# Improving North American Forest Biomass Estimates from Literature Synthesis and Meta-Analysis of Existing Biomass Equations

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***Abstract**: Thousands of published equations purport to estimate biomass of individual trees. These equations are often based on very small samples, however, and can provide widely different estimates for trees of the same species. We addressed this issue in a previous study by devising 10 new equations that estimated total aboveground biomass for all species in North America (Jenkins et al. 2003). We selected 318 total biomass equations (out of 2,626 identified in the literature), based on applicability for estimating biomass from only diameter measurements, and used a modified meta-analysis to develop new equations. This was done by using regression analysis on data generated from those 318 equations for tree sizes within the diameter bounds of the original data. We also included two sets of ratio equations, for hardwood and softwood species, to separate out biomass of different tree components—foliage, branches, bark, and roots.*

*The Joint Fire Science Program funded this work to create more generalized biomass equations for regional fire-fuels managers by extending our literature synthesis. We are updating our work with literature published through 2008. We will devise new equations to allow for more differences within North American regions and provide greater accuracy for local use. The new analysis will use equations from the literature that include height as well as diameter, but will result in biomass equations that do not require height as an input variable.*

*The results of our analyses to date suggest that allometric scaling theory may be applied in future studies to more accurately estimate tree biomass from diameter and whole-tree density measurements.*

**Keywords:** allometric equations, tree biomass, biomass estimation, tree carbon

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# Introduction

We previously developed a series of national-scale tree biomass estimation equations that can be used with inventory data for producing forest carbon budgets. We are updating this work for the Joint Fire Science Program, in an effort to develop generalized estimators for regional land management use. In the future, we plan to use allometric scaling theory to resolve issues associated with estimation of forest biomass.

# Previous Study

## Equation Compilation

In our previous work (Jenkins et al. 2003), we compiled biomass equations from literature published through 1999. Our resulting database included 2,626 biomass equations for either total tree biomass or tree components including bole, bark, branches, foliage, and roots. From the equation database, we determined 318 diameter-based equations for over 100 species from 104 published sources were useful for our analysis for estimating total aboveground biomass. In a modified meta-analysis, we generated data for each published equation at 5-cm intervals within the diameter ranges of the original equations—resulting in what we called "pseudodata" (following the concept pioneered by John Tukey on jackknife estimation [Mosteller and Tukey 1977]). We then fit these pseudodata into 10 species-group-specific equations by using regression and log transformation.

## Modeling pseudodata

Using a simple log form (Eq. 1) we modeled pseudodata with 5 equations for conifer species groups (cedar and larch, Douglas fir, pine, spruce, and true firs and hemlocks), 4 equations for hardwood groups (aspen, alder, and poplar; soft maple and birch; maple, oak, and hickory; and mixed hardwood), and a woodland equation including both conifer and hardwood dryland forest species.

$$\ln BM = a + b \ln dbh \qquad (1)$$

Where

BM = total biomass,
dbh = stem diameter at breast height

## Pine Pseudodata

Data from the pine species group illustrate our rationale for combining species into broad groups that corresponded to overlapping ranges within the pseudodata. The widely planted loblolly pine in the Southeastern United States has a biomass range that includes that of the much different pinyon and lodgepole pines found in the Western United States (Figure 1). This observed variation does not seem to be explained by other factors such as tree growth form, site, or climate; three distinct patterns would have been expected.

Because collecting new biomass samples across the full continental range of species and regions would be impractical, we concluded that fitting new equations using species-grouped pseudodata represented the most reasonable option for producing a consistent set of biomass equations for all North American species. We sorted through all pseudodata and distinguished 10 species groups for final equation development.

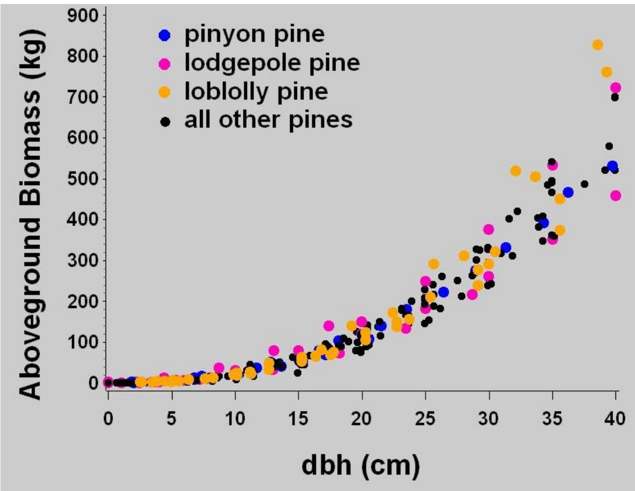


**Figure 1:** Modeled pseudodata depicting aboveground biomass of pinyon, lodgepole, and loblolly pines show no distinct pattern for separating species (biomass expressed in kg as a function of stem diameter at breast height; from Jenkins et al. [2003]).

## Component ratio equations

We also developed generalized hardwood and conifer ratio equations to partition the estimates into foliage, stem bark, stem wood, and coarse root components (Figure 2). The hardwood and conifer models are similar except the conifer model shows less branch variation with diameter and more foliage variation.

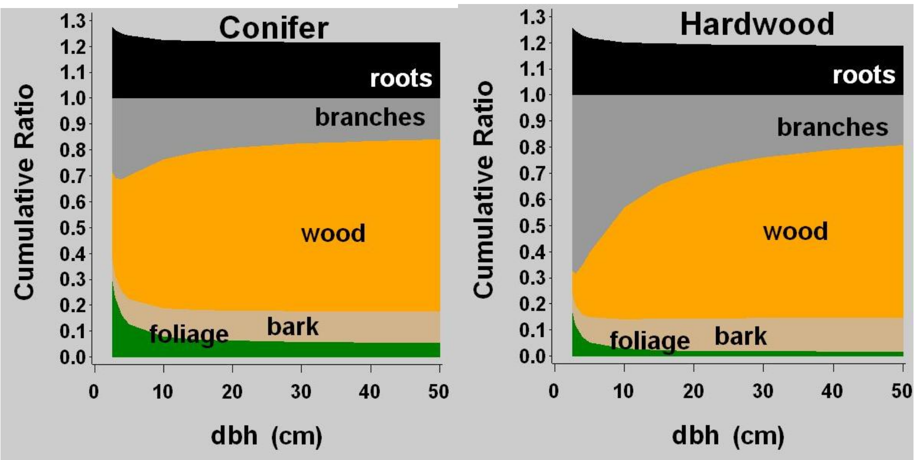


**Figure 2:** Biomass component ratios for conifer and hardwood species as a function of stem diameter at breast height, from equations in Jenkins et al. (2003).

Because pseudodata for biomass components were much more variable than for total biomass, and because there were few studies that measured biomass components in a consistent fashion, all pseudodata were grouped into two general models (hardwood and conifer). The resulting ratio equations serve as a first approximation until more data are available for detailed modeling of component biomass. The woodland species group, which included both conifer and hardwood species, was omitted from this analysis; there were not enough component equations in the literature for analysis with these species.

## FIA Data Comparison

We compared tree-level data results from the ten equations against county-scale biomass calculations from the old Eastwide FIA database from the 1990s (Hansen et al. 1992) by subtracting Hansen et al. (1992) biomass estimates from the Jenkins et al. (2003) biomass estimates, and then dividing by the latter and multiplying by 100 to express the results as a percentage (Figure 3).

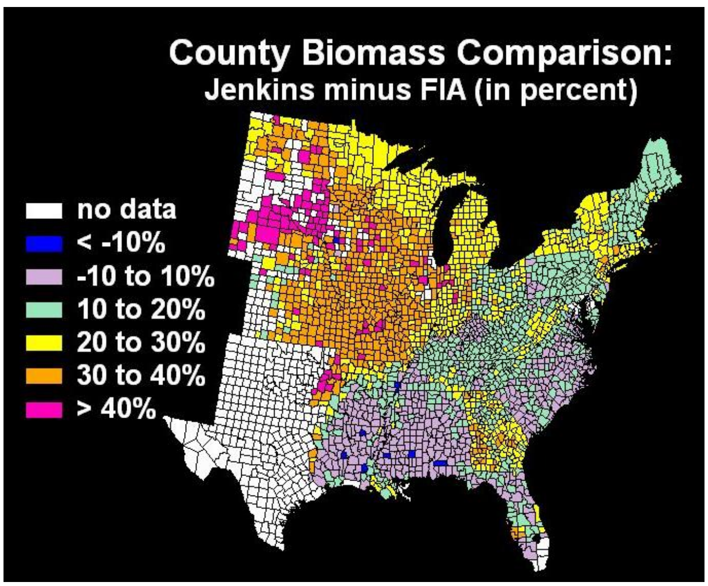


**Figure 3:** Amount Jenkins et al. (2003) biomass estimates generally exceed those of FIA (Hansen et al. 1992), expressed as a percent of Jenkins et al. (2003) estimates.

It is difficult to say which equations are better. Jenkins et al. (2003) equations used consistent methodology throughout, which is a plus, but unidentified, unquantified biases for certain species may exist. In the FIA approach, each FIA unit uses the best methods for a particular state or region. However, this is less consistent, particularly when equations change at state boundaries. For example, the map patterns in Figure 3 showing straight-line boundaries—particularly in the southeastern United States—suggest variation introduced by biomass equation choice. Also, FIA estimates should theoretically be a little smaller than those of Jenkins et al. (2003) because they do not include foliage, but foliage should account for only about 5%.

# Current Work

Our current objective is more focused toward regional biomass estimation for fire fuels managers, and will likely result in more than 10 equations. We are updating the literature synthesis to include data published through 2008.

We are also going back to the earlier literature to include previously omitted equations that use both diameter and height as predictor variables. Our initial plan is to generate pseudodata as before—based on diameter only—but to use a height-to-diameter equation for inclusion of height variation. We plan to use FIA data to develop a series of simple height-to-diameter equations for this purpose. This will allow use of biomass equations that include height but will also allow us to fit final regression equations from pseudodata from diameter only. Equations for predicting shrub biomass may be added to our analyses if resources permit.

# Allometric Scaling Theory Applied To Biomass Estimation

## Allometric Scaling Theory

Allometric scaling theory may hold promise for biomass estimation. This theory explains why dimensions of biological organisms are scaled in proportion to one another (Enquist et al. 1998, 1999; West et al. 1997, 1999a, 1999b). An analysis based on this theory could greatly improve our meta-analysis work. Tree biomass and volume are proportional to dbh, as are a host of other tree measures, but to date there is no coherent theory explaining exactly why this might be true. Allometric scaling theory uses fractal dimensions of tree architecture and physics of fluid transport up a tree to offer an explanation in terms of a generalized biomass model. Parameterization of this model is postulated to hold regardless of tree species and regardless of tree size.

## Generalized Tree Biomass Equation

The biomass equation described by allometric scaling theory (Eq. 2) suggests that the exponent on dbh is not a parameter to be estimated; rather, it is fixed at eight-thirds or 2.67.

$$\text{Biomass} = (C\,\rho)\,\text{dbh}^{2.67} \qquad (2)$$

Where

C = proportionality constant
$\rho$ = component-integrated tree specific gravity

The measure of specific gravity included here is not specific gravity of bole wood commonly reported, but a measure of specific gravity integrated over the entire tree and including bark, wood, branches, and foliage. We refer to this as "component-integrated tree specific gravity," or "CIT specific gravity." It would be difficult to obtain CIT specific gravity for every tree species in the United States. However, as the scaling theory is postulated to hold for small and large trees, CIT specific gravity might be measured for saplings of each species rather easily and cost-effectively. The proportionality constant C is postulated to be a constant independent of species.

### Allometric Theory Equation Applied

The 10 equations from Jenkins et al. (2003) can be expressed as a constant (α) times dbh raised to β, where β is the scaling coefficient in the allometric scaling model (Table 1). In 9 of our 10 biomass equations, the scaling parameter estimated from pseudodata is fairly close to the theoretical eight-thirds or 2.67 for the allometric scaling model. Only the woodland equation differs markedly; this is likely due to inconsistent biomass measurements for a diverse group of evergreen hardwood and some softwood species that grow in Southwestern U.S. dryland forests. Thus, anecdotal evidence indicates that allometric scaling theory may provide a sound theoretical basis for tree biomass estimation, but field measurements of biomass and whole-tree specific gravity of some trees are needed in order to apply it.

**Table 1**: Estimated β-values for Jenkins et al. (2003) equations expressed in the form of the allometric scaling equation: Biomass = $\alpha \text{ dbh}^{\beta}$, where dbh = stem diameter at breast height. In the generic allometric scaling model equation, β = 8/3 or 2.67.

| **Conifer** | | **Hardwood** | |
|---|---|---|---|
| **Species Group** | **β** | **Species Group** | **β** |
| Cedar and Larch | 2.3 | Aspen and Alder | 2.4 |
| Douglas Fir | 2.4 | Soft Maple and Birch | 2.4 |
| Pine | 2.4 | Maple, Oak, and Hickory | 2.4 |
| Spruce | 2.3 | Mixed Hardwood | 2.5 |
| True Fir and Hemlock | 2.5 | | |
| | | **Woodland** (both conifer and hardwood) | 1.7 |

## Summary

The goal of our work is to improve forest biomass estimates. To that end, we are pursuing the following:

- An update of our earlier database and synthesis of individual tree biomass equations for North America
- Development of regional-scale biomass equations that will include both diameter and height variation
- Future research considering allometric scaling theory as the basis for biomass estimation

## Acknowledgments

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