with the greatest amount of biomass in the FIADB, pignut hickory and mountain hemlock had no samples in the legacy tree database (Table 2). Additional species with no samples included Pacific silver fir, shagbark hickory, and common pinyon (Table S2). It is worth noting that although more hickory trees were sampled, they were rarely identified to species (e.g., Clark et al. 1986, Wiant 1977). Additional ash, poplar, elm, birch, hackberry, and oak species were also sampled, but were not identified to species (see Appendix 2 in this document and Appendix S2 in supplemental tables file for the complete list of species and genera in this study).

Sample Size, Size Classes, and Diameter Distributions

Relatively few studies sample trees over 20 inches (500 mm) in d.b.h. and sample more than 500 trees. Given this finding, studies that sampled a high number of trees, including large trees, were noted as higher in importance. An importance index (sample size * maximum d.b.h. in inches/100) was calculated for each study, and the studies with the 30 highest importance indexes (Table 4, Fig. 1) contained 21,659 of the 47,684 trees evaluated for this analysis. These included the work of Alexander Clark (Clark and Saucier 1990; Clark and Schroeder 1986; Clark et al. 1985, 1986), which contributed 4,712 trees in a rather comprehensive sampling of the southeast region; Young et al. (1980), who sampled an estimated 965 trees in Maine; and
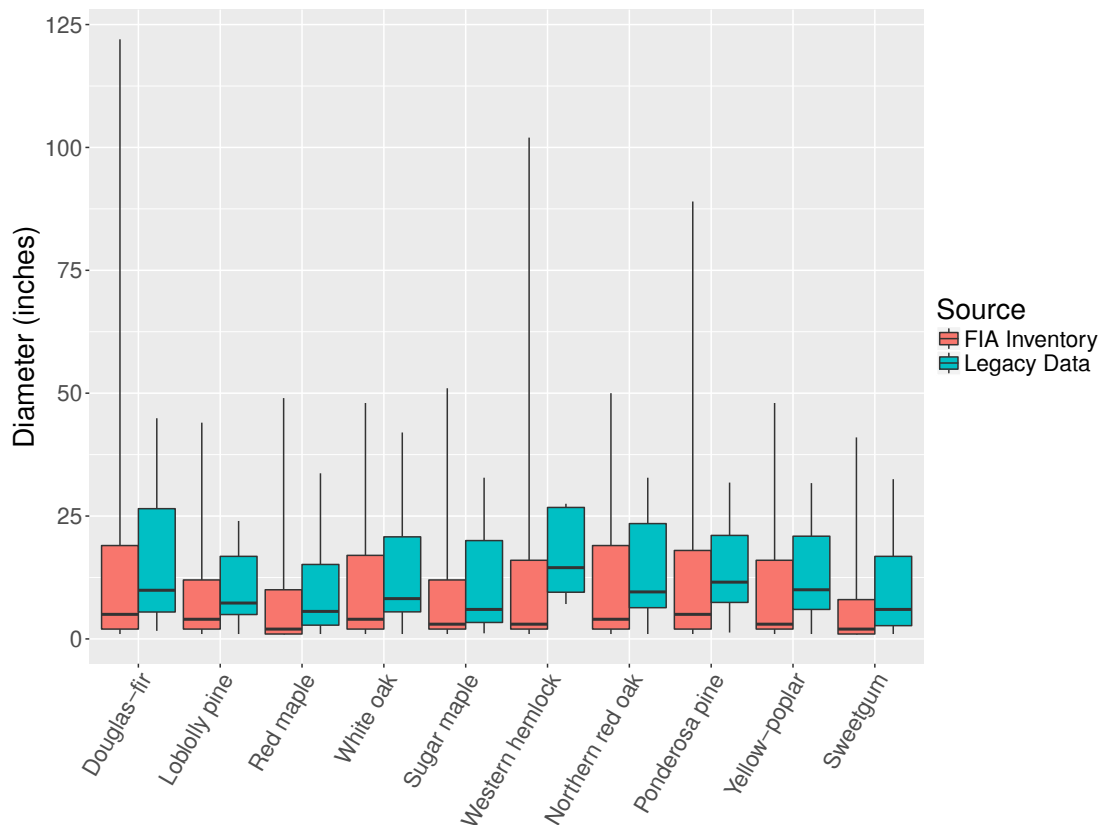
7

Figure 2.—The boxplot shows the diameter distributions of forest land trees in the FIA database compared to trees in the legacy tree database for the 10 species with the most biomass. The 25th and 95th quantiles are represented by the bottom and top of the box, respectively, and maximum and minimum values are represented by the top and bottom of the lines, respectively. The line that dissects the box marks the median value. Additional figures for the remaining 30 species with the most biomass in the FIADB are available as supplemental materials (Figs. S2.2 and S2.3).

Perala and Alban (1994), who sampled extensively across the Great Lakes region (NC region). The works of Sillett et al. (2010, 2015) are highly influential, being the only U.S. studies to measure above-stump biomass for trees over 50 inches in d.b.h. The redwoods sampled in California are by far the largest trees sampled across North America. Otherwise, the majority of the 30 studies with the highest importance index occurred in the eastern United States, with more than half from the southeast (Table 4).

For most species, the largest trees were generally undersampled (Fig. 2). Across the United States, the largest tree sampled for biomass was generally greater than 95 percent of the trees in the FIADB; however, for a given species, the largest destructively sampled tree was often less than half the size of the largest tree in the FIADB (Fig. 2). By count, hardwood trees with a d.b.h. from 1 to 19 inches and conifers with a d.b.h. from 1 to 23 inches represented 99 percent of trees across the landscape. While the vast majority of trees were in the smaller diameter classes, the greatest proportion of biomass was in the mid-range diameter classes (Fig. 3). By individual species, distribution peaks consistently shifted from saplings (1 to <5 inches d.b.h.) when examining the proportion of trees by count to small trees (5 to <15 inches d.b.h.) when examining the proportion of biomass by size class (Figs. S3.1 to S3.30). A shift in the peaks of the distribution from small diameter classes in the FIADB to larger diameter classes in the legacy tree database was also generally observed, suggesting that trees were destructively sampled to cover a selected range of diameters rather than being sampled strictly according to the distribution. However, these trends likely vary by state based on current composition and past management.
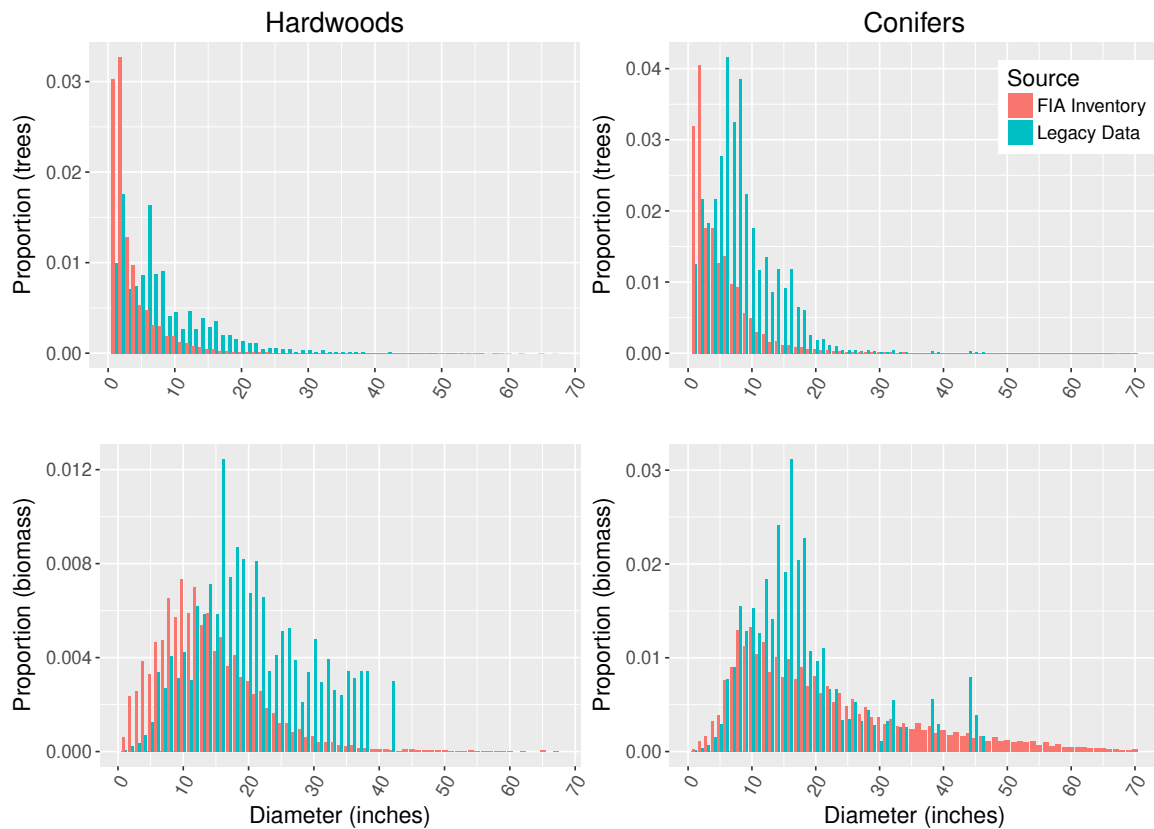
Figure 3.—Tree frequency by diameter class in the FIA and legacy tree databases for hardwoods and conifers (top panels) and the proportion of biomass by diameter in the FIA and legacy tree databases (bottom panels). Given the overwhelming proportion of biomass in redwood trees in the legacy tree database, they were excluded from this figure. Individual species figures for the 30 species with the most biomass in the FIADB are available as supplemental materials ([Fig. S3](#)).

Tree Sampling Restrictions Based on Form, Risk of Mortality, or Vigor

For many studies, it was difficult to determine whether sampling restrictions were imposed. Of the 326 studies (47,684 trees) examined, it was determined that 67 studies (10,080 trees) imposed sampling restrictions, while 46 studies (10,903 trees) described their sampling design as random and did not indicate any sampling restrictions. For the remaining 211 studies, tree selection methods were unclear. Clark et al. (1985, 1986) classified trees as growing stock, rough, and rotten/cull, and we assumed that there were no sampling restrictions; Perala and Alban (1994) randomly selected trees and recorded rot and stain, while Schlaegel (1975) took diligent note of external defect and measured rot and stain. Generally, sampling restrictions were evidenced in methodologies that avoided trees that were open grown, heavily defoliated, broken at the top, low-forked, diseased, or otherwise distorted (Brown 1978). In other cases, only good to average form or "healthy" trees were selected (Hocker and Earley 1983, Levia 2008). In one case, if trees were over 12 inches d.b.h., only poor form or less vigorous trees were selected (Bridge 1979). In other cases, the sample may have been biased toward a particular class of trees according to the objectives of a thinning study (Goldsmith and Hocker 1978).
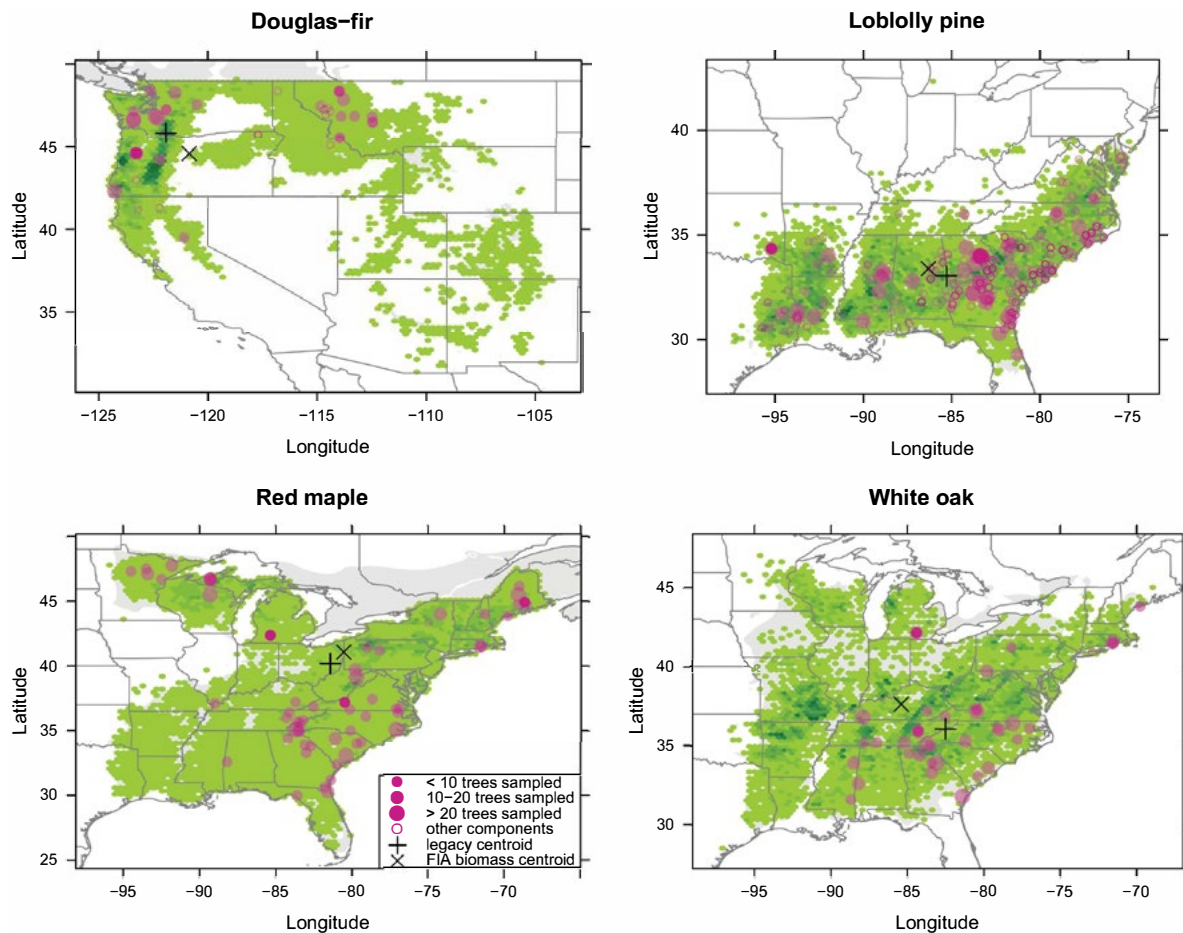
Figure 4.—Known biomass study locations and maximum sample size sampled for the four most prevalent species by biomass across the United States plotted over biomass per acre as estimated from the FIA database. Low biomass sites appear in lighter shades of yellow and green and high biomass sites appear in shades of dark green and blue. Species level maps for the 30 species with the most biomass in the FIADB are available as supplemental materials (Fig. S4).

Geography, Site Selection, and Location

A comparison of FIADB-estimated biomass per acre across the species range and known biomass study locations showed some variation for the four species with the most biomass (Fig. 4). For red maple, over 95 percent of reported biomass was in only 22 of the 31 states where this species occurs. In particular, the Allegheny Plateau in northwestern Pennsylvania and southwestern New York represented areas of high red maple biomass. However, prior to FIA sampling in 2014, no more than eight red maple trees had been sampled in these areas (Wood 1971), and none of these trees had a d.b.h. greater than 11.8 inches. In contrast, sampling for loblolly pine appeared to be relatively complete across its range, while Douglas-fir could be further studied in the southeast portion of its range, and white oak could be further studied in eastern Missouri. Comparisons between the legacy and FIA biomass centroids for Douglas-fir, loblolly pine, and red maple showed relatively good agreement, with differences of 6.4, 4.0, and 3.5 percent, respectively (Table 5). By comparison, white oak showed a southeasterly sampling bias of approximately 9.7 percent (311 miles), which would be alleviated by sampling towards the western edge of its range. Individual maps comparing the FIADB-estimated biomass per acre across the species range and known biomass study locations are available for the 30 species with the greatest biomass (Fig. S4.1-S4.30).

Over half of the trees sampled in the United States came from the southeastern region ([Table 3](#)), which included states as far west as Texas. While 42,962 trees were sampled in the eastern states (NE, NC, SE), only 4,722 trees (9.9 percent) were sampled in the western states (PNW and IMW).

Data Gaps by Region, Tree Species, and Diameter Class

The percentage of total biomass and the number of legacy trees sampled for aboveground wood and bark biomass (with or without foliage) were calculated for species by region by diameter class combinations. The 30 combinations with the greatest amount of biomass accounted for approximately a third of the cumulative biomass in the FIADB, and tentative sampling objectives were met for most of these groupings ([Table 6](#)). The sampling objective was not met in all cases, however, and the 30 species with the most biomass where the sampling objective was not met (i.e., SCV<1) are highlighted in [Table 7](#). In the SE, species including loblolly pine, yellow-poplar, and white oak were adequately sampled in both the 10 and 20 inch diameter classes, as were slash pine, red maple, and water oak in the 10 inch diameter class. However, when examining all groupings, species such as pignut hickory and sugar maple in the 10 inch diameter class and loblolly pine in the 30 inch diameter class were undersampled (see Table S7 for all tree groupings). In the PNW, large Douglas-fir (40 to 50 inch diameter classes) and western hemlock (10 to 30 inch diameter classes) were noticeably undersampled, along with 20 to 30 inch Douglas-fir and grand fir in the IMW. In the north-central region, no 20 inch black oak, 10 inch green ash, or 10 inch black ash trees were sampled. In the northeast region, species such as red maple and northern red oak (*Quercus rubra* L.) in the 20 inch diameter class were notably undersampled. Large Douglas-fir was also underrepresented, while loblolly pine was perhaps overrepresented with more than 1,400 trees sampled in the 10 inch diameter class (i.e., 10 inch loblolly pine make up 4.6 percent of the biomass in the FIADB and 10.1 percent of the trees in the legacy tree database). In addition to 20-40 inch Douglas-fir, the most underrepresented trees included 10 inch red maple, 20 inch western hemlock, 10 inch lodgepole pine, and 10 inch sugar maple ([Table 8](#)).

DISCUSSION

Alternatives for Further Sampling

The main objective of this research was to identify current gaps in tree biomass data so that future studies might optimize sampling, and thereby reduce uncertainty in predictive biomass models. This work highlighted some of the gaps that exist in currently available data by tree components ([Table 1](#)), species ([Table 2](#)), and regions ([Table 3](#)). In addition, the maps (Figs. 4 and 4S) can be used to assess where spatial gaps exist for a given species. For example, a total of 219 Douglas-fir; 2,168 loblolly pine; 445 red maple; and 360 white oak legacy trees were destructively sampled for above stump biomass (above stump legacy trees in [Table 1](#)). This might provide an adequate sample for predicting aboveground biomass for these species if the trees were spatially well-distributed. However, because they are not (see Fig. 4), additional sampling may be necessary to fill gaps across the species ranges where key landscapes and habitats are not represented, thereby minimizing the potential influence of spatially distinct patterns. Lastly, the results illustrate the lack of a representative sample in terms of diameter distributions, which are shifted towards larger trees but rarely contain the largest trees. (Figs. 2 and 3).

Overall, the most robust assessment of gaps seems to come from comparing biomass pool proportions in the FIADB to sample sizes in the legacy tree database. To match the effective population, the largest gaps for a given biomass pool are defined as having a low number of trees and a high amount of biomass in the FIADB. Regionally, the most prominent data gaps were in the PNW and IMW regions and tended to align with tree size rather than species. Despite being well represented in the FIADB, groupings in the 20- to 50-inch diameter classes appeared to be the most undersampled. For future sampling efforts, one approach might be to set a tentative sampling completeness value (SCV) goal of one and sample from each group until this goal is met. In particular, this approach would suggest sampling large Douglas-fir trees in the PNW region as well as northern red oak and red maple in the NE region (Table 7). The sampling objectives presented in Tables 6 and 7 could be increased based on user's objectives and available resources. Representation (i.e., the proportion of trees in the legacy tree database compared to the proportion of biomass for a given biomass pool) is important to consider because an unrepresentative database would result in erroneous projections of model error if not dealt with appropriately.

Although these are imperfect assessments, they serve as reasonable prioritizations of current needs (i.e., by species, diameter class, and region) until a more robust assessment of uncertainty and required sample size is undertaken within a specific modeling framework. For instance, recent work by Clough et al. (2016) suggests that the greatest relative uncertainties in AGB are in the southern portions of the IMW (where woodland species dominate) and eastern portions of the PNW. Ultimately, continued sampling for a given biomass pool would be determined by the number of trees sampled and model uncertainty after accounting for diameter and height.

Sampling to mirror the effective population is practical for many applications. From a modeling perspective, however, it may be useful to sample across the range of attributes in the population. Using this approach, the legacy tree database and literature may have oversampled small trees, undersampled large trees, and failed to sample species up to the edge of their range, and thus, the current literature and available data may not adequately capture the full range of attributes or variability in the population. In contrast to sampling to match the effective population, an alternative approach would be to sample at the "fringe" to best understand the broad range of variability for a population. This would include sampling less prevalent species, sampling at the edge of a species' range, and sampling the largest trees. For instance, large trees are presently a relatively small part of the landscape, but shifts in management practices may create the potential to greatly increase carbon stores (Stephenson et al. 2014).

Model-based Approaches to Fill Data Gaps

The cost of extensive sampling may make it prohibitive to adequately represent species and size classes across the entire United States. As such, in this section modeling techniques are considered, including (1) validating and developing species-group models; (2) using spatially explicit models; and (3) using pseudodata to fill gaps where the greatest paucity of data exists. These approaches may offer solutions for modeling gaps in available data, but species-group and spatial models may support a rationale to sample across the widest range of possible attributes rather than sampling to match the effective population. Errors associated with each approach are largely unquantified so these approaches will need testing, and continued sampling is recommended to update and validate a selected modeling approach.

Nonspecific Models and Species-group Models

When few data points are available for a given species, a species-group approach (i.e., predicting biomass for a single species using species that share similar traits or phylogeny) may be useful. However, a model fit to genus-level data then applied to individual species may incur bias, and this bias has largely been unquantified (Weiskittel et al. 2015). The literature review revealed that only a few studies have grouped species. When employed, the grouping was mainly based on apical dominance (e.g., Brenneman et al. 1978). Hence, the relative advantages and disadvantages of grouping species remain largely unexplored. The species groups presented in Jenkins et al. (2003) were based primarily on phylogenetic similarities, while Chojnacky et al. (2013) incorporated species' specific gravity. A nonspecific modeling approach was supported when quantifying volume across a large area since estimates and uncertainties using nonspecific models did not substantially deviate from specific models (i.e., models developed for each species). Mean volume estimates were within 3 percent, and standard errors improved with the nonspecific models for both coniferous and deciduous species (McRoberts and Westfall 2014).

A species-group approach may further support sampling a broad spectrum of species, including the 200+ species that currently do not have a model or data point. This approach also suggests sampling less common species with no observations to validate species-group models since there is a theoretical threshold at which the sampling of the most common species ceases to improve predictions of biomass and uncertainty. In addition, considering that species distributions and abundance are ever-changing in the face of climate change (Iverson and Prasad 1998), disease and pest outbreaks (e.g., eastern hemlock and white ash), and human disturbance (e.g., red maple [Abrams 1998]), models that are sensitive to these factors should be sought. These prospects may warrant model exploration that extends beyond taxonomy to include physiologically meaningful categories such as species tolerances (e.g., Niinemets and Valladares 2006), or not grouping at all and predicting with wood properties such as wood density. For instance, modeling approaches that incorporate wood density across many species have been shown to work well in the tropics (e.g., Chave et al. 2014) and in the northern United States (MacFarlane 2015).

Spatial Considerations and Spatially Explicit Models

Since site selection is generally opportunistic, bias may occur; thus users will need to consider whether a model is suitable for a given application. Ideally, site-related factors would be included in models, but as noted earlier, problems arise because there is little consistency in how sites and treatments are described, and different authors use various classification systems for soils and geographic factors. Incorporating tree height may help to account for these potential site differences, but only 44 percent of the studies with models incorporated height as a predictor variable (Table 4). It is interesting that height is not incorporated into biomass models more frequently. This may, in part, be due to the study scope. For example, studies that collect data only across homogeneous growing conditions probably warrant a diameter-only regression model. In contrast, studies that sample across a wide range of sites require height in their models (e.g., Clark et al. 1985, 1986) or height and site for some species (e.g., Perala and Alban 1994). Incorporating height (which is generally available in the legacy tree database) into models will likely help to explain site and stand characteristics that cannot be explained in diameter-only models. Additional variation may be explained by age and soil, but this information is not always easily measured in an inventory.

The general lack of a representative sample across the entire United States may require that users employ more sophisticated modeling techniques to improve parameter and error estimates that result from spatial dependence and clustering for some species. Work in

the northeastern United States suggests spatial variability in height-diameter relationships between sites, but no systematic relationship to latitude and longitude were found (Westfall 2015). Mixed-effects modeling may offer a solution considering that the fixed-effects structure predicts across the entire dataset, while the inclusion of random effects parameters may improve local predictions (De-Miguel et al. 2014, Westfall 2016). By assessing differences in a fixed-only versus mixed-modeling approach, one may determine whether variation between ecoregions (e.g., Bailey 1995) or states exists and to what extent the variation exists, but sample size may be a limiting factor. Models that include explicit spatial modifiers on parameters and parameter standard error estimates might be most appropriate (e.g., Babcock et al. 2013). The effect of this would likely be expressed as greater uncertainty as predictions are made beyond the general availability of existing data.

Pseudodata Vs. Actual Data

The number of destructively sampled trees in terms of the whole body of "literature" (i.e., all studies with and without models) and the number of trees in the legacy tree database were quantified. Over half of the trees (25,187) that were identified as having been destructively sampled are not currently available in the legacy tree database, but the majority of these trees (24,388) had associated models. The trees in the legacy tree database can be viewed as actual data, and while using actual data is preferred, a model could be used to predict pseudodata where large spatial, species, or size gaps exist.

The generalized models presented in Jenkins et al. (2003) were fit after generating pseudodata from regression models reported in the literature (Pastor et al. 1984). Models developed from pseudodata, however, have some important limitations (see Lambert et al. 2005) and may introduce error when back-predicting from the original regression model (Baskerville 1972, Snowdon 1991). Additionally, the models have only a tenuous link to empirical data, and the error estimates are propagated using pseudo-ranges (see Jenkins et al. 2004). As such, while the approach may lead to reasonable mean estimates across multiple studies and large regions, it does not provide realistic error estimates, particularly within a site or study.

Generating more realistic measures of uncertainty is integral to providing more realistic simulated data. This requires measures of uncertainty, such as the standard error, that accompany models used to generate pseudodata. Of the 326 studies that were reviewed, 252 studies presented models to predict biomass of at least one tree component. Across all studies, standard error (generally on the mean rather than the parameters) was reported for 55 percent of the models. R^2 values were reported more frequently, and recent work shows that using R^2 values may provide improved pseudodata estimates (Wayson et al. 2015). Bayesian approaches to simulating data are also proposed in Henry et al. (2015). However, questions remain about the suitability of pseudodata, and standard errors on the parameter estimates tend to be underestimated (Magnussen and Negrete 2015). The legacy tree database could be a valuable tool for testing methodologies for generating pseudodata. However, when available, we advocate using actual data in all model development.

Sampling for Trees of Varying Form, Risk, and Vigor, and Improving Estimates of Component Allometry

Of the 113 studies for which tree selection methods were determined, more than half of the studies imposed sampling restrictions by selecting trees of average and better vigor and by avoiding forked (as noted by MacFarlane and Weiskittel 2016) and otherwise deformed trees. Using models that avoid trees that are poorly formed (e.g., low forking or with a broken top) or at a high risk of mortality (i.e., of low vigor), as evidenced by broken branches, severe

mechanical damage, and fungal pathogens (Pelletier et al. 2013), may overestimate the biomass of low vigor/high risk trees, leading to overestimates at larger strata.

The height to the tree's lowest branch and the size of the largest branch may help explain the proportion of bole-to-branch biomass (MacFarlane 2011) and bole-to-AGB. Height to the lowest branch was almost never included as a predictor, and only a few biomass studies assessed the influence of form or health on biomass estimates (e.g., Bickelhaupt 1979). In addition, classifying trees in terms of form and risk (Pelletier et al. 2013) may improve estimates of tree merchantable volume (Castle et al. 2017) and decay (Frank et al. 2018), which in turn affects volume and biomass estimates when discounted from gross volume. It is recommend that future studies examine how variation in tree form and health may influence biomass estimates by sampling diseased and deformed trees. Further, a clear and broadly applicable classification or measurement protocol is necessary for assessing standing tree form and risk to mortality.

Although root biomass can constitute approximately 30 percent of the total tree biomass (aboveground + belowground) (Grier and Milne 1981, Young et al. 1980), roots were the most undersampled component. Of the studies observed, only 4 sampled root biomass for Douglas-fir and only 13 sampled root biomass for loblolly pine, while only a single study examined red maple root mass, and no studies included belowground biomass for western hemlock. Hence, it is important to investigate root biomass in western hemlock and red maple. In addition, although above-stump biomass (including foliage) is available in over 12,000 trees in the legacy tree database, only 9,383 of the trees were sampled for all major components (i.e., stem wood, stem bark, branch, and foliage). We recommend weighing all major aboveground components separately for any destructive sampling endeavor.

SUMMARY, LIMITATIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

Summary

This review included 326 studies with 47,684 trees that were destructively sampled for at least one tree component. This is a conservative estimate of the data available because not all existing biomass studies were located and reviewed, and more trees have been sampled since these numbers were tabulated. For example, the following articles are known to contain relevant root biomass data in the United States, but were located after this analysis was completed: Samuelson et al. 2014 (36 longleaf pine trees); Litton et al. 2003 (45 lodgepole pine trees); Omdal et al. 2001 (80 lodgepole pine trees); Pearson et al. 1984 (89 ponderosa pine trees); Foster (1985 (9 balsam fir trees). Additional studies and root biomass data are also presented in Cairns et al. (1997).

As of March 2016, the actual data from 159 studies have been located, accounting for 22,497 trees in the continental United States (including Alaska), including 9,383 trees that have data for each major component (i.e., stem wood, stem bark, branch, and foliage). Presently, these data are available in a permanent online repository available at legacytreedata.org (Radtke et al. 2015) where researchers can share data and analyses to improve biomass and carbon estimation at various scales.

Based on this comprehensive assessment of existing literature, the most notable gaps in tree biomass data included (1) very large trees (>40 inches d.b.h.), particularly large conifers in the PNW region; (2) root and stump biomass from most species; and (3) trees that diverge

from an idealized form for timber production or that have low vigor. In addition, although the literature was not formally explored for these factors, very few studies included open-grown trees, trees in urban landscapes, and dead and dying standing trees. The lack of studies of the latter supports recommendations that additional research is required to quantify this carbon pool and meet UNFCCC reporting requirements (Woodall et al. 2011a).

Limitations

This gap assessment focused on how existing data and past studies are limited in terms of the species, tree components, and size classes of trees sampled, but there are some limitations to this approach. The most obvious data gaps were defined and compared to the effective tree population, which was estimated using the FIA database. However, exactly matching the effective population ultimately may not be necessary because the variation in a biomass pool determines whether there are enough trees sampled. In addition, depending on the adopted modeling framework (e.g., a nonspecific approach could replace a specific approach), sampling a wider range of less common species may be warranted rather than sampling a higher number of common species.

In addition to limitations in this gap assessment approach, how these data were collected must also be considered. First, since the data were often collected opportunistically and do not reflect a representative sample, more sophisticated modeling techniques may be necessary, and careful consideration should be given to the appropriateness of a model for a given biomass pool. Second, within-tree variation is often not accounted for and protocols can vary widely between studies, leading to random sources of variation.

Recommendations for Continued Research

The data that are preserved in the legacy tree database provide a valuable resource for addressing questions pertaining to biomass and carbon estimation at multiple scales (ranging from within-tree to national). A substantial number of biomass prediction studies hailing from the past 60 years have been preserved; however, data are missing from nearly half of the trees sampled. This result highlights the value of archiving all data because models and data generated from these efforts can be useful for large-scale modeling efforts. The FIA program continues to collaborate with university and industry partners to archive and digitize past datasets and to target trees for destructive sampling from those species and size classes needed to fill in data gaps. Additional collaboration is sought where feasible, and future destructive sampling efforts should consider adopting existing protocols (available at legacytreedata.org) to improve data compatibility across studies.

Studies that examine within-tree variation and compare different methodologies are needed and may shift prioritizations of future sampling requirements. In addition, optimal sample sizes will need to be considered as a function of uncertainty for a given biomass pool, as these will offer more appropriate objectives for future sampling.

Table 1.—Summary of number of trees and studies sampled for component biomass for the 30 species with the greatest biomass in the FIADB. For each tree component, estimates are given for (1) the total numbers sampled in the literature (including trees in the legacy tree database); (2) the number of studies in the literature (including trees in the legacy tree database; in brackets); and (3) the number of trees available in the legacy tree database. Zero indicates that there are no known destructively sampled trees or studies. Data for all 148 species sampled are available in Table S1.

Common name	Stem			Branch			Above stump			Stem and above stump			Roots		
	Total # of trees	# of studies	# trees in DB	Total # of trees	# of studies	# trees in DB	Total # of trees	# of studies	# trees in DB	Total # of trees	# of studies	# trees in DB	Total # of trees	# of studies	# trees in DB
Douglas-fir	761	[16]	332	829	[21]	431	598	[16]	219	585	[14]	211	134	[4]	9
Loblolly pine	5307	[46]	4203	2962	[44]	1810	2743	[41]	2168	2265	[29]	2078	515	[13]	156
Red maple	921	[22]	544	783	[17]	488	825	[21]	445	700	[15]	412	70	[1]	0
White oak	528	[13]	444	451	[10]	431	428	[11]	360	359	[8]	348	18	[2]	4
Sugar maple	427	[17]	273	326	[14]	196	421	[16]	238	377	[15]	238	56	[2]	14
Western hemlock	79	[4]	60	90	[5]	71	37	[3]	18	30	[2]	11	0	[0]	0
Northern red oak	257	[11]	204	313	[12]	171	137	[9]	82	102	[7]	78	14	[1]	0
Ponderosa pine	366	[11]	246	459	[15]	394	232	[10]	161	226	[9]	161	0	[1]	0
Yellow-poplar	411	[13]	335	377	[11]	331	291	[11]	210	224	[9]	208	0	[1]	0
Sweetgum	1040	[10]	806	1188	[10]	793	879	[8]	734	868	[7]	723	59	[3]	0
Lodgepole pine	205	[8]	135	202	[10]	202	95	[7]	76	91	[6]	76	0	[1]	0
Chestnut oak	193	[8]	140	209	[9]	140	159	[6]	87	127	[5]	87	0	[0]	0
Black oak	90	[5]	64	90	[5]	64	89	[5]	55	43	[2]	43	0	[0]	0
Engelmann spruce	113	[4]	84	121	[6]	92	51	[3]	19	48	[2]	19	0	[0]	0
Quaking aspen	717	[13]	672	438	[15]	393	389	[13]	240	249	[10]	214	46	[3]	8
American beech	196	[10]	134	146	[8]	84	150	[11]	86	134	[9]	72	58	[2]	15
Black cherry	113	[8]	82	102	[7]	82	130	[9]	61	91	[6]	60	0	[0]	0
White ash	90	[5]	72	58	[4]	40	65	[4]	7	25	[3]	7	0	[0]	0
Eastern white pine	299	[9]	221	263	[8]	190	189	[7]	136	155	[6]	102	43	[1]	0
Water oak	206	[2]	206	396	[3]	206	215	[3]	215	206	[2]	206	0	[0]	0
Slash pine	2582	[21]	1281	1318	[18]	784	1308	[17]	988	1176	[13]	988	94	[5]	58
White fir	22	[2]	10	34	[3]	22	12	[1]	0	12	[1]	0	0	[0]	0
Post oak	30	[3]	30	30	[3]	30	63	[3]	30	28	[1]	28	0	[0]	0
Mountain hemlock	6	[1]	0	6	[1]	0	6	[1]	0	6	[1]	0	0	[0]	0
Subalpine fir	72	[4]	63	68	[4]	59	9	[1]	0	9	[1]	0	0	[0]	0
Sitka spruce	40	[2]	23	24	[2]	6	17	[1]	0	17	[1]	0	0	[0]	0
Grand fir	27	[1]	27	69	[3]	69	0	[0]	0	0	[0]	0	0	[0]	0
Pignut hickory	0	[0]	0	0	[0]	0	0	[0]	0	0	[0]	0	0	[0]	0
Eastern hemlock	167	[7]	120	136	[6]	89	83	[5]	36	83	[5]	36	47	[1]	0
Scarlet oak	141	[5]	141	127	[4]	127	80	[3]	80	78	[2]	78	0	[0]	0
All 148 species	27080	[221]	17301	22197	[197]	12783	24791	[199]	12177	17251	[160]	11402	2840	[38]	363

Table 1.—continued

Common name	Stem wood Total # of trees	Stem wood # of studies	Stem wood # trees in DB	Stem bark Total # of trees	Stem bark # of studies	Stem bark # trees in DB	Total wood Total # of trees	Total wood # of studies	Total wood # trees in DB	Crown Total # of trees	Crown # of studies	Crown # trees in DB	Foliage Total # of trees	Foliage # of studies	Foliage # trees in DB
Douglas-fir	503	[10]	147	503	[10]	147	694	[16]	315	906	[21]	434	926	[25]	489
Loblolly pine	7280	[41]	5418	4003	[34]	3583	2057	[26]	1695	2726	[29]	2280	2897	[45]	2015
Red maple	595	[11]	418	591	[10]	418	930	[23]	537	682	[14]	414	680	[16]	415
White oak	397	[8]	379	393	[7]	379	605	[15]	468	375	[9]	364	363	[8]	363
Sugar maple	265	[11]	231	265	[11]	231	444	[14]	196	377	[15]	238	349	[13]	195
Western hemlock	40	[3]	21	40	[3]	21	65	[4]	46	164	[6]	66	97	[5]	78
Northern red oak	170	[5]	170	170	[5]	170	302	[14]	185	158	[8]	78	162	[9]	82
Ponderosa pine	77	[6]	50	77	[6]	50	255	[11]	184	444	[14]	397	529	[18]	424
Yellow-poplar	327	[8]	283	327	[8]	283	468	[14]	377	224	[9]	208	225	[8]	210
Sweetgum	1146	[7]	802	1146	[7]	802	1195	[11]	795	783	[5]	723	1085	[8]	725
Lodgepole pine	63	[4]	48	63	[4]	48	139	[7]	120	239	[11]	224	206	[11]	202
Chestnut oak	130	[4]	130	130	[4]	130	270	[11]	143	129	[5]	90	129	[5]	90
Black oak	87	[4]	61	87	[4]	61	173	[8]	107	69	[3]	43	55	[4]	55
Engelmann spruce	79	[3]	50	79	[3]	50	108	[5]	76	98	[5]	69	99	[6]	67
Quaking aspen	690	[11]	671	664	[10]	645	415	[14]	363	279	[12]	244	292	[13]	250
American beech	65	[6]	65	65	[6]	65	216	[10]	98	135	[9]	73	131	[9]	69
Black cherry	58	[4]	58	58	[4]	58	132	[8]	86	91	[6]	60	81	[6]	61
White ash	39	[3]	39	39	[3]	39	113	[6]	80	26	[3]	8	26	[3]	8
Eastern white pine	121	[4]	121	121	[4]	121	206	[6]	153	207	[6]	154	273	[9]	200
Water oak	396	[3]	206	396	[3]	206	396	[3]	206	206	[2]	206	396	[3]	206
Slash pine	3423	[23]	2137	1526	[19]	1255	844	[11]	784	1048	[12]	988	1327	[18]	784
White fir	12	[1]	0	12	[1]	0	22	[2]	10	34	[3]	22	34	[3]	22
Post oak	29	[2]	29	29	[2]	29	32	[3]	32	28	[1]	28	63	[3]	30
Mountain hemlock	6	[1]	0	6	[1]	0	6	[1]	0	6	[1]	0	6	[1]	0
Subalpine fir	43	[3]	34	46	[3]	37	50	[3]	41	69	[4]	60	51	[3]	42
Sitka spruce	0	[0]	0	0	[0]	0	23	[2]	6	24	[2]	6	24	[2]	6
Grand fir	0	[0]	0	0	[0]	0	15	[1]	15	72	[4]	72	73	[3]	73
Pignut hickory	0	[0]	0	0	[0]	0	0	[0]	0	0	[0]	0	0	[0]	0
Eastern hemlock	64	[4]	64	64	[4]	64	126	[6]	58	104	[5]	57	138	[7]	91
Scarlet oak	138	[5]	138	138	[5]	138	147	[6]	147	92	[3]	92	80	[3]	80
All 148 species	25618	[164]	17328	20283	[150]	14548	22560	[178]	12308	19154	[166]	13057	21262	[206]	12511

18

Table 2.—Tree sample sizes and number of studies [shown in brackets] for the 30 tree species with the greatest biomass in the FIADB (for at least one tree component) and the minimum (min.) and maximum (max.) diameters for trees previously summarized in Jenkins et al. (2003) compared to legacy tree data presently accumulated. Totals also include legacy tree data from previously summarized articles (Both) and from articles that were not previously summarized and that have no legacy tree data (Additional literature). Additional literature was further separated into studies with models and studies without models. Total n = 47,684 trees for all species. Data for all 148 species sampled are available in Table S2.

| Common name | Tree sample size [number of studies] by study type | | | | | | D.B.H. range (inches) | | | |
	Legacy tree database	Jenkins database	Both	Additional literature with models	Additional literature without models	Total	Jenkins min.	Jenkins max.	Legacy min.	Legacy max.
Douglas-fir	458 [15]	555 [7]	54 [3]	61 [2]	49 [3]	1177 [30]	0.3	63.0	1.0	44.9
Loblolly pine	6318 [37]	200 [5]	86 [4]	3347 [26]	16 [1]	9967 [73]	1.3	22.1	1.0	24.0
Red maple	202 [7]	479 [9]	400 [10]	65 [4]	23 [1]	1169 [31]	0.1	26.0	1.0	33.7
White oak	98 [5]	182 [6]	383 [6]	82 [4]	6 [1]	751 [22]	0.1	25.2	1.0	42.0
Sugar maple	136 [5]	247 [6]	137 [6]	85 [2]	26 [2]	631 [21]	0.1	27.4	1.1	32.8
Western hemlock	65 [3]	98 [2]	38 [2]	0 [0]	0 [0]	201 [7]	1.1	43.3	1.1	30.6
Northern red oak	36 [2]	96 [5]	182 [7]	108 [3]	33 [1]	455 [18]	0.1	28.7	1.0	32.8
Ponderosa pine	445 [11]	47 [2]	42 [1]	107 [3]	6 [1]	647 [18]	1.0	34.0	1.0	41.3
Yellow-poplar	90 [5]	102 [5]	291 [4]	55 [3]	59 [2]	597 [19]	0.2	25.6	1.0	31.7
Sweetgum	79 [3]	0 [0]	738 [2]	485 [9]	0 [0]	1302 [14]	1.0	20.7	1.0	32.5
Lodgepole pine	189 [7]	0 [0]	35 [3]	55 [2]	4 [1]	283 [13]	1.1	11.3	1.0	23.6
Chestnut oak	7 [1]	110 [4]	136 [4]	49 [3]	16 [1]	318 [13]	1.1	22.6	1.2	26.5
Black oak	7 [2]	60 [2]	100 [4]	40 [1]	0 [0]	207 [9]	0.2	34.8	1.1	24.0
Engelmann spruce	98 [4]	29 [1]	9 [1]	0 [0]	3 [1]	139 [7]	1.1	30.0	1.1	33.3
Quaking aspen	549 [9]	47 [2]	185 [3]	143 [3]	7 [1]	931 [18]	1.1	19.5	1.0	23.8
American beech	42 [4]	101 [3]	106 [5]	19 [1]	0 [0]	268 [13]	0.1	26.0	1.1	31.4
Black cherry	32 [3]	75 [4]	54 [3]	20 [1]	0 [0]	181 [11]	0.1	20.0	1.0	28.0
White ash	49 [3]	55 [2]	63 [2]	18 [1]	0 [0]	185 [8]	0.2	20.0	1.3	32.2
Eastern white pine	172 [4]	78 [3]	93 [4]	0 [0]	0 [0]	343 [11]	0.1	26.0	1.0	32.0
Water oak	13 [2]	0 [0]	202 [1]	190 [1]	0 [0]	405 [4]	1.0	20.0	1.0	20.0
Slash pine	2163 [16]	100 [1]	0 [0]	2508 [14]	0 [0]	4771 [31]	-	-	1.0	21.0
White fir	22 [2]	12 [1]	0 [0]	0 [0]	0 [0]	34 [3]	2.8	38.6	7.5	26.2
Post oak	1 [1]	0 [0]	31 [2]	33 [1]	0 [0]	65 [4]	3.0	20.9	3.0	20.9
Mountain hemlock	0 [0]	6 [1]	0 [0]	0 [0]	0 [0]	6 [1]	6.7	21.5	-	-
Subalpine fir	66 [3]	0 [0]	16 [1]	9 [1]	0 [0]	91 [5]	1.0	12.7	1.0	24.6
Sitka spruce	23 [1]	18 [1]	0 [0]	0 [0]	0 [0]	41 [2]	1.2	30.6	7.8	23.1
Grand fir	52 [3]	0 [0]	32 [1]	0 [0]	0 [0]	84 [4]	1.0	15.6	1.0	33.2
Pignut hickory	0 [0]	0 [0]	0 [0]	0 [0]	0 [0]	0 [0]	-	-	-	-
Eastern hemlock	89 [5]	68 [2]	34 [2]	0 [0]	0 [0]	191 [9]	0.1	33.5	1.0	33.5
Scarlet oak	4 [1]	0 [0]	157 [6]	0 [0]	0 [0]	161 [7]	1.1	22.2	1.1	27.8
All 148 species	16013 [133]	5704 [60]	6484 [26]	18684 [94]	799 [13]	47684 [326]	0.1	63.0	1.0	334.9

Table 3.—Estimates of the number of trees sampled by species and region for the 30 tree species with the greatest biomass in the FIADB. For each region estimates are given for (1) the total numbers sampled in the literature (including trees in the legacy tree database); (2) the number of studies in the literature (including trees in the legacy tree database; in brackets); and (3) the number of trees available in the legacy tree database. A dash indicates the species is not present in a given region in the FIA database, and zero indicates that there are no known destructively sampled trees or studies. Studies may bridge more than one region, leading to discrepancies between the apparent number of studies listed here and the totals listed in Table 2. Data for all 148 species sampled are available in Table S3.

Common name	Intermountain West (IMW)			Pacific Northwest (PNW)			Northeast (NE)			Southeast (SE)			North Central (NC)		
	Total # of trees	# of studies	# trees in DB	Total # of trees	# of studies	# trees in DB	Total # of trees	# of studies	# trees in DB	Total # of trees	# of studies	# trees in DB	Total # of trees	# of studies	# trees in DB
Douglas-fir	203	[8]	130	974	[24]	382	0	[0]	0	0	[0]	0	0	[0]	0
Loblolly pine	-	-	-	-	-	-	0	[0]	0	9967	[72]	6404	0	[0]	0
Red maple	-	-	-	-	-	-	495	[18]	188	346	[9]	259	328	[6]	155
White oak	-	-	-	-	-	-	217	[10]	65	478	[12]	400	56	[2]	16
Sugar maple	-	-	-	-	-	-	380	[12]	115	11	[3]	10	240	[8]	148
Western hemlock	12	[1]	12	189	[6]	91	-	-	-	-	-	-	-	-	-
Northern red oak	-	-	-	-	-	-	203	[11]	78	142	[6]	108	110	[5]	32
Ponderosa pine	383	[13]	316	264	[7]	171	-	-	-	0	[0]	0	0	[0]	0
Yellow-poplar	-	-	-	-	-	-	189	[9]	43	352	[10]	282	56	[2]	56
Sweetgum	-	-	-	0	[0]	0	0	[0]	0	1302	[14]	817	0	[0]	0
Lodgepole pine	138	[8]	134	145	[7]	90	-	-	-	-	-	-	0	[0]	0
Chestnut oak	-	-	-	-	-	-	95	[5]	21	207	[8]	122	16	[1]	0
Black oak	-	-	-	-	-	-	89	[4]	55	78	[4]	52	40	[1]	0
Engelmann spruce	125	[6]	93	14	[1]	14	-	-	-	0	[0]	0	0	[0]	0
Quaking aspen	48	[3]	41	160	[3]	27	30	[3]	30	0	[0]	0	693	[10]	636
American beech	-	-	-	-	-	-	200	[10]	80	52	[4]	52	16	[1]	16
Black cherry	-	-	-	-	-	-	141	[8]	46	34	[3]	34	6	[1]	6
White ash	-	-	-	-	-	-	114	[6]	41	31	[1]	31	40	[1]	40
Eastern white pine	-	-	-	-	-	-	115	[4]	72	183	[6]	163	45	[4]	30
Water oak	-	-	-	-	-	-	0	[0]	0	405	[4]	215	0	[0]	0
Slash pine	-	-	-	-	-	-	-	-	-	4771	[31]	2163	-	-	-
White fir	12	[1]	12	22	[2]	10	-	-	-	0	[0]	0	0	[0]	0
Post oak	-	-	-	-	-	-	0	[0]	0	65	[4]	32	0	[0]	0
Mountain hemlock	0	[0]	0	6	[1]	0	-	-	-	-	-	-	-	-	-
Subalpine fir	91	[5]	82	0	[0]	0	-	-	-	0	[0]	0	-	-	-
Sitka spruce	-	-	-	41	[2]	23	-	-	-	-	-	-	-	-	-
Grand fir	50	[2]	50	34	[3]	34	-	-	-	-	-	-	-	-	-
Pignut hickory	-	-	-	-	-	-	0	[0]	0	0	[0]	0	0	[0]	0
Eastern hemlock	-	-	-	-	-	-	104	[5]	36	71	[5]	71	16	[1]	16
Scarlet oak	-	-	-	-	-	-	49	[3]	49	112	[4]	112	0	[0]	0
All species	1555	[28]	1173	3167	[52]	1526	6121	[50]	1774	29901	[167]	16094	6940	[0]	1930

Table 4.—The 30 studies with the highest importance (import.) index (=sample size * maximum d.b.h.[in inches]/100) ranked from highest to lowest. Indicator (ind.) values of 1 = yes and 0 = no identify if a biomass model (Eq.) was presented, height (Ht.) was included, standard (Std.) error given, or sampling restrictions (Samp. rest.) imposed based on form/risk/vigor class. It is also noted if the article was present in the legacy tree database (Leg. tree), Jenkins et al. (2004), or Chojnacky et.al (2014). A proportion between 0 and 1 indicates that only a portion of the data has the given attribute. Data for all studies are available in Table S4.

Author	Region	Import. index	Sample size (no.)	Min. d.b.h. (inches)	Max. d.b.h. (inches)	Eq. ind.	Ht. ind.	Std. error ind.	Samp. rest. ind.	Leg. tree ind.	Chojnacky et al. 2014	Jenkins et al. 2004
Clark et al. 1985, 1986	SE	916	3580[a]	1	25.6	1	1	1	0	1	1	1
FIA 2016	All	642	1430	1	44.9	0	-	-	1	1	0	0
Sillett et al. 2015	PNW	466	139	1.6	334.9	1	0	1	0	1	0	0
Young et al. 1980	NE	251	965	0.1	26	1	0	0	-	0	1	1
Schlaegel (n.d.)[b]	SE	221	582	1	37.9	-	-	-	-	1	0	0
Clark and Saucier 1990	SE	217	1132	5	19.2	0	-	-	-	1	0	0
Perala and Alban 1994	NC	151	774	1.1	19.5	1	1	0	1	1	1	1
Sollins and Anderson 1971	SE	120	357	1.1	33.5	1	1	0	-	1	1	1
Pienaar et al. 1990	SE	117	838	3	14	1	1	0	-	0	0	0
Clutter et al. 1984	SE	107	762	2	14	1	1	0	-	0	0	0
Snell and Max 1985	PNW	101	160	3.9	63	1	0	0	1	0	1	1
Flowers 1978	SE	98	724	2.2	13.6	1	1	0	1	1	0	0
Reed et al. 1995	NC	96	3083	0.1	3.1	1	1	0	0	0	0	0
Lohrey 1985	SE	89	467	1.3	19.1	1	1	1	-	1	0	0
Hyink et al. 1972	SE	88	632	5	14	1	1	0	0	0	0	0
Madgwick and Kreh 1980	SE	87	501	0.6	17.4	1	1	1	-	0	0	0
Burkhart and Clutter 1971	SE	86	701	3.1	12.2	1	1	0	-	1	0	0
Monteith 1979	NE	84	402	1	20.8	1	1	-	1	0.8	1	1
Bailey et al. 1982	SE	82	686	3	12	1	1	0	-	0	0	0
Queen and Pienaar 1977	SE	82	685	2.6	12	1	1	0	1	1	0	0
Brenneman et al. 1978	NE	81	407	2	20	1	0	0	0	0	1	1
Burkhart et al. 1972	SE	78	551	2.5	14.1	0	-	-	1	1	0	0
Brown 1978	IMW	71	210	1	34	1	1	1	1	1	1	1
Schlaegel 1975a	NC	71	426	1.1	16.7	1	1	1	0	1	0	0
Jordan et al. 2008	SE	59	407	5.5	14.4	-	-	-	-	1	0	0
Bailey et al. 1985	SE	57	472	1	12	1	1	0	-	0	0	0
Sillet et al. 2010	PNW	54	21	22.8	255.1	0	-	-	-	1	0	0
Clark and Taras 1976	SE	53	221	5.6	24	0	-	-	-	1	0	0
Reinhardt 2000	IMW	53	201	1	26.4	0	0	0	1	1	0	0
Storey et al. 1955	IMW+ PNW	53	143	1.5	37	1	1	1	1	1	1	0

[a] The figure of 3,580 trees sampled by Alexander Clark likely includes trees sampled from Clark et al. (1985), Clark et al. (1986), and Clark and Schroeder (1986). These studies along with Clark and Saucier (1990) reused data from four previous species-specific studies that he did on yellow-poplar, southern red oak, northern red oak, and scarlet oak. These four studies were not cited in this analysis.

[b] Schlaegel (n.d.) includes multiple bottomland hardwood reports from the early to mid-1980s.

Table 5.—Centroid coordinates for the legacy and FIA databases for the 30 species with the greatest estimated biomass across the United States. Distances between the centroids and the diagonal distance across the range of the species' are given in miles (mi). Error (%) is calculated using the centroid error and the diagonal distance error. A dash indicates that there was insufficient data to determine the legacy centroids.

FIA species code	Legacy centroid longitude	Legacy centroid latitude	FIA centroid longitude	FIA centroid latitude	Distance between centroids (mi)	Longitudinal difference (mi)	Latitudinal difference (mi)	FIA diagonal distance (mi)	Error (%)
Douglas-fir	-121.9	45.9	-120.8	44.6	167.4	-83.7	145.0	2613.0	6.4
Loblolly pine	-85.3	33.0	-86.3	33.4	102.8	95.3	-38.5	2555.0	4.0
Red maple	-81.4	40.2	-80.5	41.1	124.6	-74.6	-99.8	3566.9	3.5
White oak	-82.5	36.1	-85.4	37.6	310.9	257.9	-173.7	3193.1	9.7
Sugar maple	-83.7	45.0	-81.8	43.2	254.5	-158.0	199.5	3229.9	7.9
Western hemlock	-124.3	46.4	-124.9	49.3	320.9	41.5	-318.2	3427.4	9.4
Northern red oak	-82.0	38.6	-82.4	41.2	297.7	34.7	-295.7	3300.0	9.0
Ponderosa pine	-115.1	39.1	-116.3	42.2	358.0	102.0	-343.2	3221.1	11.1
Yellow-poplar	-83.0	36.1	-82.3	36.8	99.1	-65.2	-74.6	2510.4	3.9
Sweetgum	-83.5	33.7	-85.9	34.0	221.9	219.9	-29.9	4511.9	4.9
Lodgepole pine	-114.6	43.2	-115.2	44.3	133.8	45.8	-125.7	3644.8	3.7
Chestnut oak	-82.6	36.5	-81.5	37.6	157.9	-97.7	-124.0	2090.1	7.6
Black oak	-79.5	38.3	-85.4	38.9	518.4	514.1	-67.3	3107.4	16.7
Engelmann spruce	-111.2	43.7	-111.3	42.9	91.7	6.9	91.4	2403.6	3.8
Quaking aspen	-93.2	48.3	-96.5	44.6	480.6	250.8	410.1	6592.9	7.3
American beech	-79.3	40.5	-78.8	40.9	56.9	-34.8	-45.0	3127.7	1.8
Black cherry	-80.5	38.3	-81.4	40.5	258.5	84.6	-244.2	3771.2	6.9
White ash	-84.9	37.4	-80.6	41.1	555.3	-371.9	-412.5	3429.6	16.2
Eastern white pine	-81.6	38.5	-79.0	42.9	530.2	-217.7	-483.5	2924.0	18.1
Water oak	-82.5	32.5	-87.6	32.5	479.3	479.3	3.4	2456.8	19.5
Slash pine	-88.0	31.3	-84.5	30.7	339.0	-331.5	70.8	2228.8	15.2
White fir	-123.0	44.1	-119.8	40.4	488.1	-266.9	408.8	2288.0	21.3
Post oak	-86.8	36.4	-92.0	35.0	495.4	470.4	155.7	3148.8	15.7
Mountain hemlock	-	-	-125.4	49.7	-	-	-	3755.0	-
Subalpine fir	-113.3	45.2	-113.7	44.9	37.4	26.2	26.7	3639.6	1.0
Sitka spruce	-133.2	55.9	-135.2	55.7	126.6	125.3	18.3	3336.1	3.8
Grand fir	-121.1	45.7	-118.1	46.0	234.1	-232.8	-24.8	1434.0	16.3
Pignut hickory	-	-	-83.9	36.9	-	-	-	3124.1	-
Eastern hemlock	-82.3	38.8	-77.1	43.1	648.4	-441.2	-475.4	2535.8	25.6
Scarlet oak	-82.1	36.8	-82.2	37.4	62.2	9.1	-61.5	2426.9	2.6

Table 6.—Percentage of biomass (% bio) and cumulative biomass percentage estimated by using the FIADB, number of trees in the legacy tree database (nleg) with above-stump woody biomass (with or without foliage), and diameter at breast height or diameter at ground line for the 30 region/species/d.b.h. class combinations with the greatest biomass in the FIADB. Diameter classes are grouped by saplings (1 to <5 inches) then by 10 inch increments (d.b.h. class 10 = 5 to <15 inch trees, etc.) The sampling completeness value (SCV) = nleg/%bio *10 and indicates how well sampled a group is. Representation (Rep.) is the difference between the percentage that the group comprises out of the entire legacy tree database by number and the percentage of biomass that the group comprises in the FIA database. In total 14,073[a] trees with aboveground biomass (with and without foliage) were used here. Data for all region/species/d.b.h. class combinations are available in Table S6.

Region	Common name	D.b.h. class	% of biomass (%)	Cumulative biomass (%)	Number of trees in legacy tree database	Sampling Objective	SCV	Rep.
SE	Loblolly pine	10	4.6	4.6	1431	46	30.9	5.5
PNW	Douglas-fir	20	2.4	7.0	83	24	3.4	-1.8
PNW	Douglas-fir	10	1.9	8.9	116	19	6.2	-1.0
NE	Red maple	10	1.7	10.6	80	17	4.7	-1.1
SE	Loblolly pine	20	1.6	12.2	240	16	14.7	0.3
PNW	Douglas-fir	30	1.5	13.7	16	15	1.1	-1.4
SE	White oak	10	1.2	14.9	237	12	20.6	0.8
IMW	Lodgepole pine	10	1.1	16.0	38	11	3.3	-0.8
NE	Sugar maple	10	1.1	17.1	38	11	3.4	-0.8
SE	Sweetgum	10	1.1	18.2	444	11	40.8	2.7
PNW	Western hemlock	20	1.1	19.3	14	11	1.3	-1.0
IMW	Douglas-fir	10	1.1	20.4	30	11	2.8	-0.8
SE	White oak	20	1.0	21.4	86	10	8.4	-0.3
IMW	Douglas-fir	20	1.0	22.4	1	10	0.1	-1.0
PNW	Douglas-fir	40	1.0	23.4	6	10	0.6	-0.9
PNW	Western hemlock	10	0.9	24.3	21	9	2.2	-0.7
SE	Slash pine	10	0.9	25.2	599	9	67.0	4.5
NE	Northern red oak	20	0.8	26.0	7	8	0.9	-0.7
SE	Red maple	10	0.8	26.8	134	8	17.7	0.5
SE	Yellow-poplar	20	0.7	27.5	65	7	8.9	-0.1
SE	Post oak	10	0.7	28.2	26	7	3.6	-0.5
NE	Red maple	20	0.7	28.9	5	7	0.7	-0.7
NC	Sugar maple	10	0.7	29.6	66	7	9.9	0.0
SE	Yellow-poplar	10	0.7	30.3	159	7	23.8	0.9
NE	Sugar maple	20	0.6	30.9	15	6	2.3	-0.5
PNW	Western hemlock	30	0.6	31.5	4	6	0.6	-0.6
IMW	Engelmann spruce	20	0.6	32.1	10	6	1.7	-0.5
IMW	Engelmann spruce	10	0.6	32.7	36	6	6.2	-0.2
SE	Water oak	10	0.6	33.3	98	6	17.3	0.4
PNW	Douglas-fir	50	0.6	33.8	0	6	0.0	-0.6

Table 7.—The 30 groups that were most undersampled by region/species/d.b.h. class group where SCV was less than one. All groupings are ranked according to the percentage of biomass in the FIA database. Data for all region/species/d.b.h. class combinations are available in Table S7.

Region	Common name	D.B.H. class	% of biomass	FIADB Rank	Number of trees in legacy tree database	Sampling Objective	SCV
IMW	Douglas-fir	20	1.0	14	1	10	0.1
PNW	Douglas-fir	40	1.0	15	6	10	0.6
NE	Northern red oak	20	0.8	18	7	8	0.9
NE	Red maple	20	0.7	22	5	7	0.7
PNW	Western hemlock	30	0.6	26	4	6	0.6
PNW	Douglas-fir	50	0.6	30	0	6	0.0
NE	White ash	10	0.5	43	3	5	0.7
NE	Eastern hemlock	10	0.4	45	1	4	0.3
IMW	Utah juniper	20	0.4	49	3	4	0.8
PNW	Mountain hemlock	20	0.4	50	0	4	0.0
NE	Yellow-poplar	20	0.4	53	2	4	0.5
SE	Pignut hickory	10	0.3	58	0	3	0.0
SE	Mockernut hickory	10	0.3	59	0	3	0.0
NE	White oak	20	0.3	62	2	3	0.6
PNW	Ponderosa pine	30	0.3	63	0	3	0.0
NE	Black cherry	20	0.3	64	1	3	0.3
NE	Chestnut oak	20	0.3	67	2	3	0.6
PNW	Mountain hemlock	10	0.3	69	0	3	0.0
NE	White ash	20	0.3	70	2	3	0.7
IMW	Common or two-needle pinyon	10	0.3	77	0	3	0.0
NE	Eastern hemlock	20	0.3	85	0	3	0.0
PNW	Douglas-fir	60	0.3	87	0	3	0.0
PNW	Sitka spruce	20	0.3	89	2	3	0.8
PNW	Western hemlock	40	0.3	91	0	3	0.0
IMW	Douglas-fir	30	0.3	92	0	3	0.0
PNW	Sitka spruce	30	0.3	96	0	3	0.0
PNW	Pacific silver fir	20	0.3	98	0	3	0.0
PNW	White fir	30	0.2	100	1	2	0.4
NE	Black oak	20	0.2	101	1	2	0.4
PNW	Canyon live oak	10	0.2	104	0	2	0.0

Table 8.—The 30 most underrepresented region/species/d.b.h class combinations. Representation was calculated as the percentage of trees in legacy tree database – percentage of biomass in the FIADB. Data for all region/species/ d.b.h. class combinations are available in Table S8.

Region	Common name	D.B.H class	% of biomass	FIADB Rank	Number of trees in legacy tree database	Representation
PNW	Douglas-fir	20	2.4	2	83	-1.8
PNW	Douglas-fir	30	1.5	6	16	-1.4
NE	Red maple	10	1.7	4	80	-1.1
IMW	Douglas-fir	20	1.0	14	1	-1.0
PNW	Western hemlock	20	1.1	11	14	-1.0
PNW	Douglas-fir	10	1.9	3	116	-1.0
PNW	Douglas-fir	40	1.0	15	6	-0.9
IMW	Lodgepole pine	10	1.1	8	38	-0.8
NE	Sugar maple	10	1.1	9	38	-0.8
IMW	Douglas-fir	10	1.1	12	30	-0.8
PNW	Western hemlock	10	0.9	16	21	-0.7
NE	Northern red oak	20	0.8	18	7	-0.7
NE	Red maple	20	0.7	22	5	-0.7
PNW	Western hemlock	30	0.6	26	4	-0.6
PNW	Douglas-fir	50	0.6	30	0	-0.6
NE	Sugar maple	20	0.6	25	15	-0.5
IMW	Engelmann spruce	20	0.6	27	10	-0.5
SE	Post oak	10	0.7	21	26	-0.5
IMW	Ponderosa pine	20	0.5	33	9	-0.4
NE	White ash	10	0.5	43	3	-0.4
NE	Eastern hemlock	10	0.4	45	1	-0.4
PNW	Mountain hemlock	20	0.4	50	0	-0.4
SE	Pignut hickory	10	0.3	58	0	-0.3
SE	Mockernut hickory	10	0.3	59	0	-0.3
NE	Eastern white pine	20	0.4	46	4	-0.3
IMW	Utah juniper	20	0.4	49	3	-0.3
NE	Yellow-poplar	20	0.4	53	2	-0.3
PNW	Ponderosa pine	30	0.3	63	0	-0.3
IMW	Quaking aspen	10	0.5	42	12	-0.3
NE	Black cherry	20	0.3	64	1	-0.3

ACKNOWLEDGMENTS

LITERATURE CITED

Aalde, H.; Gonzalez, P.; Gytarsky, M. [et al.]. 2006. **Forest land.** In: Eggleston, H.S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K., eds. 2006 IPCC guidelines for national greenhouse gas inventories. Hayama, Japan: Institute for Global Environmental Strategies: 4.1-4.83. Chapter 4.

Abrams, M.D. 1998. **The red maple paradox.** BioScience. 48(5): 355-364. https://doi.org/10.2307/1313374.

Babcock, C.; Matney, J.; Finley, A.O.; Weiskittel, A.; Cook, B.D. 2013. **Multivariate spatial regression models for predicting individual tree structure variables using LiDAR data.** IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 6(1): 6-14. https://doi.org/10.1109/jstars.2012.2215582.

Bailey, R.G. 1995. **Delineation of ecosystem regions.** Environmental Management. 7(4): 365-373. https://doi.org/10.1007/bf01866919.

Baskerville, G.L. 1972. **Use of logarithmic regression in the estimation of plant biomass.** Canadian Journal of Forestry. 2(1): 49-53. https://doi.org/10.1139/x72-009.

Behre, E.; Bruce, D.; Munns, E.; Chapman, H.; Hansen, T.; Mason, D.; Illick, J.; Pratt, M.; Siecke, E.O. 1926. **Methods of preparing volume and yield tables, report of the committee on standardization of volume and yield tables.** Journal of Forestry. 24: 653-666.

Bickelhaupt, D.H. 1979. **Biomass and elemental contents of sugar maple as affected by branching characteristics.** New York City, NY: University of New York College of Environmental Science and Forestry. 179 p. M.S. thesis.

Brenneman, B.B.; Frederick, D.J.; Gardner, W.E.; Schoenhofen, L.H.; Marsh, P.L. 1978. **Biomass of species and stands of West Virginia hardwoods.** In: Pope, P., ed. Proceedings, Central Hardwood Forest Conference II; 1978 November 14-16. West Lafayette, IN: Purdue University: 159-178.

Burns, R.M.; Honkala, B.H., tech. cords. 1990a. **Silvics of North America: 1. conifers**. Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture, Forest Service. 675 p.

Burns, R.M.; Honkala, B.H., tech. cords. 1990b. **Silvics of North America: 2. hardwoods**. Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture, Forest Service. 877 p.

Bridge, J.A. 1979. **Fuelwood production of mixed hardwoods on mesic sites in Rhode Island.** West Greenwich, RI: University of Rhode Island. M.S. thesis.

Brown, J.K. 1978. **Weight and density of crowns of Rocky Mountain conifers.** Res. Pap. INT-197. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 56 p. https://doi.org/10.5962/bhl.title.68796.

Cairns, M.A.; Brown, S.; Helmer, E.H.; Baumgardner, G.A. 1997. **Root biomass allocation in the world's upland forests.** Oecologia. 111(1): 1-11. https://doi.org/10.1007/s004420050201.

Castle, M.; Weiskittel, A.; Wagner, R.; Ducey, M.; Frank, J.; Pelletier, G. 2017. **Variation in stem form and risk of four commercially important hardwood species in the Acadian Forest: implications for potential sawlog volume and tree classification systems.** Canadian Journal of Forest Research. 47(11): 1457-1467. https://doi.org/10.1139/cjfr-2017-0182.

Chapin, F.S.; Matson, P.A.; Mooney, H.A. 2002. **Principles of terrestrial ecosystem ecology.** New York, NY: Springer Science and Business Media Inc. https://doi.org/10.1007/978-1-4419-9504-9.

Chave, J.; Réjou-Méchain, M.; Búrquez, A.; Chidumayo; E.; Colgan, M.S.; Delitti, W.B.; Henry, M. 2014. **Improved allometric models to estimate the aboveground biomass of tropical trees.** Global Change Biology. 20(10): 3177-3190. https://doi.org/10.1111/gcb.12629.

Chojnacky, D.C.; Heath, L.S.; Jenkins, J.C. 2014. **Updated generalized biomass equations for North American tree species**. Forestry. 87(1): 129-151. https://doi.org/10.1093/forestry/cpt053.

Cifuentes-Jara, M.; Morales, D.; Henry, M. 2013. **Inventory of volume and biomass tree allometric equations for Central and South America.** UN-REDD MRV report 11, CATIE, Turalba, Costa Rica. Rome, Italy: Food and Agriculture Organization of the United Nations. 76 p.

Clark, A., III; Phillips, D.R.; Frederick, D.J. 1985. **Weight, volume, and physical properties of major hardwood species in the gulf and Atlantic coastal plains.** Res. Pap. SE-250. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 66 p. https://doi.org/10.2737/SE-RP-250.

Clark, A., III.; Phillips, D.R.; Frederick, D.J. 1986. **Weight, volume, and physical properties of major hardwood species in the Upland-South.** Res. Pap. SE-257. Asheville, NC: Southeastern Forest Experiment Station. 61 p. https://doi.org/10.2737/SE-RP-257.

Clark, A., III; Saucier, J.R. 1990. **Tables for estimating total-tree weights, stem weights, and volumes of planted and natural southern pines in the southeast.** Res. Pap. GF-RP-79. Athens, GA: Georgia Forestry Commission, Research Division. 23 p.

Clark, A., III; Schroeder, J.G. 1986. **Weight, volume, and physical properties of major hardwood species in the southern Appalachian mountains.** Res. Pap. SE-253. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. https://doi.org/10.2737/SE-RP-253.

Clark, D.A.; Brown, S.; Kicklighter, D.W.; Chambers, J.Q.; Thomlinson, J.R.; Ni, J. 2001. **Measuring net primary production in forests: concepts and field methods.** Ecological Applications. 11(2): 356-370. https://doi.org/10.1890/1051-0761(2001)011[0356:mnppif]2.0.co;2.

Clough, B.J.; Russell, M.B.; Domke, G.M.; Woodall, C.W. 2016. **Quantifying allometric model uncertainty for plot-level live tree biomass stocks with a data-driven, hierarchical framework.** Forest Ecology and Management. 372: 175-188. https://doi.org/10.1016/j.foreco.2016.04.001.

Conner, R.C; Johnson, T.G. 2011. **Estimate of biomass in logging residue and standing residual inventory following tree-harvest activity on timberland acres in the southern region.** Resourc. Bull. SRS-169. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 25 p.

De-Miguel, S.; Mehtätalo, L.; Durkaya, A. 2014. **Developing generalized, calibratable, mixed-effects meta-models for large-scale biomass prediction.** Canadian Journal of Forest Research. 44(6): 648-656. https://doi.org/10.1139/cjfr-2013-0385.

Domke, G.M.; Woodall, C.W.; Smith, J.E.; Westfall, J.A.; McRoberts, R.E. 2012. **Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates.** Forest Ecology and Management. 270: 108-116. https://doi.org/10.1016/j.foreco.2012.01.022.

Fang, J.Y.; Wang, Z.M. 2001. **Forest biomass estimation at regional and global levels with special reference to China's forest biomass.** Ecological Research. 16(3): 587-592. https://doi.org/10.1046/j.1440-1703.2001.00419.x.

Foster, J.R. 1985. **Coarse root biomass in subalpine balsam fir forests.** Forest Science. 31(4): 952-956.

Frank, J; Castle, M; Westfall, JA; Weiskittel, AR; MacFarlane, DW; Baral, S.; Radtke, PJ; Pelletier, G. 2018. **Variation in occurrence and extent of internal stem decay in standing trees across the eastern US and Canada: Evaluation of alternative modelling approaches and influential factors.** Forestry: 91(3): 382-399. https://doi.org/10.1093/forestry/cpx054.

Goldsmith, L.J.; Hocker, H.W.J. 1978. **Preliminary small-tree aboveground biomass tables for five northern hardwoods.** Res. Pap. 68. Durham, NH: University of New Hampshire Agricultural Experiment Station.

Goodman, R.C., Phillips, O.L., Baker, T.R. 2014. **The importance of crown dimensions to improve tropical tree biomass estimates.** Ecological Applications. 24(4): 680-698. https://doi.org/10.1890/13-0070.1.

Grier, C.C.; Milne, W.A. 1981. **Regression equations for calculating component biomass of young *Abies amabilis* (Dougl.)** Forbes. Canadian Journal of Forest Research. 11(1): 184-187. https://doi.org/10.1139/x81-024.

Henry, M.; Cifuentes-Jara, M.; Réjou-Méchain [et al.]. 2015. **Recommendations for the use of tree models to estimate national forest biomass and assess their uncertainty**. Annals of Forest Science. 72(6): 769-777. https://doi.org/10.1007/s13595-015-0465-x.

Henry, M.; Picard, N.; Trotta, C.; Manlay, R.J.; Valentini, R.; Bernoux, M.; Saint-André, L. 2011. **Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations**. Silva Fennica. 45(3B): 477-569. https://doi.org/10.14214/sf.38.

Hocker, H.W.J.; Earley, D.J. 1983. **Biomass and leaf area equations for northern forest species.** Res. Pap. 102. Durham, NH: University of New Hampshire Agricultural Experiment Station. 75 p.

Iverson, L.R.; Prasad, A.M. 1998. **Predicting abundance of 80 tree species following climate change in the eastern United States.** Ecological Monographs. 68(4): 465-485. https://doi.org/10.2307/2657150.

Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. 2003. **National-scale biomass estimators for United States tree species.** Forest Science. 49(1): 12-35.

Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. 2004. Comprehensive database of diameter-based biomass regressions for North American tree species. Gen. Tech. Rep. NE-319. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 45 p. [1 CD-ROM] https://doi.org/10.2737/NE-GTR-319.

Keith, H.; Barrett, D.; Keenan, R. 2000. **Review of allometric relationships for estimating woody biomass for New South Wales, the Australian Capital Territory, Victory, Tasmania, and South Australia.** National Carbon Accounting System. Technical Report no. 5b. Canberra, ACT: Australian Greenhouse Office.

Lambert, M.C.; Ung, C.H.; Raulier, F. 2005. **Canadian national tree aboveground biomass equations.** Canadian Journal of Forest Research. 35(8): 1996-2018. https://doi.org/10.1139/x05-112.

Larson, P.R. 1963. **Stem form development of forest trees.** Forest Science. 9(Suppl. 2): 1-47. https://doi.org/10.1093/forestscience/9.s2.a0001.

Levia, D.F. 2008. **A generalized allometric equation to predict foliar dry weight on the basis of trunk diameter for eastern white pine (*Pinus strobus* L.).** Forest Ecology and Management. 255(5-6): 1789-1792. https://doi.org/10.1016/j.foreco.2007.12.001.

Litton, C.M.; Ryan, M.G.; Tinker, D.B.; Knight, D.H. 2003. **Belowground and aboveground biomass in young post-fire lodgepole pine forests of contrasting tree density.** Canadian Journal of Forest Research. 33(2): 351-363. https://doi.org/10.1139/x02-181.

MacFarlane, D.W. 2011. **Allometric scaling of large branch volume in hardwood trees in Michigan, USA: implications for aboveground forest carbon stock inventories.** Forest Science. 57(6): 451-459.

MacFarlane, D.W. 2015. **A generalized tree component biomass model derived from principles of variable allometry.** Forest Ecology and Management. 354: 43-55. https://doi.org/10.1016/j.foreco.2015.06.038.

MacFarlane, D.W.; Weiskittel, A.R. 2016. **A new method for capturing stem taper variation for trees of diverse morphological types.** Canadian Journal of Forest Research. 46(6): 804-815. https://doi.org/10.1016/j.foreco.2015.06.038.

Magnussen, S.; Negrete, O.I.C. 2015. **Model errors in tree biomass estimates computed with an approximation to a missing covariance matrix.** Carbon Balance and Management. 10: 21. https://doi.org/10.1186/s13021-015-0031-8.

McRoberts, R.E.; Westfall, J.A. 2014. **The effects of uncertainty in model predictions of individual tree volume on large area volume estimates.** Forest Science. 60(1): 34-42. https://doi.org/10.5849/forsci.12-141.

Miles, P.D.; Smith, W.B. 2009. **Specific gravity and other properties of wood and bark for 156 tree species found in North America.** Res. Note NRS-38. Newtown Square, PA: U.S.

Department of Agriculture, Forest Service, Northern Research Station. 35 p. https://doi.
org/10.2737/NRS-RN-38.

Niinemets, Ü.; Valladares, F. 2006. **Tolerance to shade, drought, and waterlogging of
temperate northern hemisphere trees and shrubs.** Ecological Monographs. 76(4): 521-
547. https://doi.org/10.1890/0012-9615(2006)076[0521:ttsdaw]2.0.co;2.

O'Connell, B.M.; Conkling, B.L.; Wilson, A.M.; Burrill, E.A.; Turner, J.A.; Pugh, S.A.;
Christiansen, G.; Ridley, T.; Menlove, J. 2016. **The Forest Inventory and Analysis database:
database description and user guide, version 6.1.1 for Phase 2**. U.S. Department of
Agriculture, Forest Service. 870 p. [Online]. Available at https://www.fia.fs.fed.us/library/
database-documentation/.

Omdal, D.W.; Jacobi, W.R.; Shaw, C.G. 2001. **Estimating large-root biomass from breast-
height diameters for ponderosa pine in northern New Mexico.** Western Journal of
Applied Forestry. 16(1): 18-21.

Pan, Y.; Birdsey, R.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko,
A.; Lewis, S.L.; Canadell, J.G.; Ciais, P.; Jackson, R.B.; Pacala, S.W.; McGuire, A.D.; Piao, S.;
Rautiainen, A.; Sitch, S.; Hayes, D. 2011. **A large and persistent carbon sink in the world's
forests.** Science. 333(6045): 988-993. https://doi.org/10.1126/science.1201609.

Parker, G.R.; Schneider, G. 1975. **Biomass and productivity of an alder swamp in northern
Michigan**. Canadian Journal of Forest Research. 5: 403-409. https://doi.org/10.1139/x75-
055.

Pastor, J.; Aber, J.D.; Melillo, J.M. 1984. **Biomass prediction using generalized allometric
regressions for some northeast tree species.** Forest Ecology and Management. 7(1983-84):
265-274. https://doi.org/10.1016/0378-1127(84)90003-3.

Pearson, J.A.; Fahey, T.J.; Knight, D.H., 1984. **Biomass and leaf area in contrasting lodgepole
pine forests.** Canadian Journal of Forest Research. 14(2): 259-265. https://doi.org/10.1139/
x84-050.

Pelletier, G.; Landry, D.; Girouard, M. 2013. **A tree classification system for New Brunswick.**
Edmundston, New Brunswick: Northern Hardwoods Research Institute. 53 p. https://doi.
org/10.13140/RG.2.1.4481.0000.

Perala, D.A.; Alban, D.H. 1994. **Allometric biomass estimators for aspen-dominated
ecosystems in the upper Great Lakes.** Res. Pap. NC-314. Grand Rapids, MN: U.S.
Department of Agriculture, Forest Service, North Central Forest Experiment Station. 42 p.
https://doi.org/10.2737/NC-RP-314.

Radtke, P.J.; Walker, D.; Frank, J.; Weiskittel, A.; DeYoung, C.; MacFarlane, D.; Domke, G.;
Woodall, C.; Westfall, J. 2017. **Improved accuracy of aboveground biomass and carbon
estimates for live trees in forests of the eastern United States.** Forestry. 90(1): 32-46.
https://doi.org/10.1093/forestry/cpw047.

Radtke, P.J.; Walker, D.M.; Weiskittel, A.R.; Frank, J.; Coulston, J.W.; Westfall, J.A. 2015.
**Legacy tree data: a national database of detailed tree measurements for volume, weight,
and physical properties**. In: Stanton, S.M.; Christensen, G.A., comps. 2015. Pushing
boundaries: new directions in inventory techniques and applications: Forest Inventory
and Analysis (FIA) symposium 2015. Gen. Tech. Rep. PNW-GTR-931. Portland, OR: U.S.
Department of Agriculture, Forest Service, Pacific Northwest Research Station: 25-30.

Samuelson, L.J.; Stokes, T.A.; Butnor, J.R.; Johnsen, K.H.; Gonzalez-Benecke, C.A.; Anderson, P.; Jackson, J.; Ferrari, L.; Martin, T.A.; Cropper, W.P., Jr. 2014. **Ecosystem carbon stocks in *Pinus palustris* forests.** Canadian Journal of Forest Research. 44(5): 476-486. https://doi.org/10.1139/cjfr-2013-0446.

Schlaegel, B.E. 1975. **Estimating aspen volume and weight for individual trees, diameter classes or entire stands.** Gen. Tech. Rep. NC-20. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 16 p.

Schmitt, M.D.C.; Grigal, D.F. 1981. **Generalized biomass estimation equations for *Betula papyrifera* Marsh.** Canadian Journal of Forest Research. 11: 837 840. https://doi.org/10.1139/x81-122.

Sillett, S.C.; Van-Pelt, R.; Carroll, A.L.; Kramer, R.D.; Ambrose, A.R.; Trask, D. 2015. **How do tree structure and old age affect growth potential of California redwoods?** Ecological Monographs. 85(2): 181-212. https://doi.org/10.1890/14-1016.1.

Sillett, S.C.; Van-Pelt, R.; Koch, G.W.; Ambrose, A.R.; Carroll, A.L.; Antoine, M.E.; Mifsud, B.M. 2010**. Increasing wood production through old age in tall trees.** Forest Ecology and Management. 259: 976-994. https://doi.org/10.1016/j.foreco.2009.12.003.

Snowdon, P. 1991. **A ratio estimator for bias correction in logarithmic regressions.** Canadian Journal of Forest Research. 21: 720-724. https://doi.org/10.1139/x91-101.

Stephenson, N.L.; Das, A.J.; Condit, R. [et al.]. 2014. **Rate of tree carbon accumulation increases continuously with tree size.** Nature, 507(7490): 90-93. https://doi.org/10.1038/nature12914.

Temesgen, H.; Affleck, D.; Poudel, K.; Gray, A.; Sessions, J. 2015**. A review of the challenges and opportunities in estimating above ground forest biomass using tree-level models.** Scandinavian Journal of Forest Research. 30(40): 326-335. https://doi.org/10.1080/02827581.2015.1012114.

Ter-Mikaelian, M.T.; Korzukhin, M.D. 1997. **Biomass equations for sixty-five North American tree species.** Forest Ecology and Management. 97(1): 1-24. https://doi.org/10.1016/s0378-1127(97)00019-4.

U.S. Department of Energy (USDOE). 2011**. U.S. billion ton update: biomass supply for a bioenergy and bioproducts industry.** ORNL/TM-2011/224. Oak Ridge, TN: Oak Ridge National Laboratory. 227 p.

U.S. Environmental Protection Agency (USEPA). 2017. **Inventory of U.S. greenhouse gas emissions and sinks: 1990-2015**. EPA 430-P-17-001. Available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015 (accessed August 20, 2018).

Wang, Y. 2014. **National biomass estimator library.** Fort Collins, CO: Forest Management Service Center. 18 p. Available at https://www.fs.fed.us/forestmanagement/products/measurement/biomass/index.php (accessed August 20, 2018).

Wayson, C.A.; Johnson, K.D.; Cole, J.A.; Olguín, M.I.; Carrillo, O.I.; Birdsey, R.A. 2015. **Estimating uncertainty of allometric biomass equations with incomplete fit error information using a pseudo-data approach: methods.** Annals of Forest Science. 72(6): 825-834. https://doi.org/10.1007/s13595-014-0436-7.

Weiskittel, A.R.; MacFarlane, D.W.; Radtke, P.J.; Affleck, D.; Temesgen, H.; Woodall, C.W.; Westfall, J.A.; Coulston, J.W. 2015. **A call to improve methods for estimating tree biomass for regional and national assessments.** Journal of Forestry. 113(4): 414-424. https://doi.org/10.5849/jof.14-091.

Westfall, J. 2015. **Spatial-scale considerations for a large-area forest inventory regression model.** Forestry. 88(2): 267-274. https://doi.org/10.1093/forestry/cpv001.

Westfall, J.A. 2016. **Strategies for the use of mixed-effects models in continuous forest inventories.** Environmental Monitoring and Assessment. 188(4): 245. https://doi.org/10.1007/s10661-016-5252-0.

Wharton, E.H.; Griffith, D.M. 1993. **Methods to estimate total forest biomass for extensive forest inventories: applications in the northeastern U.S.** Res. Pap. NE-681. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 52 p. https://doi.org/10.2737/NE-RP-681.

Whittaker, R.H.; Bormann, F.H.; Likens, G.E.; Siccama, T.G. 1974. **The Hubbard Brook ecosystem study: forest biomass and production.** Ecological Monographs. 44(2): 233-254. https://doi.org/10.2307/1942313.

Wiant, H.V. 1977. **Tables and procedures for estimating weights of some Appalachian hardwoods.** Tech. Bull. 659T. Morgantown, WV: West Virginia University, Agricultural and Forestry Experiment Station.

Wood, G.W. 1971. **Biomass, production and nutrient distribution in mixed-oak stands following clear-cutting and fire.** Pennsylvania State University. Ph.D. dissertation.

Woodall, C.W.; Domke, G.M.; MacFarlane, D.W.; Oswalt, C.M. 2011a. **Comparing field- and model-based standing dead tree carbon stock estimates across forests of the US**. Forestry. 85(1): 125-133. https://doi.org/10.1093/forestry/cpr065.

Woodall, C.W.; Heath, L.S.; Domke, G.M.; Nichols, M.C. 2011b. **Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010.** Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p. https://doi.org/10.2737/NRS-GTR-88.

Young, H.E.; Ribe, J.H.; Wainwright, K. 1980. **Weight tables for tree and shrub species in Maine.** Misc. Report 230. Orono, ME: University of Maine, Life Sciences and Agriculture Experimental Station.

Yuen, J.Q.; Fung, T; Ziegler, A.D. 2016. **Review of allometric equations for major land covers in SE Asia: Uncertainty and implications for above- and below-ground carbon estimates.** Forest Ecology and Management. 360: 323-340. https://doi.org/10.1016/j.foreco.2015.09.016.

Zianis, D.; Muukonen, P.; Mäkipää, R.; Mencuccini, M. 2005. **Biomass and stem volume equations for tree species in Europe**. Silva Fennica Monographs. 4. 63 p.

APPENDIXES

Appendix 1: Bibliography of Reviewed Studies

Acuña-Maldonado, L.E. 1999. **Influence of nitrogen application time on nitrogen concentration and storage related to fruiting of pecan.** Stillwater, OK: Oklahoma State University. 51 p. Ph.D. dissertation.

Adams, J.C.; Lockaby, B.G. 1988. **Variability of understory sweetgum biomass relationships.** Southern Journal of Applied Forestry. 12(1): 5-7. https://doi.org/10.1093/sjaf/12.1.5.

Adegbidi, H.G.; Jokela, E.J.; Comerford, N.B.; Barros, N.F. 2002. **Biomass development for intensively managed loblolly pine plantations growing on spodosols in the southeastern USA.** Forest Ecology and Management. 167: 91-102. https://doi.org/10.1016/s0378-1127(01)00691-0.

Ahmed, S.S. 1956. **The effect of application of artificial fertilizer on height, radial, and branch growth of 35-year old Douglas-Fir.** Seattle, WA: University of Washington. 94 p. M.F. Thesis.

Alban, D.H.; Laidly, P.R. 1982. **Generalized biomass equations for jack and red pine in the Lake States.** Canadian Journal of Forest Research. 12(4): 913-921. https://doi.org/10.1139/x82-133.

Albaugh, T.J.; Allen, H.L; Dougherty, P.M.; Kress, L.W.; King, J.S. 1998. **Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions.** Forest Science. 44(2): 317-328.

Amateis, R.L.; Burkhart, H.E.; Dunham, P.H. 1992. **Estimating dry weight of dormant-season foliage of loblolly pine.** Biomass and Bioenergy. 3(5): 319-322. https://doi.org/10.1016/0961-9534(92)90003-9.

Anonymous. 1990. **Methods for modeling unit-area impact of environmental stresses in loblolly pine stands.** Tech. Bull. 581. Cary, NC: National Council of the Paper Industry for Air and Stream Improvement.

Antony, F.; Schimleck, L.R.; Daniels, R.F.; Clark, A.; Borders, B.E.; Kane, M.B.; Burkhart, H.E. 2015. **Whole-tree bark and wood properties of loblolly pine from intensively managed plantations.** Forest Science. 61(1): 55-66. https://doi.org/10.5849/forsci.12-030.

Archibald, R.M. 1983. **Effect of nitrogen fertilization on allometric relationships in Douglas-fir in western Washington.** Seattle, WA: University of Washington. 50 p. M.S. thesis.

Arevalo, C.; Volk, T.A.; Bevilacqua, E.; Abrahamson, L. 2007. **Development and validation of aboveground biomass estimations for four *Salix* clones in central New York.** Biomass and Bioenergy. 31(1): 1-12. https://doi.org/10.1016/j.biombioe.2006.06.012.

Aspinwall, M.J.; King, J.S.; McKeand, S.E. 2013. **Productivity differences among loblolly pine genotypes are independent of individual-tree biomass partitioning and growth efficiency.** Trees. 27(3): 533-545. https://doi.org/10.1007/s00468-012-0806-4.

Bailey, R.L.; Grider, G.E.; Rheney, J.W.; Pienaar, L.V. 1985. **Stand structure and yields for site-prepared loblolly pine plantations in the piedmont and upper coastal plain of Alabama,**

Georgia, and South Carolina. Res. Bull. 328. Athens, GA: The University of Georgia Agricultural Experiment Station. 118 p.

Bailey, R.L.; Pienaar, L.V.; Shiver, B.D.; Rheney, J.W. 1982. **Stand structure and yield of site-prepared slash pine plantations.** Res. Bull. 291. Athens, GA: The University of Georgia Agricultural Experiment Station. 17 p.

Baker, J.B. 1962. **Dry matter production in plantations of loblolly pine.** Durham, NC: Duke University. 28 p. M.S. thesis.

Baker, J.B. 1971. **Response of sapling loblolly pine (*Pinus taeda* L.) to nitrogen fertilization: growth, accumulation, and recovery.** Starkville, MS: Mississippi State University. 85 p. Ph.D. dissertation.

Baldwin, V.C. 1987. **Green and dry-weight equations for above-ground components of planted loblolly pine trees in the West Gulf region.** Southern Journal of Applied Forestry. 11(4): 212-218.

Baldwin, V.C. 1989. **Is sapwood area a better predictor of loblolly pine crown biomass than bole diameter?** Biomass. 20(3-4): 177-185. https://doi.org/10.1016/0144-4565(89)90058-9.

Baldwin, V.C.; Peterson, K.D.; Burkhart, H.E.; Amateis, R.L.; Dougherty, P.M. 1997. **Equations for estimating loblolly pine branch and foliage weight and surface area distributions.** Canadian Journal of Forest Research. 27(6): 918-927. https://doi.org/10.1139/x97-030.

Baldwin, V.C.; Peterson, K.D.; Clark, A., III. ; Ferguson, R.B.; Strub, M.R.; Bower, D.R. 2000. **The effects of spacing and thinning on stand and tree characteristics of 38-year-old loblolly pine.** Forest Ecology and Management. 137(1-3): 91-102. https://doi.org/10.1016/S0378-1127(99)00340-0.

Baldwin, V.C.; Saucier, J.R. 1983. **Aboveground weight and volume of unthinned, planted longleaf pine on West Gulf forest sites.** Res. Pap. SO-191. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 25 p. https://doi.org/10.2737/so-rp-191.

Barney, R.J.; VanCleve, K.; Schlentner, R. 1978. **Biomass distribution and crown characteristics in two Alaskan *Picea mariana* ecosystems.** Canadian Journal of Forest Research. 8(1): 36-41. https://doi.org/10.1139/x78-007.

Belanger, R.P. 1973. **Volume and weight tables for plantation-grown sycamore.** Res. Pap. SE-107. Asheville, NC: U.S Department of Agriculture, Forest Service, Southeastern Experiment Station. 9 p.

Bickelhaupt, D.H. 1979. **Biomass and elemental contents of sugar maple as affected by branching characteristics.** New York City, NY: University of New York College of Environmental Science and Forestry. 179 p. M.S. thesis.

Binkley, D. 1983. **Ecosystem production in Douglas-fir plantations: interaction of red alder and site fertility.** Forest Ecology and Management. 5(3): 215-227. https://doi.org/10.1016/0378-1127(83)90073-7.

Blackmon, B.G. 1963. **Dry matter production of several oak and hickory species in the lower piedmont.** Durham, NC: Duke University. 42 p. M.S. thesis.

Blazier, M.A.; Hennessey, T.C.; Lynch, T.B.; Wittwer, R.F.; Payton, M.E. 2004. **Productivity, crown architecture, and gas exchange of North Carolina and Oklahoma/Arkansas loblolly pine families growing on a droughty site in southeastern Oklahoma**. Forest Ecology and Management. 194(1-3): 83-94. https://doi.org/10.1016/j.foreco.2004.02.014.

Bockheim, J.; Lee, S.W. 1984. **Biomass and net primary production equations for thinned red pine plantations in central Wisconsin.** Forest Research Notes 256. Madison, WI: University of Wisconsin, College of Agriculture. 7 p.

Boerner, R.E.J.; Kost, J.A. 1986. **Biomass equations for flowering dogwood, *Cornus florida* L.** Castanea**. 51(2): 153-155.

Boring, L.R.; Swank, W.T. 1984. **The role of black locust (*Robinia pseudoacacia*) in forest succession.** Journal of Ecology. 72(3): 749-766. https://doi.org/10.1016/S0378-1127(83)80004-8.

Bormann, B.T. 1990. **Diameter-based biomass regression models ignore large sapwood-related variation in Sitka spruce.** Canadian Journal of Forest Research. 20(7): 1098-1104. https://doi.org/10.1139/x90-145.

Bower, D.R.; Clason, T.R. 1981. **Biomass estimation for managed loblolly pine plantations.** In: Brann, T.; House, L.O.; Lund, H.G. In-place resource inventories: principles and practices: proceedings of a national workshop. Bethesda, MD: Society of American Foresters: 937-942.

Box, B.H. 1967. **A study of root extension and biomass in a six year old plantation in southeast Louisiana.** Durham, NC: Duke University. Ph.D. dissertation.

Bray, A.J.R.; Dudkiewicz, L.A. 1963. **The composition, biomass and productivity of two populus forests.** Torrey Botanical Club. 90(5): 298-308.

Brennemen, B.B.; Frederick, D.J.; Gardner, W.E.; Schoenhofen, L.H.; Marsh, P.L. 1978. **Biomass of species and stands of West Virginia hardwoods.** In: Proceedings, Central Hardwood Forest Conference II; November 14-16, 1978. West Lafayette, IN: 159-178.

Bridge, J.A. 1979. **Fuelwood production of mixed hardwoods on mesic sites in Rhode Island.** West Greenwich, RI: University of Rhode Island. M.S. thesis.

Bridgen, M.R. 1982**. Biomass equations for small hardwood trees.** Res. Pap. 34. Rupert, WV: Westvaco Timberlands Division, West Virginia Forest Research Center. 8 p.

Briggs, R.D; Porter, J.H.; White, E.H. 1989. **Component biomass equations for *Acer rubrum* and *Fagus grandifolia*.** Syracuse, NY: College of Forestry and Environmental Science and Forestry. 19 p.

Brooks, J.R.; Jiang, L.; Clark, A., III. 2007. **Compatible stem taper, volume, and weight equations for young longleaf pine plantations in southwest Georgia.** Southern Journal of Applied Forestry. 31(4): 187-191.

Brown, J.K. 1965. **Estimating crown fuel weights of red pine and jack pine.** Res. Pap. LS-20. St. Paul, MN: U.S. Department of Agriculture, Forest Service, Lakes States Forest Experiment Station. 11 p. https://doi.org/10.5962/bhl.title.83807.

Brown, J.K. 1978. **Weight and density of crowns of Rocky Mountain conifers.** Res. Pap. INT-197. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: 65 p. https://doi.org/10.5962/bhl.title.68796.

Burkhart, H.E.; Clutter, J.L. 1971. **Green and dry weight yields for old-field loblolly pine plantations in the Georgia piedmont.** Tech. Rep. No. 22. Athens, GA: University of Georgia. 11 p.

Burkhart, H.F.; Parker, R.C.; Oderwald, R.G. 1972. **Yields for natural stands of loblolly pine.** Research Pub. FWS-2-72. Blacksburg, VA: Virginia Polytechnic Institute and State University. Division of Forestry and Wildlife Resources. 12 p.

Burton, A.J.; Pregitzer, K.S.; Reed, D.D. 1991. **Leaf area and foliar biomass relationships in northern hardwood forests located along an 800 km acid deposition gradient.** Forest Science. 37(4): 1041-1059.

Callaway, R.M.; DeLucia, E.H.; Schlesinger, W.H. 1994. **Biomass allocation of montane and desert ponderosa pine: an analog for response to climate.** Ecology. 75(5): 1474-1481. https://doi.org/10.2307/1937470.

Callaway, R.M.; Sala, A.; Keane, R.E. 2000. **Succession may maintain high leaf area: sapwood ratios and productivity in old subalpine forests.** Ecosystems. 3(3): 254-268. https://doi.org/10.1007/s100210000024.

Carpenter, E.M. 1983. **Above-ground weights for tamarack in northeastern Minnesota.** Res. Pap. NC-245. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 9 p.

Carter, M.C.; White, E.H. 1971**. Dry weight and nutrient accumulation in young stands of Cottonwood (*Poulus deltoids* Bartr.).** Circular 190. Auburn, AL: Agricultural Experiment Station, Auburn University. 13 p.

Chapman, J.W.; Gower, S.T. 1991. **Aboveground production and canopy dynamics in sugar maple and red oak trees in southwestern Wisconsin.** Canadian Journal of Forest Research. 21(10): 1533-1543. https://doi.org/10.1139/x91-214.

Chapman, R.C.; Clausnitzer, R.R.; Baldwin, V.C. 1985. **Bole oven dry weight equations and weight/basal area tables for northeastern Washington conifers.** Pullman, WA: Agricultural Research Bulletin XB 0948. Washington State University, College of Agriculture and Home Economics. 8 p.

Chojnacky, D.C. 1984. **Volume and biomass for curlleaf cercocarpus in Nevada.** Res. Pap. INT-332. Ogden, UT: U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station. 8 p. https://doi.org/10.2737/INT-RP-332.

Clark, A., III. 1976. **Sumpter study.** Unpublished data.

Clark, A., III. 1977. **Complete tree biomass of a 17-year old slash pine plantation from Calhoun County, Florida.** Unpublished data.

Clark, A., III. 2015. **Weight, volume, and physical properties of pond cypress from Florida.** Unpublished data.

Clark, A., III. (N.d.). **Aboveground biomass of planted slash pine collected by the Buckeye Cellulose Company,** Athens, GA. Unpublished data.

Clark A., III. (N.d.). **Aboveground biomass of slash pine collected by the Buckeye Cellulose Company,** Athens, GA. Unpublished data.

Clark, A., III. (N.d.). **Influence of provenance and environment on juvenile wood formation and wood properties of loblolly pine.** Athens, GA. Unpublished data.

Clark, A., III. (N.d.). **IP study.** Unpublished data.

Clark, A., III. (N.d.). **NCSU study.** Unpublished data.

Clark, A., III.; Phillips, D.R.; Frederick, D.J. 1985. **Weight, volume, and physical properties of major hardwood species in the gulf and Atlantic coastal plains.** Res. Pap. SE-250. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 66 p. https://doi.org/10.2737/SE-RP-250.

Clark, A., III. ; Phillips, D.R.; Frederick, D.J. 1986. **Weight, volume, and physical properties of major hardwood species in the Upland-South.** Res. Pap. SE-257. Asheville, NC: U.S Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 61 p. https://doi.org/10.2737/SE-RP-257.

Clark, A., III.; Saucier, J.R. 1969. **Wood density surveys of the minor species of yellow pine in the eastern United States: part III -- table-mountain pine (*Pinus pungens* Lamb.).** Res. Pap. SE-52. Asheville, NC: U.S. Department of Agriculture, Forest Service. 12 p.

Clark, A., III; Saucier, J.R. 1987. **Biomass response of loblolly pine to applied sewage sludge four years after treatment.** Res. Pap. Athens, GA: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 9 p.

Clark, A., III.; Saucier, J.R. 1990. **Tables for estimating total-tree weights, stem weights, and volumes of planted and natural southern pines in the southeast.** Georgia Forest Res. Pap. 79. Dry Branch, GA: Georgia Forestry Commission, Research Division. 23 p.

Clark, A., III.; Schroeder, J.G. 1986. **Weight, volume, and physical properties of major hardwood species in the southern Appalachian mountains.** Res. Pap. SE-253. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 63 p. https://doi.org/10.2737/SE-RP-253.

Clark, A., III.; Taras, M.A. 1969. **Wood density surveys of the minor species of yellow pine in the eastern United States: part II -- sand pine (*Pinus clausa* (Chapm.) vasey).** Res. Pap. SE-51. Asheville, NC: U.S. Department of Agriculture, Forest Service. 14 p.

Clark, A., III.; Taras, M.A. 1970. **Wood density surveys of the minor species of yellow pine in the eastern United States: Part VII -- South Florida slash pine (*Pinus elliottii* var. *densa* Little and Dorman).** Res. Pap. SE-66. Asheville, North Carolina: U.S. Department of Agriculture, Forest Service 11 p**.**

Clark, A., III.; Taras, M.A. 1976. **Comparison of aboveground biomass of the four major southern pines.** Forest Products Journal. 26(10): 25-29.

Clark, A., III.; Wahlgren, H.E. 1970. **Wood density surveys of the minor species of yellow pine in the eastern United States.** Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Clary, W.P.; Tiedemann, A.R. 1986. **Distribution of biomass within tree and shrub form *Quercus gambelii* stands.** Forest Science. 32(1): 234-242.

Clary, W.P.; Tiedemann, A.R. 1987. **Fuelwood potential in large-tree *Quercus gambelii* stands.** Western Journal of Applied Forestry. 2(3): 87-90.

Clebsch, E.E.C.; DeSelm, H.R. 1963. **Vegetation studies related to movement of radioactive wastes.** Scientific Report. Knoxville, TN: University of Tennessee, The Atomic Energy Commission. 4 p.

Clutter, J.L.; Harms, W.R.; Brister, G.H.; Rheney, J.W. 1984. **Stand structure and yields of site-prepared loblolly pine plantations in the lower coastal plain of the Carolinas, Georgia, and North Florida.** Gen. Tech. Rep. SE-27. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.173 p. https://doi.org/10.2737/SE-GTR-27.

Cochran, P.H.; Jennings, J.W.; Youngberg, C.T. 1984. **Biomass estimators for thinned second-growth ponderosa pine trees.** Res. Note PNW-415. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 6 p. https://doi.org/10.2737/PNW-RN-415.

Colbert, S.R.; Jokela, E.J.; Neary, D.G. 1990. **Effects of annual fertilization and sustained weed control on dry matter partitioning leaf area and growth efficiency of juvenile loblolly and slash pine.** Forest Science. 36(4): 995-1014.

Collicott. L.V.; Strickland, J.R.; Stonecypher, R.W. 1968. **Dry-weight yields of slash pine plantations.** Tech. Note 27. Bainbridge, GA: Southlands Experimental Forest. 12 p.

Coltrin, W.R. 2010. **Biomass quantification of live trees in a mixed evergreen forest using diameter-based allometric equations.** Arcata, CA: Humboldt State University. M.S. thesis.

Comerford, N.; Leaf, A. 1982. **An evaluation of techniques for sampling the crown for total nutrient content.** Forest Science. 28(3): 471-480.

Conde, L.F.; Smith, J.E.; Swindel, B.F.; Hollis, C A.I., III. 1979. **Aboveground live biomass of major pine flatwoods tree species.** Gainesville, FL: The University of Florida, School of Forest Resources and Conservation. 16 p.

Coyle, D R.; Coleman, M.D.; Aubrey, D.P. 2008**. Above- and below-ground biomass accumulation production and distribution of sweetgum and loblolly pine grown with irrigation and fertilization.** Canadian Journal of Forest Research. 38: 1335-1348. https://doi.org/10.1139/x07-231.

Crow, T.R. 1971**. Estimation of biomass in an even-aged stand: regression and "mean tree" techniques.** Science Journal Paper Series Paper no.7487. St. Paul, MN: University of Minnesota, Agricultural Experiment Station.

Crow, T.R. 1977. **Biomass and production regressions for trees and woody shrubs common to Enterprise Forest.** In: Zavitkovski, J., ed. The Enterprise radiation forest: radioecological

studies. Rep. TID-26113-P2. Washington, DC: U.S. Energy Researh and Development Administration: 63-67.

Crow, T.R. 1983. **Comparing regressions by site and stand age for red maple.** Canadian Journal of Forest Research. 13(2): 283-288. https://doi.org/10.1139/x83-040.

Crow, T.R.; Blank, R.W. 1992. **Distribution of biomass and production for several northern woody species.** Res. Note. NC-239. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 3 p.

Cunia, T.; Briggs, R.D. 1984. **Forcing additivity of biomass tables: some empirical results.** Canadian Journal of Forest Research. 14(3): 376-384. https://doi.org/10.1139/x84-067.

Czapowskyj, M.M.; Robison, D.J.; Briggs, R.D.; White, E.H. 1985. **Component biomass equations for black spruce in Maine.** Res. Pap. NE-564. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 9 p.

Davis, A.A.; Trettin, C.C. 2006. **Sycamore and sweetgum plantation productivity on former agricultural land in South Carolina.** Biomass & Bioenergy. 30(8-9): 770-777. https://doi.org/10.1016/j.biombioe.2005.08.001.

Devine, W.D.; Footen, P.W.; Harrison, R.B.; Terry, T.A.; Harrington, C.A.; Holub, S.M.; Gould, P.J. 2013. **Estimating tree biomass, carbon, and nitrogen for two vegetation control treatments in an 11-year-old Douglas-fir plantation on a highly productive site.** Res. Pap. PNW-RP-591. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 19 p. https://doi.org/10.2737/PNW-RP-591.

Dice, S.F. 1970. **The biomass and nutrient flux in a second growth Douglas-fir ecosystem (a study in quantitative ecology).** Seattle, WA: University of Washington. 50 p. Ph.D. dissertation.

Dickman, D.I.; Steinbeck, K.; Skinner, T. 1985. **Leaf area and biomass in mixed and pure plantations of sycamore and black locust in the Georgia piedmont.** Forest Science. 31(2): 509-517.

Domec, J.C.; Lachenbruch, B.; Pryun, M.; Spicer, R. 2012. **Effects of age-related increases in sapwood area leaf area and xylem conductivity on height-related hydraulic costs in two contrasting coniferous species.** Annals of Forest Science. 69(1): 17-27. https://doi.org/10.1007/s13595-011-0154-3.

Dunlap, W.H. 1967. **Density and weight prediction of standing white oak, red maple, and red pine.** State College, PA: The Pennsylvania State University. 64 p. M.S. thesis.

Dyer, R.F. 1967. **Fresh and dry weight, nutrient elements and pulping characteristics of northern white cedar, *Thuja occidentalis*.** Tech. Bull. 27. Orono, ME: Maine Agricultural Experiment Station. 40 p.

Edwards, M.B.; McNab, W.H. 1979. **Biomass prediction for young southern pines.** Journal of Forestry. 77(5): 291-292.

Elliot, K.J.; Boring, L.R.; Swank, W.T. 2002. **Aboveground biomass and nutrient accumulation 20 years after clear-cutting a southern Appalachian watershed.** Canadian Journal of Forest Research. 32(4): 667-683. https://doi.org/10.1139/x02-009.

Espinosa Bancalari, M.A.; Perry, D.A. 1987. **Distribution and increment of biomass in adjacent young Douglas-fir stands with different early growth rates.** Canadian Journal of Forest Research. 17(7): 722-730. https://doi.org/10.1139/x87-115.

Fassnacht, K.S. 1996. **Characterization of the structure and function of upland forest ecosystems in north central Wisconsin.** Madison, WI: University of Wisconsin. 21 p. Ph.D. dissertation.

Fatemi, F.R. 2007. **Aboveground biomass and nutrients in developing northern hardwood stands in New Hampshire, USA.** Syracuse, NY: SUNY College of Environmental Science and Forestry. 97 p. M.S. thesis.

Felker, P.; Clark, P R.; Osborn, J.F.; Cannell, G.H. 1982. **Biomass estimation in a young stand of mesquite (*Prospopis* spp.), ironwood (*Olneya tesota*), palo verde (*Cercidium floridium*, and *Parkinsonia aculeata*), and leucaena (*Leucaena leucocephala*).** Journal of Range Management. 35(1): 87-89. https://doi.org/10.2307/3898527.

Fernow Experimental Forest. 1992. **Vegetation sampling: watersheds 3 and 7.** Tucker County, West Virginia. Unpublished data.

FIA. 2016. **FIA biomass sampling data. Unpublished data.** On file with: U.S. Department of Agriculture, Forest Service. Northeastern Research Station, Newtown Square, PA.

Finto, A.S.; Daniels, R.F.; Clark, A., III. Borders, B.E. 2015. **Whole-tree bark and wood properties of loblolly pine from intensively managed plantations.** Forest Science. 61(1): 55-66. https://doi.org/10.5849/forsci.12-030.

Flowers, W.R.J. 1978. **Individual tree weight and volume equations for site prepared loblolly pine plantations in the coastal plain of the Carolinas, Georgia, and North Florida.** University of Georgia. 41 p. M.S. thesis.

Forbush, J.; Richardson, A. 1998. **Sassafras allometry at Totoket Mountain, North Branford, CT.**

Franchi, B.L.; Savellle, I.W.; Watson, W.F.; Stokes, B.J. 1984. **Predicting biomass of understory stems in the Mississippi and Alabama coastal plains.** Tech. Bull. 124. Mississippi State, MS: Mississippi Agricultural and Forestry Experiment Station. 8 p.

Fujimori, T.; Kawanabe, S.; Saito, H.; Grier, C.C.; Shidei, T. 1976. **Biomass and primary productivity in forest of three major vegetation zones of the Northwestern United States.** Journal of the Japanese Forestry Society. 58(10): 360-373.

Garber, S.M.; Maguire, D.A. 2005. **The response of vertical foliage distribution to spacing and species composition in mixed conifer stands in central Oregon.** Forest Ecology and Management. 211(3): 341-355. https://doi.org/10.1016/j.foreco.2005.02.053.

Garbett, W.S. 1977. **Aboveground biomass and nutrient content of a mixed slash-longleaf pine stand in Florida.** Gainesville, FL: University of Florida. 36 p. M.S. thesis.

Ghoz, H.L. 1980. **Structure and productivity of *Juniperus occidentalis* in central Oregon.** American Midland Naturalist. 103(2): 251-261. https://doi.org/10.2307/2424623.

Gholz, H.L.; Fisher, R.F. 1982. **Organic matter production and distribution in slash pine (*Pinus elliottii*) plantations.** Canadian Journal of Forest Research. 63(6): 1827-1839. https://doi.org/10.2307/1940124.

Gholz, H.L.; Grier, C C.; Campbell, A.G.; Brown, A.T. 1979. **Equations for estimating biomass and leaf area of plants in the Pacific Northwest.** Res. Pap. 41. Corvallis, OR: Oregon State University, School of Forestry. 39 p.

Gholz, H.L.; Vogel, S.A.; Cropper, W.P.; Mckelvey, K.; Ewel, K.C.; Teskey, R.O.; Curran, P J. 1991**. Dynamics of canopy structure and light interception in *Pinus elliottii* stands.** Ecological Monographs. 61(1): 33-51. https://doi.org/10.2307/1942998.

Gholz. (N.d.). **FV study.** Unpublished data.

Gibson, M.D.; McMillin, C.W.; Shoulders, E. 1985. **Above- and below-ground biomass of four species of southern pine growing on three sites in Louisiana.** Final Report FS-SO-3201-59. Pineville, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 272 p.

Gilmore, D.W.; Zenner, E.K. 2005. **Foliage-sapwood area relationships for balsam fir in north central Minnesota.** Northern Journal of Applied Forestry. 22(3): 203-210.

Glover, G.R. 1981. **Equations for predicting total tree volumes and weights from renewable resources evaluation inventories in Alabama.** Res. Pap. Auburn, AL: Auburn University Department of Forestry. 40 p.

Goddard, R.E.; Strickland, R.K. 1968. **Volume and weight tables for five-year-old plantation grown slash pine.** Res. Pap. 14. Gainesville, FL: University of Florida, School of Forestry. 7 p.

Gower, S.T.; Grier, C.C.; Vogt, D.J.; Vogt, K.A. 1987. **Allometric relations of deciduous (*Larix occidentalis*) and evergreen conifers (*Pinus contorta* and *Pseudotsuga menziesii*) of the Cascade Mountains in central Washington.** Canadian Journal of Forest Research. 17: 630-634. https://doi.org/10.1139/x87-103.

Gower, S.T.; Haynes, B.; Fassnacht, K.; Running, S.; Hunt, E. J. 1993a**. Influence of fertilization on the allometric relations for two pines in contrasting environments.** Canadian Journal of Forest Research. 23(8): 1704-1711. https://doi.org/10.1139/x93-212.

Gower, S.T.; Reich, P.B.; Son, Y. 1993b. **Canopy dynamics and aboveground production of five tree species with different leaf longevities.** Tree physiology. 12(4): 327–345. https://doi.org/10.1093/treephys/12.4.327.

Gower, S.T.; Vogt, K.A.; Grier, C.C. 1992. **Carbon dynamics of Rocky Mountain Douglas-fir: influence of water and nutrient availability.** Ecological Monographs. 62(1): 43-65. https://doi.org/10.2307/2937170.

Gresham, C.A. 1982. **Biomass relations of *Gordonia lasianthus*, loblolly-bay.** In: Baldwin, V.C., Jr.; Lohrey, R., eds. Proceedings, Southern forest biomass working group workshop; 1982 June 16-18; Alexandria, LA. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 81-87.

Grier, C.C.; Elliott, K.J.; McCullough, D.G. 1992. **Biomass distribution and productivity of *Pinus edulis-Juniperus monosperma* woodlands of north-central Arizona.** Forest Ecology and Management. 50: 331-350. https://doi.org/10.1016/0378-1127(92)90346-b.

Grier, C.C.; Lee, K.M.; Archibald, R.M. 1984. **Effect of urea fertilization on allometric relationships in young Douglas-fir trees.** Canadian Journal of Forest Research. 14(6): 900-904. https://doi.org/10.1139/x84-160.

Grier, C.C.; Logan, R.S. 1977. **Old-growth *Pseudotsuga menziessii* communities of a western Oregon watershed: biomass distribution and production budgets.** Ecological Monographs. 47(4): 373-400. https://doi.org/10.2307/1942174.

Grier, C.C.; Milne, W.A. 1981. **Regression equations for calculating component biomass of young *Abies amabilis* (Dougl.) Forbes.** Canadian Journal of Forest Research. 11(1): 184–187. https://doi.org/10.1139/x81-024.

Gyawali, N. 2008. **Aboveground biomass partitioning due to thinning in naturally regenerated even-aged shortleaf pine (*Pinus echinata* Mill.) stands in southeast Oklahoma.** Stillwater, OK: Oklahoma State University. 85 p. M.S. thesis.

Harding, R.B.; Grigal, D.F. 1985. **Individual tree biomass estimations equations for plantation-grown white spruce in northern Minnesota.** Canadian Journal of Forest Research. 15(4): 738-739. https://doi.org/10.1139/x85-122.

Harrington, T.; Tappeiner, J.; Walstad, J. 1984. **Predicting leaf area and biomass of 1- to 6-year-old tanoak (*Lithocarpus densiflorus*) and Pacific madrone (*Arbutus menziesii*) sprout clumps in southwestern Oregon.** Canadian Journal of Forest Research. 14(2): 209-213. https://doi.org/10.1139/x84-041.

Harris, W.F.; Goldstein, R.A.; Henderson, G.S. 1973. **Analysis of forest biomass pools, annual primary production and turnover of biomass for mixed deciduous forest watershed.** Res. Pap. Oak Ridge, TN: Oak Ridge National Laboratory, Environmental Sciences Division. 23 p.

Harrison, R.B. 1981. **Biomass calcium magnesium and potassium dynamics of young even-aged White Mountain, New Hampshire forest stands regenerating from clear-cutting.** Raleigh, NC: North Carolina State University. 130 p. M.S. thesis.

Harrison, R.B.; Terry, T.A.; Licata, C.W.; Flaming, B.L.; Meade, R.; Guerrini, I.A.; Strahm, B.D.; Xue, D.; Lolley, M.R.; Sidell, A.R.; Wagoner, G.L.; Briggs, D.; Turnblom, E.C. 2009. **Biomass and stand characteristics of a highly productive mixed Douglas-fir and western hemlock plantation in coastal Washington.** Western Journal of Applied Forestry. 24(4): 180-186.

Hauser, J.W; Aust, W.M.; Burger, J.A.; Zedaker, S.M. 1993. **Drainage effects on plant diversity and productivity in loblolly pine (*Pinus taeda* L.) plantations on wet flats.** Forest Ecology and Management. 61: 109-126. https://doi.org/10.1016/0378-1127(93)90193-q.

Haynes, B.E.; Gower, S.T. 1995. **Belowground carbon allocation in unfertilized and fertilized red pine plantations in northern Wisconsin.** Tree Physiology. 15(5): 317-325. https://doi.org/10.1093/treephys/15.5.317.

Heilman, P.E. 1961. **Effects of nitrogen fertilization on the growth and nitrogen nutrition of low-site Douglas-fir stands.** Seattle, WA: University of Washington. 41 p. Ph.D. dissertation.

Helgerson, O.T.; Cromack, K.; Stafford, S.; Miller, R.E.; Slagle, R. 1988. **Equations for estimating aboveground components of young Douglas-fir and red alder in a coastal**

Oregon plantation. Canadian Journal of Forest Research. 18(8): 1082-1085. https://doi.org/10.1139/x88-164.

Hepp, T.E.; Brister, G.H. 1982. **Estimating crown biomass in loblolly pine plantations in the Carolina flatwoods (*Pinus taeda*).** Forest Science. 28(1): 115-127.

Hocker, H.W.J.; Earley, D.J. 1983. **Biomass and leaf area equations for northern forest species.** Res. Pap. 102. Durham, NH: University of New Hampshire, Agricultural Experiment Station. 75 p.

Hogg. 2007. **WMSP-Profile and weight study documentation.** Unpublished Report.

Houser, J.N. 1980. **Estimation of aboveground biomass and inorganic nutrient content of a 25-year-old loblolly pine (*Pinus taeda* L.) plantation.** College Station, TX: Texas A&M University. 71 p. M.S. thesis.

Hutnik, R.J. 1964. **Accumulation and production of dry matter in red pine (*Pinus resinosa* AIT.) plantations at various spacings.** Durham, NC: Duke University. 188 p. Ph.D. dissertation.

Hyink, D.M.; Lenhart, D.J.; Somberg, S. I. 1972. **Oven dry weights for loblolly pine trees in old-field plantations in the interior West Gulf coastal plain.** Res. Pap. 17. Nacogdoches, TX: Stephen F. Austin State University, School of Forestry. 3 p.

Ishii, H.; Kadotani, T. 2006. **Biomass and dynamics of attached dead branches in the canopy of 450-year-old Douglas-fir trees.** Canadian Journal of Forest Research. 36(2): 378-389. https://doi.org/10.1139/x05-244.

Jacobs, D.F.; Selig, M.F.; Severeid, L.R. 2009. **Aboveground carbon biomass of plantation-grown American chestnut (*Castanea dentata*) in absence of blight.** Forest Ecology and Management. 258(3): 288-294. https://doi.org/10.1016/j.foreco.2009.04.014.

Jiang, L. 2007. **An evaluation of modeling techniques for stem taper, volume, and weight for yellow-poplar and red pine in West Virginia.** Morgantown, WV: West Virginia University. 109 p. Ph.D. dissertation.

Jiang, L.; Brooks, J.R.; Wang, J. 2005. **Compatible taper and volume equations for yellow-poplar in West Virginia.** Forest Ecology and Management. 213(1-3): 399-409. https://doi.org/10.1016/j.foreco.2005.04.006.

Johansen, R.W.; McNab, W.H. 1977. **Estimating logging residue weights from standing slash for prescribed burns.** Southern Journal of Applied Forestry. 1(2): 1-6.

Johnston, R.S.; Bartos, D.L. 1977. **Summary of nutrient and biomass data from two aspen sites in western United States.** Res. Note INT-227. Ogden, UT: U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station. 16 p.

Jokela, E.J. 1981. **Biomass and nutrient equations for mature *Betula papyrifera* Marsh.** Canadian Journal of Forest Research. 11: 298-305. https://doi.org/10.1139/x81-040.

Jokela, E.J.; Martin, T.A. 2000. **Effects of ontogeny and soil nutrient supply on production allocation and leaf area efficiency in loblolly and slash pine stands.** Res. Pap. R-07600. Gainesville, FL: University of Florida, School of Forest Resources and Conservation.

Jokela, E.J.; Van Gurp K.P.; Briggs, R.D.; White E.H. 1986. **Biomass estimation equations for Norway spruce in New York.** Canadian Journal of Forest Research. 16: 413-415. https://doi.org/10.1139/x86-075.

Jordan, L.; Clark, A., III. ; Schimleck, R.; Hall, D.B.; Daniels, R.F. 2008. **Regional variation in wood specific gravity of planted loblolly pine in the United States.** Canadian Journal of Forest Research. 38(4): 698-710. https://doi.org/10.1139/x07-158.

Jordan, L.; Souter, R.A.; Parresol, B.R.; Daniels, R.F. 2006. **Application of algebraic difference approach for developing self-referencing specific gravity and biomass equations.** Forest Science. 52(1): 81-92.

Kapeluck, P.R.; VanLear, D.H. 1995. **A technique for estimating below-stump biomass of mature loblolly pine plantations.** Canadian Journal of Forest Research. 25(2): 355-360. https://doi.org/10.1139/x95-039.

Karlik, J.F.; Chojnacky, D.C. 2013. **Biomass and carbon data from blue oaks in a California oak savanna.** Biomass and Bioenergy. 62: 228-232. https://doi.org/10.1016/j.biombioe.2013.11.018.

Kaye, J.P.; Hart, S.C.; Fulé, P.Z; Covington, W.W.; Moore, M.M.; Kaye, M.W. 2005. **Initial carbon, nitrogen, and phosphorus fluxes following ponderosa pine restoration treatments.** Ecological Applications. 15(5): 1581-1593. https://doi.org/10.1890/04-0868.

King, J.S; Giadina, C.P; Pregitzer, K.S.; Friend, A.L. 2007. **Biomass partitioning in red pine (*Pinus resinosa*) along a chronosequence in the upper peninsula of Michigan.** Canadian Journal of Forest Research. 37: 93-102. https://doi.org/10.1139/x06-217.

King, W.; Schnell, R.L. 1972. **Biomass estimates of black oak tree components.** Tech. Note B1. Norris, TN: Tennessee Valley Authority Division of Forestry, Fisheries, and Wildlife Development. 24 p.

Kizha, A.R.; Han, H.S. 2016. **Predicting aboveground biomass in second growth coast redwood: comparing localized with generic allometric models.** Forests. 7(5): 96. https://doi.org/10.3390/f7050096.

Kline, J.R.; Reed, K.L.; Waring, R.H.; Stewart, M.L. 1973. **Direct measurement of transpiration and biomass in coniferous trees.** Tech. Rep. 123. Argonne, IL: Argonne National Laboratory. 15 p.

Kloeppel, B.D. 1998. **Carbon and nitrogen allocation and resource use efficiency in mixed *larix* spp. and evergreen conifer forests along a resource availability gradient.** Madison, WI: University of Wisconsin. 88 p. Ph.D. dissertation.

Koerper, G.J.; Richardson, C.J. 1980. **Biomass and net annual primary production regressions for *Populus grandidentata* on three sites in Northern lower Michigan.** Canadian Journal of Forest Research. 10(1): 92-101. https://doi.org/10.1139/x80-015.

Ku, T.T.; Wheeler, G.L.; Colvin, R.J.; Webb, B G. 1993. **Comparisons of biomass and nutrient accumulations in loblolly and shortleaf pines from an uneven aged pine forest in Arkansas.** In: Brissette, J., ed. Proceedings of the Seventh Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SO-93. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 287-292.

Landis, T.; Mogren, E.W. 1975. **Tree strata biomass of subalpine spruce-fir stands in southwestern Colorado.** Forest Science. 21(1): 9-12.

Laxson, J.D.; Schacht, W.H.; Owens, M.K. 1997. **Above-ground biomass yields at different densities of honey mesquite.** Journal of Range Management. 50(5): 550-554. https://doi.org/10.2307/4003712.

Levia, D.F. 2008. **A generalized allometric equation to predict foliar dry weight on the basis of trunk diameter for eastern white pine (*Pinus strobus* L.).** Forest Ecology and Management. 255(5-6): 1789-1792. https://doi.org/10.1016/j.foreco.2007.12.001.

Lohrey, R.E. 1972. **Precommercial thinning of direct-seeded loblolly pine.** Res. Note. SO-139. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 4 p.

Lohrey, R.E. 1985. **Aboveground biomass of planted and direct-seeded slash pine in the west gulf region.** Res. Pap. Pineville, LA: United States Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 7 p.

Lojewski, N.R.; Fischer, D.G.; Bailey, J.K.; Schweitzer, J.A; Whitham, T.G.; Hart, S.C. 2009. **Genetic basis of aboveground productivity in two native *Populus* species and their hybrids.** Tree physiology. 29(9): 1133-1142. https://doi.org/10.1093/treephys/tpp046.

Loomis, R.M.; Blank, R.W. 1981. **Estimating northern red oak crown component weights in the northeastern United States.** Res. Pap. NC-194. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 12 p.

Loomis, R.M.; Phares, R.E.; Crosby, J.S. 1966. **Estimating foliage and branchwood quantities in shortleaf pine.** Forest Science. 12(1): 30-39.

Lykins, R.W. 1995. **Estimation of aboveground eastern redcedar biomass.** Stillwater, OK: Oklahoma State University. 30 p. M.S. thesis.

Mack, M.C.; Treseder, K.K.; Manies, K.L.; Harden, J.W.; Schuur, E.A.G.; Vogel, J.G.; Randerson, J.T.; Chapin, F.S., III. 2008. **Recovery of aboveground plant biomass and productivity after fire in mesic and dry black spruce forests of Interior Alaska.** Ecosystems. 11: 209-225. https://doi.org/10.1007/s10021-007-9117-9.

Madgwick, H.A.I.; Kreh, R.E. 1980. **Biomass estimation for Virginia pine trees and stands.** Forest Science. 26(1): 107-111.

Madgwick, H.A.I.; Olah, F.D.; Burkhart, H.E. 1977. **Biomass of open-grown Virginia pine.** Forest Science. 23(1): 89-91.

Maguire, D.A; Brissette, J.C.; Gu, L. 1998. **Crown structure and growth efficiency of red spruce in uneven-aged, mixed-species stands in Maine.** Canadian Journal of Forest Research. 28(8): 1233-1240. https://doi.org/10.1139/cjfr-28-8-1233.

Manis, S.V. 1977. **Biomass and nutrient distribution within plantation and natural slash pine stands on wet coastal sites.** Gainesville, FL: The University of Florida. 142 p. M.S. thesis.

Marks, P.L. 1971. **The role of *Prunus pennsylvanica* L. in the rapid revegetation of disturbed sites.** New Haven, CT: Yale University. 116 p. Ph.D. dissertation.

Marrs, G R. 1980. **North Carolina biomass study.** Unpublished personal communication.

Martin, J.G.; Kloeppel, B.D.; Schaefer, T.L.; Kimbler, D.L.; McNulty, S.G. 1998. **Aboveground biomass and nitrogen allocation of ten deciduous southern Appalachian tree species.** Canadian Journal of Forest Research. 28(11): 1648-1659. https://doi.org/10.1139/x98-146.

McElligott, K.M.; Bragg, D.C. 2013. **Deriving biomass models for small-diameter loblolly pine on the Crossett Experimental Forest.** Journal of the Arkansas Academy of Science. 67: 94-102.

McNab, W.H. 1981. **Total tree and firewood weights and volumes of scrub oaks in the Georgia sandhills.** Georgia Forest Res. Pap. 22. Dry Branch, GA: Georgia Forestry Commission, Research Division. 15 p.

McNab, W.H.; Berry, C.R. 1985. **Distribution of aboveground biomass in three pine species planted on a devastate site amended with sewage sludge or inorganic fertilizer.** Forest Science. 31(2): 373-382.

McNab, W.H.; Clark, A., III. 1982**. Total tree and major component green weight of white pine and hemlock in north Georgia.** Georgia Forest Res. Pap. 31. Dry Branch, GA: Georgia Forestry Commission, Research Division. 14 p.

McNab, W.H.; Outcalt, K.W.; Brendemuehl, R.H. 1985. **Weight and volume of plantation-grown Choctawhatchee sand pine.** Res. Pap. SE-252. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Research Station. 44 p. https://doi.org/10.2737/SE-RP-252.

Mead, D.J. 1971. **Movement of added nitrogen and phosphorus in a pine forest ecosystem.** Gainesville, FL: University of Florida. 266 p. Ph.D. dissertation.

Metz, L.J.; Wells, C.G. 1965. **Weight and nutrient content of the aboveground parts of some loblolly pines.** Res. Pap. SE-17. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 21 p.

Meyer, S.R. 2005. **Leaf area as a growth predictor of *Abies balsamea* and *Picea rubens* in managed stands in Maine.** Orono, ME: University of Maine. 117 p. M.S. thesis.

Miller, E.L.; Meeuwig, R.O.; Budy, J.D. 1981. **Biomass of singleleaf pinyon and Utah juniper.** Res. Pap. INT-273. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experimental Station. 18 p. https://doi.org/10.2737/INT-RP-273.

Mitchell, R.J.; Wilson, C.A.; Hendricks, J.J.; Boring, L.R. 1999. **Patterns and controls of ecosystem function in longleaf pine wire grass savannas. 1. Aboveground net primary production.** Canadian Journal of Forest Research. 29(29): 743-751. https://doi.org/10.1139/x99-051.

Mitsch, W.J.; Ewel, K.C. 1979**. Comparative biomass growth of cypress in Florida wetlands.** American Midland Naturalist. 101(2): 417-426. https://doi.org/10.2307/2424607.

Monserud, R.A; Marshall, J.D. 1999. **Allometric crown relations in three northern Idaho conifer species.** Canadian Journal of Forest Research. 29(5): 521-535. https://doi.org/10.1139/x99-015.

Monteith, D.B. 1979. **Whole tree weight tables for New York.** AFRI Res. Pap. 40. Syracuse, NY: State University of New York, College of Environmental Science and Forestry, Applied Forestry Research Institute.

Mroz, G.D.; Gale, M.R.; Jurgensen, M.F.; Frederick, D.J.; Clark, A., III. 1985. **Composition, structure, and aboveground biomass of two old growth northern hardwood stands in upper Michigan.** Canadian Journal of Forest Research. 15(1): 78-82. https://doi.org/10.1139/x85-014.

Mueller, C.W. 1976. **The accumulations of dry matter in plantations of eastern cottonwood on alluvial sites of the Mississippi river valley.** Starkville, MS: Mississippi State University. 87 p. M.S. thesis.

Myers, C.; Polak, D.J.; Raisanen, D.; Schlesinger, R.C.; Stortz, L.S. 1980. **Weight and volume equations and tables for six upland hardwoods in southern Illinois.** Gen. Tech. Rep. NC-60. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 17 p.

Naidu, S.L.; DeLucia, E.H.; Thomas, R.B.1998. **Contrasting patterns of biomass allocation in dominant and suppressed loblolly pine.** Canadian Journal of Forest Research. 28(8): 1116-1124. https://doi.org/10.1139/x98-083.

Nay, S.M.; Bormann, B.T. 2014**. Site-specific Douglas-fir biomass equations from the Siskiyou Mountains, Oregon, compared with others from the Pacific Northwest.** Forest Science. 60: 1140-1147. https://doi.org/10.5849/forsci.13-084.

Neisch, D.A. 1980**. Estimating aboveground biomass for shortleaf and loblolly pines in east Texas.** Nacogdoches, TX: Austin State University. 62 p. M.S. thesis.

Nelson, A. 2013. **Production ecology and stand dynamics of young Acadian forest stands in response to silvicultural intensity and compositional objectives.** Tech. Bull. 73. Orono, ME: University of Maine.

Nelson, L.E.; Switzer, G.L. 1975. **Estimating weights of loblolly pine trees and their components in natural stands and plantations in central Mississippi.** Tech. Bull. 73. Mississippi State, MS: Mississippi Agricultural and Forestry Experiment Station. 14 p.

Nemeth, J.C. 1973. **Dry-matter production in young loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.) plantations.** Ecological Monographs. 43(1): 21-41. https://doi.org/10.2307/1942157.

Nicholas, N.S. 1992. **Stand structure, growth, and mortality in southern Appalachian spruce-fir.** Blacksburg, VA: Virginia Polytechnic Institute and State University. 35 p. Ph.D. dissertation.

Norris, M.D.; Blair, J.M.; Johnson, L.C.; McKane, R.B. 2001. **Assessing changes in biomass, productivity, and carbon and nitrogen stores following *Juniperus virginiana* forest expansion into tallgrass prairie.** Canadian Journal of Forest Research. 31(11): 1940-1946. https://doi.org/10.1139/x01-132.

Nowak, D.J. 1996. **Estimating leaf area and leaf biomass of open-grown deciduous urban trees.** Forest Science. 42(4): 504-507.

Nygaard, S.L. 1980. **Evaluation of a subsampling technique for crown nutrients and biomass of aspen.** Minneapolis, MN: University of Minnesota. 59 p. M.S. thesis.

Oderwald, R.G.; Yaussy, D.A. 1980. **Main stem green and dry weights of red oak, white oak, and maple in the Appalachian region of Virginia.** Publication No. FWS-3-80. Blacksburg, VA: Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources. 12 p.

Olah, F.D. 1972. **Growth characteristics of open-grown Virginia pine (*Pinus virginiana*, Mill.).** Blacksburg, VA: Virginia Polytechnic Institute and State University.

Oswald, B.; Botting, R.; Coble, D.; Farrish, K. 2010. **Aboveground biomass estimation for three common woody species in the post oak savannah of Texas.** Southern Journal of Applied Forestry. 34(2): 91-94.

Overton, W.S.; Lavender, D.P.; Herman, R.K. 1973. **Estimation of biomass and nutrient capital in stands of old-growth Douglas-fir.** Res. Pap. Corvallis, OR: Oregon State University, School of Forestry: 90-103.

Parker, G.; Schneider, G. 1975. **Biomass and productivity of an alder swamp in northern Michigan.** Canadian Journal of Forest Research. 5: 403-409. https://doi.org/10.1139/x75-055.

Pastor, J.; Bockheim, J.G. 1981.**Biomass and production of an aspen – mixed hardwood – spodosol ecosystem in northern Wisconsin.** Canadian Journal of Forest Research. 11(1): 132-138. https://doi.org/10.1139/x81-018.

Pehl, C.E. 1981. **The influence of site preparation upon production of young loblolly pine plantations in east Texas.** College Station, TX: Texas A&M University. 58 p. Ph.D. dissertation.

Perala, D.A.; Alban, D.H. 1994. **Allometric biomass estimators for aspen-dominated ecosystems in the upper Great Lakes.** Res. Pap. NC-314. Grand Rapids, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 42 p. https://doi.org/10.2737/NC-RP-314.

Phillips, D.R. 1977. **Total tree weights and volume for understory hardwoods.** Tappi. 60(6): 68-71.

Phillips, D.R. 1981**. Predicted total-tree biomass of understory hardwoods.** Res. Pap. SE-223. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 21 p.

Phillips, D.R.; McNab, H. W. 1982**. Total-tree green weights of sapling-size pines in Georgia.** Georgia Forest Res. Pap. 39. Dry Branch, GA: Georgia Forestry Commission, Research Division. 17 p.

Pienaar, L.V.; Grider, G.E. 1984**. Standard volume and weight equations for site-prepared loblolly pine plantations in the piedmont of South Carolina, Georgia and Alabama.** Tech. Rep. 1984-3. Athens, GA: University of Georgia, School of Forest Resources. 12 p.

Pienaar, L.V.; Harrison, W.M.; Rheney, J.W. 1990. **Volume, weight, and yield tables for slash pine plantations in southeastern coastal plain.** Georgia Forest Res. Pap. 78. Dry Branch, GA: Georgia Forestry Commission, Research Division. 47 p.

Queen, W.R.; Pienaar, L.V. 1977. **Green and dry stem weight equations for site-prepared slash pine plantations in the coastal plain of Georgia and North Florida.** Res. Pap. 1. Athens, GA: University of Georgia, School of Forest Resources. 55 p.

Ralston, C.W. 1973**. Annual primary productivity in a loblolly pine plantation.** Contribution No. 105. Funded by the National Science Foundation; agreement AG199, 40-193-69 with the Atomic Energy Commission, Oak Ridge Laboratory. From the Eastern Deciduous Forest Biome, International Biological Program (IBP).

Ramseur, G.S.; Kelly, J M. 1981. **Forest characterization and biomass estimates for two sites on the Cumberland Plateau.** Journal of the Tennessee Academy of Science. 56(3): 99-104.

Reams, G.A.; Sullivan, A.D.; Matney, T.G.; Stevens, R.R. 1982. **Estimating above-ground biomass of slash pine and sweetgum.** Tech. Bull. 110. Mississippi State, MS: Mississippi State University, Mississippi Agricultural & Forestry Experiment Station. 11 p.

Reed, D D.; Mroz, G.D.; Liechty, H.O.; Jones, E.A.; Cattelino, P.J.; Balster, N.J.; Zhang, Y. 1995. **Above- and below-ground biomass of precompetitive red pine in northern Michigan.** Canadian Journal of Forest Research. 25: 1064-1069. https://doi.org/10.1139/x95-117.

Reid, C.P.P; Odegard, J; Hokenstrom, J.C.; McConel, W.; Frayer, W. 1974**. Effects of clearcutting on nutrient cycling in lodgepole pine forests.** Res. Pap. Ft. Collins, CO: Colorado State University, College of Forestry and Natural Resources. 321 p.

Reinhardt, E; Keane, R.; Scott, J.; Brown, J.K. 2000. **Quantification of canopy fuels in conifer forests: assessing crown fuel characteristics using destructive and non-destructive methods.** Fire Effects Project RWU4403 Study Plan. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Lab, Missoula, MT.

Reynolds, P.; Carlson, K.G.; Fromm, T.W.; Gigliello, K.A.; Kaminski, R.J. 1978. **Phytosociology, biomass, productivity and nutrient budget for the tree stratum of a southern New Jersey hardwood swamp.** In: Pope, P.E., ed. Proceedings of Central Hardwood Forest Conference II. West LaFayette, IN: Purdue University: 123-129.

Ribe, J.H. 1979**. A study of multi-stage sampling and dimensional analysis of puckerbrush stands.** Tech. Bull. 1. Orono, ME: The University of Maine. 87 p.

Ritchie, M.W.; Zhang, J.; Hamilton, T.A. 2013. **Aboveground tree biomass for *Pinus ponderosa* in northeastern California.** Forests. 4(1): 179-196. https://doi.org/10.3390/f4010179.

Roberts, S D.; Dean, T.J.; Evans, D.L. 2003. **Family influences on leaf area estimates derived from crown and tree dimensions in *Pinus taeda*.** Forest Ecology and Management. 172(2-3): 261-270. https://doi.org/10.1016/s0378-1127(01)00796-4.

Roberts, S.D.; Friend, A.L.; Gerard, P.D. 2004. **The effect of large applications of nutrients from organic waste on biomass allocation and allometric relations in loblolly pine.** In: Connor, K.F., ed. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-71. Asheville, NC: U.S Department of Agriculture, Forest Service, Southern Research Station: 398-402.

Rockwood, D.L.; Conde, L.F.; Brendemuehl, R.H. 1980. **Biomass production of closely spaced Choctawhatchee sand pines.** Res. Note. SE-293**.** Asheville, NC: U.S Department of Agriculture, Forest Service, Southeast Forest Experiment Station. 5 p.

Roeh, R.L.; Maguire, D.A. 1997. **Crown profile models based on branch attributes in coastal Douglas-fir.** Forest Ecology and Management. 96(1-2): 77-100. https://doi.org/10.1016/s0378-1127(97)00033-9.

Rogerson, T.L. 1964. **Estimating foliage on loblolly pine.** Res. Note. SO-16. New Orleans, LA: U.S Department of Agriculture, Forest Service, Southern Forest Experiment Station. 3 p.

Rolfe, G.; Akhtar, M.; Arnold, L. 1978. **Nutrient distribution and flux in a mature oak-hickory forest.** Forest Science. 41: 122-130.

Roth, B.E. 2010. **Genotype x environment interactions in selected loblolly (*Pinus taeda* L.) and slash pine (*P. elliottii* Engelm. var. elliottii) plantations in the southeastern United States.** Gainesville, FL: University of Florida. 158 p. Ph.D. dissertation.

Rowell, C.E.; Carpenter, S.B. 1983. **Black locust biomass prediction on eastern Kentucky strip mines.** Southern Journal of Applied Forestry. 7(1): 27-30.

Ruark, G.; Bockheim, J.G. 1987. **Below-ground biomass of 10-, 20-, and 32-year-old *Populus tremuloides* in Wisconsin.** Pedobiologia. 30: 207-217.

Ruark, G.; Bockheim, J.; Martin, G. 1987. **Comparison of constant and variable allometric ratios for estimating *Populus tremuloides* biomass.** Forest Science. 33(2): 294-300.

Rubilar, R.A. 2003. **Biomass and nutrient accumulation comparison between successive loblolly pine rotation on the upper coastal plain** of Alabama. Raleigh, NC: North Carolina State University. 55 p. M.S. thesis.

Sabatia, C.O. 2007. **Effect of thinning on partitioning of aboveground biomass in naturally regenerated shortleaf pine (*Pinus echinata* mill.).** Eldoret, Kenya: Moi University. 70 p. M.S. thesis.

Sachs, D. 1983. **Management effects on nitrogen nutrition and long-term productivity of western hemlock stands: an exercise in simulation with FORCYTE.** Oregon State University. M.S. thesis.

Samuelson, L.J.; Johnsen, K.; Stokes, T. 2004. **Production, allocation, and stemwood growth efficiency of *Pinus taeda* L. stands in response to 6 years of intensive management.** Forest Ecology and Management. 192(2004): 59-70. https://doi.org/10.1016/j.foreco.2004.01.005.

Santee, W.R. 1970. **A dimensional analysis of eastern hemlock.** Athens, GA: Adolphus College. 48 p. M.S. thesis.

Saucier, J.R.; Boyd, J.A. 1982. **Aboveground biomass of Virginia pine in North Georgia.** Res. Pap. SE-232. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Saucier, J.R.; Clark, A. 1970. **Wood density surveys of the minor species of yellow pine in the eastern United States: Part IV--Pitch pine (*Pinus rigida* Mill.)** Res. Pap. SE-63. Asheville, NC: U.S Department of Agriculture, Forest Service, Southeastern Experiment Station. 10-16.

Schlaegel, B E. 1975a. **Yields of four 40-year-old conifers and aspen in adjacent stands.** Canadian Journal of Forest Research. 5(2): 278-280. https://doi.org/10.1139/x75-037.

Schlaegel, B.E. 1975b. **Estimating aspen volume and weight for individual trees, diameter classes or entire stands.** Gen. Tech. Rep. NC-20. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 16 p.

Schlaegel, B.E. 1981. **Willow oak volume and weight tables for Mississippi delta.** Res. Pap. SO-173. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 14 p. https://doi.org/10.2737/SO-RP-173.

Schlaegel, B.E. 1984a**. Overcup oak volume and weight tables.** Res. Pap. SO-204. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 13 p.

Schlaegel, B.E. 1984b. **Green ash volume and weight tables.** Res. Pap. SO-206. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 12 p. https://doi.org/10.2737/SO-RP-206.

Schlaegel, B.E. 1984c. **Sugarberry volume and weight tables.** Res. Pap. SO-205. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 15 p. https://doi.org/10.2737/SO-RP-205.

Schlaegel, B.E. 1984d. **Sweetgum volume and weight tables.** Res. Pap. SO-204. New Orleans, LA. US Department of Agriculture, Forest Service, Southern Experiment Station. 18 p.

Schlaegel, B.E. (N.d.). **Schlaegel MS dataset**. Unpublished data.

Schlaegel, B.E.; Kennedy, H.E. 1986. **Deriving biomass estimation equations for seven plantation hardwood species.** In: Rockwood, D.L., ed. Proceedings of the 1985 Southern Forest Biomass Workshop; 1985 June 11-14; Gainesville, FL. Gainesville, FL: Institute of Food and Agricultural Sciences, University of Florida: 31-39.

Schlaegel, B.E.; Willson, R.B. 1983. **Nuttall oak volume and weight tables.** Res. Pap. SO-186. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 14p. https://doi.org/10.2737/SO-RP-186.

Schmitt, M.D.C. 1979. **Biomass and elemental content distribution in fertilized and unfertilized *Betula papyrifera* Marsh. and *Populus grandidentata* Michx.** NY: State University of New York. M.S. thesis.

Schnell, R.L. 1976. **Biomass estimates of eastern redcedar tree components**. Tech. Note B15. Norris, TN: Tennessee Valley Authority, Division of Forestry, Fisheries, and Wildlife Development.

Schnell. R.L. 1978. **Biomass estimates of hickory tree components.** Tech. Note B30. Norris, TN: Tennessee Valley Authority, Division of Forestry, Fisheries, and Wildlife Development.

Seiler, T.J.; Rasse, D.P.; Li, J.; Dijkstra, P.; Anderson, H.P.; Johnson, D.P.; Powell, T. L.; Hungate, B.A.; Hinkle, C.R.; Drake, B.G. 2009. **Disturbance, rainfall and contrasting species responses mediated aboveground biomass response to 11 years of CO2 enrichment in a Florida scrub-oak ecosystem.** Global Change Biology. 15: 356-367. https://doi.org/10.1111/j.1365-2486.2008.01740.x.

Shannon, C.A. 1976. **Uptake and distribution of biomass and nutrient elements in balsam fir.** University of Minnesota. M.S. thesis.

Shelton, M.G.; Nelson, L.E.; Switzer, G.L. 1984. **The weight, volume and nutrient status of plantation-grown loblolly pine trees in the interior flatwoods of Mississippi.** Tech. Bull. 121. Mississippi State, MS: Mississippi State University, Mississippi Agricultural & Forestry Experiment Station. 18 p.

Shenoy, A.; Johnstone, J.F.; Kasischke, E.S.; Kielland, K. 2011**. Persistent effects of fire severity on early successional forests in interior Alaska.** Forest Ecology and Management. 261(3): 381-390. https://doi.org/10.1016/j.foreco.2010.10.021.

Sillett, S.C.; Van-Pelt, R.; Carroll, A.L.; Kramer, R.D.; Ambrose, A.R.; Trask, D. 2015. **How do tree structure and old age affect growth potential of California redwoods?** Ecological Monographs. 85(2): 181-212. https://doi.org/10.1890/14-1016.1.

Sillett, S.C.; Van-Pelt, R.; Koch, G.W.; Ambrose, A.R.; Carroll, A.L.; Antoine, M.E.; Mifsud, B.M. 2010**. Increasing wood production through old age in tall trees.** Forest Ecology and Management. 259(5): 976-994. https://doi.org/10.1016/j.foreco.2009.12.003.

Singer, F.P. 1964. **Accumulation of organic matter in red pine and Norway spruce plantations of various spacings.** University Park, PA: Pennsylvania State University. M.S. thesis.

Sirois, D.L. 1983. **Biomass of four hardwoods from lower Piedmont pine-hardwood stands in Alabama.** Gen. Tech. Rep. SO-46. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 22 p.

Smith, C.T. 1984. **Nutrient removal and soil leaching from a whole-tree harvest of a red spruce (*Picea rubens* Sarg.) balsam fir (*Abies balsamea* (L.) Mill.) stand in northcentral Maine.** Orono, ME: University of Maine. Ph.D. dissertation. 212 p.

Smith, J H.G. 1962. **The net dry weight production and nitrogen uptake of even-aged loblolly pine (*Pinus taeda* L.) stands on sub-optimal sites.** Vancouver, BC: University of British Columbia: 400-410.

Smith, M.W.; Wood, B.W. 2006. **Pecan tree biomass estimates.** HortScience. 41(5): 1286-1291.

Snell, J.A.K.; Little, S.N. 1983**. Predicting crown weight and bole volume of five western hardwoods.** Gen. Tech. Rep. PNW-GTR-151. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 42 p. https://doi.org/10.2737/PNW-GTR-151.

Snell, J.A.K.; Max, T.A. 1985**. Estimating the weight of crown segments for old-growth Douglas-fir and western hemlock.** Res. Pap. PNW-329. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 28 p. https://doi.org/10.2737/PNW-RP-329.

Sollins, P.; Anderson, R.M. 1971. **Dry-weight and other data for trees and woody shrubs of the southeastern United States.** Report ORNL-IBP-71-6. Oak Ridge, TN: Oak Ridge National Laboratory. 80 p.

St. Clair, J.B. 1993. **Family differences in equations for predicting biomass and leaf area in Douglas-fir (*Pseudotsuga menziesii* var. menziesii).** Forest Science. 39(4): 743-755.

Stancioiu, P.T.; O'Hara, K.L. 2005. **Sapwood area-leaf area relationships for coast redwood.** Canadian Journal of Forest Research. 35(5): 1250-1255. https://doi.org/10.1139/x05-039.

Starks, P.J.; Venuto, B.C.; Eckroat, J.A.; Lucas, T. 2011**. Measuring eastern redcedar (*Juniperus virginiana* L.) mass with the use of satellite imagery**. Rangeland Ecology & Management. 64(2): 178-186. https://doi.org/10.2111/rem-d-10-00057.1.

Storey, T.G.; Bush, A.F.; Leonard, J.J.; Yundt, W.H. 1969**. An investigation of mass fire (1964-1967).** On file with: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA. 100 p.

Storey, T.G.; Fons, W.L.; Sauer, F.M. 1955. **Crown characteristics of several coniferous tree species: relations between weight of crown, branchwood and foliage and stem diameter.** Interim Technical Report AFSWP – 416. On file with: U.S. Department of Agriculture, Forest Service, Division of Fire Research. 84 p.

Stortz, L.A. 1975**. Total tree volume and weight equations and tables for four upland hardwoods in southern Illinois.** Carbondale, IL: Southern Illinois University. M.S. thesis.

Sundahl, W.E. 1966**. Crown and tree weight of madrone, black oak and tan oak.** Res. Note. PSW-101. Berkley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 4 p.

Swank, W.T.; Schreuder, H.T. 1974. **Comparison of three methods of estimating surface area and biomass for a forest of young eastern white pine.** Forest Science. 20(1): 91-100.

Swindel, B.F.; Hollis, C.A., III; Conde, L.F.; Smith, J.E. 1979**. Aboveground live biomass of slash pine trees in natural stands. IMPAC reports 4(1).** Gainesville, FL: University of Florida.

Taras, M.A. 1980. **Aboveground biomass of Choctawhatchee sand pine in northwest Florida.** Res. Pap. SE-210. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 23 p. https://doi.org/10.2737/SE-RP-210.

Taras, M.A.; Saucier, J.R. 1968. **Wood density surveys of minor species of yellow pine in the eastern United States: part I – spruce pine (*Pinus glabra* Walt.).** Res. Pap. SE-34. Asheville, NC: U.S. Department of Agriculture, Forest Service. 15 p.

Taras, M.A.; Saucier, J.R. 1970. **Wood density surveys of the minor species of yellow pine in the eastern United States: Part VI – pond pine (*Pinus serotina* Michx.).** Res. Pap. SE-65. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Terry, H.M. 1976. **Volume and weight equations for old-field loblolly pine plantations in the central gulf coastal plain.** Starkville, MS: Mississippi State University. M.S. thesis.

Tew, D.T.; Morris, L.A.; Allen, H. L.; Wells, C.G. 1986**. Estimates of nutrient removal displacement and loss resulting from harvest and sites preparation of a *Pinus taeda* plantation in the piedmont of North Carolina.** Forest Ecology and Management. 15(4): 257-267. https://doi.org/10.1016/0378-1127(86)90163-5.

Thies, W.G.; Cunningham, P.G. 1996. **Estimating large root biomass from stump and breast-height diameters for Douglas-fir in western Oregon.** Canadian Journal of Forest Research. 26(2): 237-243. https://doi.org/10.1139/x26-027.

Thomas, C.E.; Parresol, B.R.; Lê, Kim H.N.; Lohrey, R.E. 1995**. Biomass and taper for trees in thinned and unthinned longleaf pine plantations.** Southern Journal of Applied Forestry. 1(19): 29-35.

Tossey, G.B. 1982. **Biomass equations of small trees of four rocky mountain species with reference to habitat.** Fort Collins, CO: Colorado State University. M.S. thesis.

Tuskan, G. A. 1980**. Genetic variation and prediction equations for biomass components in plantation-grown American sycamore.** Starkville, MS: Mississippi State University. M.S. thesis.

Tuskan, G.A.; Rensema, R.R. 1992. **Clonal differences in biomass characteristics, coppice ability, and biomass prediction equations among four *Populus* clones grown in eastern North Dakota .** Canadian Journal of Forest Research. 22(3): 348-354. https://doi.org/10.1139/x92-045.

U.S.D.A. Forest Service. 1986. Unpublished data from University of Georgia (UGA) planted loblolly pine biomass study 50.

Vaidya, M.S.L. 1961**. Dry matter production and nutrient accumulation in plantations of shortleaf pine.** Durham, NC: Duke University. Ph.D. dissertation.

Van, T.K.; Rayachhetry, M.B.; Center, T.D.; Van, T.K. 2000. **Estimating above-ground biomass of *Melaleuca quinquenervia* in Florida, USA.** Journal of Aquatic Plant Management. 38: 62-27.

Van Gurp, K.P. 1984**. Biomass and elemental content of Picea abies (L.) karst growing in unthinned stands in central New York.** State University of New York. M.S. thesis.

Van Lear, D.H.; Waide, J.B.; and Teuke, M.J. 1984. **Biomass and nutrient content of a 41-year-old loblolly pine (*Pinus taeda* L.) plantation in South Carolina.** Forest Science 30: 395-404.

Wade, D.D. 1969**. Estimating slash quantity from standing loblolly pine.** Res. Note SE-125. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 4 p.

Wartluft, J.L. 1977. **Weights of small Appalachian hardwood trees and components.** Res. Pap NE-366. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 4 p.

Wartluft, J.L. 1978**. Estimating top weights of hardwood sawtimber.** Res. Pap NE-427. Broomall, PA: United States Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 7 p.

Weaver, A.T.; Forcella, F. 1977. **Biomass of fifty conifer forests and nutrient exports associated with their harvest.** The Great Basin Naturalist. 37(3): 395-401.

Wendel, G.W. 1960. **Fuel weights of pond pine crowns.** Res. Notes. SE-149. Asheville, NC: U.S. Department of Agriculture, Forest Service. Southeastern Forest Experiment Station. 2 p.

Westman, W. 1987. **Aboveground biomass, surface area, and production relations of red fir (*Abies magnifica*) and white fir (*A. concolor*).** Canadian Journal of Forest Research. 17(4): 311-319. https://doi.org/10.1139/x87-052.

Westman, W.E.; Whittaker, R.H. 1975. **The pygmy forest region of northern California: studies on biomass and primary productivity.** Journal of Ecology. 63(2): 493-520. https://doi.org/10.2307/2258732.

Whittaker, R.H. 1956. **Vegetation of the Great Smoky Mountains.** Ecological Monographs. 26(1): 1-80. https://doi.org/10.2307/1943577.

Whittaker, R.H.; Bormann, F.H.; Likens, G.E.; Siccama, T.G. 1974. **The Hubbard Brook ecosystem study: forest biomass and production.** Ecological Monographs. 44(2): 233-254. https://doi.org/10.2307/1942313.

Whittaker, R.H.; Niering, W.A. 1975. **Vegetation of the Santa Catalina Mountains, Arizona. V. Biomass, production, and diversity along the elevation gradient.** Ecology. 56(4): 771-790. https://doi.org/10.2307/1936291.

Whittaker, R.H.; Woodwell, G.M.. 1968. **Dimension and production relations of trees and shrubs in the Brookhaven Forest, New York**. Journal of Ecology. 56(1): 1-25. https://doi.org/10.2307/2258063.

Wiant, H.V. 1977. **Tables and procedures for estimating weights of some Appalachian hardwoods.** Tech. Bull. 659T. Morgantown, WV: West Virginia University, Agricultural and Forestry Experiment Station.

Williams, R.A. 1986. **Comparison of site index and biomass production on four soil drainage classes from the Chesuncook catena for spruce-fir stands in northwestern Maine.** Orono, ME: University of Maine. Ph.D. dissertation.

Williams, R.A.; Gresham, C.A. 2006. **Biomass accumulation in rapidly growing loblolly pine and sweetgum.** Biomass and Bioenergy. 30(4): 370-377. https://doi.org/10.1016/j.biombioe.2005.07.017.

Williams, R.A.; McClenehan, J.R. 1984. **Biomass prediction equations for seedling sprouts and sapling of ten central hardwood species.** Forest Science. 30(2): 523-527.

Willson, R.B.; Schlaegel, B.E.; Kennedy, H.E., Jr. 1982. **Individual tree biomass models for plantation grown American sycamore.** In: Baldwin, V.C.; Lohrey, R.E., eds. Southern Forest Biomass Working Group Workshop Proceedings reprint. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 89-94.

Witherspoon, J.P.J.; Auerbach, S.; Olson, J. 1962. **Cycling of cesium-134 in white oak trees on sites of contrasting soil type and moisture.** Report ORNL-3328. Oak Ridge, TN: Oak Ridge National Laboratory. 163 p. https://doi.org/10.2172/4767344.

Wood, G.W. 1971. **Biomass, production and nutrient distribution in mixed-oak stands following clearcutting and fire.** State College, PA: The Pennsylvania State University. Ph.D. dissertation.

Woodard, P.M. 1974. **Predicting crown slash weights.** Seattle, WA: University of Washington. 40 p. M.S. thesis.

Woods, K.D.; Feiveson, A.H.; Botkin, D.B. 1991**. Statistical error analysis for biomass density and leaf area index estimation.** Canadian Journal of Forest Research. 21(7): 974-989. https://doi.org/10.1139/x91-135.

Xydias, G.K. 1964. **Dry matter and nutrient element relations in *Pinus resinoa* ait. plantations.** Syracuse, NY: Syracuse University. M.S. thesis.

Yarie, B.J.; Kane, E.; Hall, B. 2007. **Aboveground biomass equations for the trees of interior Alaska.** Tech. Bull. 115. Fairbanks, AK: Alaska Agricultural and Forestry Experiment Station.

Young, H.E. 1981. **Quantifying forest science with biomass: III. Estimation of needle weight by age classes.** Proceedings of the Working party on forest biomass, XVII IUFRO World Congress. Kyoto, Japan: IUFRO.

Young, H.E.; Ribe, J.H.; Wainwright, K. 1980. **Weight tables for tree and shrub species in Maine.** Orono, ME: University of Maine, Life Sciences and Agriculture Experimental Station.

Zaebst, T.W. 1997. **Recovery status of a cypress (*Taxodium distichum*)-water tupelo (*Nyssa aquatica*) wetland seven years after harvest disturbance.** Blacksburg, VA: Virginia Polytechnic Institute and State University. M.S. thesis.

Zavitowski, J.; Stevens, R.D. 1972**. Primary productivity of red alder ecosystems.** Ecology. 53(2): 235-242. https://doi.org/10.2307/1934076.

Zhang, Y.; Borders, B.E.; Bailey, R.L. 2002. **A compatible stem taper-volume-weight system for intensively managed fast growing loblolly pine.** Forest Science. 48(3): 595-607.

Zhou, X.; Brandle, J.R.; Awada, T.N.; Schoeneberger, M.M.; Martin, D.L.; Xin, Y.; Tang, Z. 2011. **The use of forest-derived specific gravity for the conversion of volume to biomass for open-grown trees on agricultural land.** Biomass and Bioenergy. 35(5): 1721-1731. https://doi.org/10.1016/j.biombioe.2011.01.019.

Zimmerman, G.L. 1979**. The wood and bark biomass and production of *Populus tremuloides*, *Abies lasiocarpa*, and *Picea engelmannii* in northern Utah.** Logan, UT: Utah State University. M.S. thesis.

Appendix 2: Common and scientific names for species mentioned in the text and the 30 tree species with the most biomass in the FIADB

Common name[a]	Genus	Species	Full scientific name with authority[b]	FIA Species code[c]
Pacific silver fir	*Abies*	*amabilis*	*Abies Amabilis* Dougl. ex Forbes	11
White fir	*Abies*	*concolor*	*Abies concolor* (Gord. & Glend.) Lindl. Ex Hildebr.	15
Grand fir	*Abies*	*grandis*	*Abies grandis* (Dougl. ex D. Don) Lindl.	17
Subalpine fir	*Abies*	*lasiocarpa*	*Abies lasiocarpa* (Hook.) Nutt.	19
Engelmann spruce	*Picea*	*engelmannii*	*Picea engelmannii* Parry ex Engelm.	93
Sitka spruce	*Picea*	*sitchensis*	*Picea sitchensis* (Bong.) Carr.	98
Common or two-needle pinyon	*Pinus*	*edulis*	*Pinus edulis* Engelm.	106
Lodgepole pine	*Pinus*	*contorta*	*Pinus contorta* Dougl. ex. Loud.	108
Slash pine	*Pinus*	*elliottii*	*Pinus elliottii* Engelm.	111
Ponderosa pine	*Pinus*	*ponderosa*	*Pinus ponderosa* Dougl. ex Laws.	122
Eastern white pine	*Pinus*	*strobus*	*Pinus strobus* L.	129
Loblolly pine	*Pinus*	*taeda*	*Pinus taeda* L.	131
Douglas-fir	*Pseudotsuga*	*menziesii*	*Pseudotsuga menziesii* (Mirb.) Franco	202
Redwood	*Sequoia*	*sempervirens*	*Sequioa sempervirens* (D. Don) Endl.	211
Eastern hemlock	*Tsuga*	*canadensis*	*Tsuga canadensis* (L.) Carr.	261
Western hemlock	*Tsuga*	*heterophylla*	*Tsuga heterophylla* (Raf.) Sarg.	263
Mountain hemlock	*Tsuga*	*mertensiana*	*Tsuga mertensia* (Bong.) Carr.	264
Red maple	*Acer*	*rubrum*	*Acer rubrum* L.	316
Sugar maple	*Acer*	*saccharum*	*Acer saccharum* Marsh.	318
Birch spp.	*Betula*	spp.	*Betula* L.	370
Pignut hickory	*Carya*	*glabra*	*Carya glabra* (Mill.) Sweet	403
Shagbark hickory	*Carya*	*ovata*	*Carya ovata* (Mill.) K. Koch	407
Hackberry spp.	*Celtis*	spp.	*Celtis* L.	460
American beech	*Fagus*	*grandifolia*	*Fagus grandifolia* Ehrh.	531
Ash spp.	*Fraxinus*	spp.	*Fraxinus* L.	540
White ash	*Fraxinus*	*americana*	*Fraxinus americana* L.	541
Black ash	*Fraxinus*	*nigra*	*Fraxinus nigra* Marsh.	543
Green ash	*Fraxinus*	*pennsylvanica*	*Fraxinus pensylvanica* Marsh.	544
Sweetgum	*Liquidambar*	*styraciflua*	*Liquidambar styraciflua* L.	611
Yellow-poplar	*Liriodendron*	*tulipifera*	*Liriodendron tulipifera* L.	621
Cottonwood and poplar spp.	*Populus*	spp.	*Populus* L.	740
Quaking aspen	*Populus*	*tremuloides*	*Populus tremuloides* Michx.	746
Black cherry	*Prunus*	*serotina*	*Prunus serotina* Ehrh.	762
Oak spp.	*Quercus*	spp.	*Quercus* L.	800
White oak	*Quercus*	*alba*	*Quercus alba* L.	802
Scarlet oak	*Quercus*	*coccinea*	*Quercus coccinea* Muenchh.	806
Water oak	*Quercus*	*nigra*	*Quercus nigra* L.	827
Chestnut oak	*Quercus*	*prinus*	*Quercus prinus* L.	832
Northern red oak	*Quercus*	*rubra*	*Quercus rubra* L.	833
Post oak	*Quercus*	*stellata*	*Quercus stellata* Wangenh.	835
Black oak	*Quercus*	*velutina*	*Quercus velutina* Lam.	837
Elm spp.	*Ulmus*	spp.	*Ulmus* L.	970

[a] A list of all species examined in this analysis is available in Appendix S2 located in <u>supplemental tables file</u>.
[b] Scientific names from Burns and Honkala 1990a and 1990b.
[c] Forest Inventory and Analysis species codes (O'Connell et al. 2016).

When estimating tree-level biomass and carbon, it is common practice to develop generalized
models across numerous species and large spatial extents. However, sampling efforts are
generally incomplete and trees are not randomly selected. In this analysis, of the more
than 1,000 biomass-related articles that were reviewed, trees were destructively sampled
in over 300 studies to estimate biomass in the United States. Studies were summarized and
past sampling efforts were explored to illuminate where the largest data gaps occurred in
terms of tree components sampled, tree size, tree form, tree species, and location. The most
prominent gaps were in large trees, particularly in Douglas-fir trees in the Pacific Northwest.
In addition, tree roots were notably undersampled. Lastly, trees of poor or unusual form and
low vigor were often not sampled, and this may introduce a systematic bias if not dealt with
appropriately. More than 200 species did not have a biomass model or a single data point. The
gaps presented here can be viewed as suggestions for future destructive sampling efforts, but
the magnitude of a gap for a given model will ultimately depend on the selected modeling
framework and the user's objectives.

KEY WORDS: U.S. Forest Carbon Inventory, allometric modeling, tree component biomass,
gaps, tree form and vigor