GAPS IN SAMPLING AND LIMITATIONS TO TREE BIOMASS ESTIMATION: A REVIEW OF PAST SAMPLING EFFORTS OVER THE PAST 50 YEARS

Aaron Weiskittel, Jereme Frank, James Westfall, David Walker, Phil Radtke, David Affleck, David Macfarlane[1]

Abstract—Tree biomass models are widely used but differ due to variation in the quality and quantity of data used in their development. We reviewed over 250 biomass studies and categorized them by species, location, sampled diameter distribution, and sample size. Overall, less than half of the tree species in Forest Inventory and Analysis database (FIADB) are without a published biomass model and most of the sampled trees are less than 13 inches diameter at breast height (d.b.h.). Although some species are well represented with biomass sampled, most focus on the aboveground components and as a result, there are important spatial gaps in their sampling as there was general divergence between the observed and sampled biomass centroids. In addition, most studies we analyzed did not sample trees of poor form or vigor, which means the models may not be representative of the larger population. Currently, this information is being used to address existing biomass sampling gaps in order to develop more robust prediction models.

Tree-level biomass models are generally derived by destructively sampling a subset of trees, drying and weighing their components, and using allometry to relate some easily measured metric (e.g., diameter) to the whole tree or component dry weight. Due to high costs, most biomass studies sample a small number of trees over a limited area, thus making extrapolation to different locations or larger areas difficult due to differences in climate, site characteristics, management practices, tree form, and other properties across the landscape. As such, those seeking to derive stand- and landscape-level biomass estimates generally rely on geographically generalized allometric models that use data from multiple studies and locations to refit models to a larger area (e.g., Schmitt and Grigal 1981) or use pseudo-data (Jenkins et al. 2003, Pastor et al. 1984).

In addition, many biomass studies group species to ensure an adequate sample size for model fitting. For example, the ratio estimators of Jenkins et al. (2003) were generalized for 10 species groups across the United States. In theory, generalized models should perform well at the scale for which they are developed, however, when applied to a single site or region or a particular species, errors could be high.

With the assumption that gaps in previous sampling efforts could cause generalized model bias, we formally examined the existing body of biomass literature. Our objectives were to document existing studies' coverage in terms of: 1) geography; 2) species; 3) components measured; 4) size and diameter distribution; and 5) sample size. We utilized USDA Forest Service FIA database (FIADB; O'Connell et al. 2014) for comparisons to a substantial compilation of destructively sampled "legacy" trees to assess gaps.

[1] Associate Professor (AW) and Research Assistant (JF), School of Forest Resources, 201 Nutting Hall, University of Maine, Orono, ME 04469-5755; Research Forester (JW), Northern Research Station, USDA Forest Service; Research Associate (DW)/ and Associate Professor (PR), Department of Forest Resources and Environmental Conservation, Virginia Tech University; Associate Professor (DA), College of Forestry and Conservation, University of Montana; and Associate Professor (DM), Department of Forestry, Michigan State University. AW is corresponding author: to contact, e-mail at aaron.weiskittel@maine.edu.

METHODS

For each published biomass study, we recorded the author, year, species, and location. All studies we examined were conducted in the United States. Sample size, average, minimum, and maximum tree diameter, and sampled components by location and species were noted. We examined each article to determine if tree sampling restrictions were imposed as evidenced by avoiding trees of poor form (e.g., low forks or broken tops), poor health (e.g., high risk of mortality, lacking vigor, or diseased).

Generally, we could estimate the geographic coordinates within 0.05°. However, for some articles, the coordinate precision was considerably lower because the location description was too general or area sampled too large. To assess whether the sampled biomass represented the biomass distribution across a species' range, we developed maps showing past biomass study locations for the 20 most voluminous eastern species and 10 most voluminous western species with FIA derived biomass per acre. The observed aboveground FIA biomass centroid and the derived legacy biomass centroid were also plotted.

The number of trees sampled was summarized by five specific geographic regions: 1) Northeast (NE); 2) Southeast (SE); 3) Inter-mountain West (IMW), 4) Pacific Northwest (PNW) and 5) North Central (NORCEN).

Although Wang (2014) identifies 47 different biomass component classes, eight major component groups were summarized in this analysis, which included: 1) stem wood; 2) stem bark; 3) total stem (wood & bark); 4) branch wood and bark; 5) total aboveground wood and bark (excluding foliage); 6) total aboveground (including foliage); 7) foliage; and 8) root biomass. As a metric for balancing the number of trees sampled (n_legacy) and the percentage of biomass across the landscape (pct_bio), we calculated a sampling completeness value (SCV) as n_legacy/pct_bio/10

RESULTS

We examined 262 studies with 43,006 trees. Thirty studies contained nearly 62 percent of these trees with the work of Clark et al. (1986) contributing nearly 5,000 trees and a comprehensive sampling across the SE. Young et al. (1980) sampled over 900 trees in Maine, while Perala and Alban (1980) sampled extensively across the Great Lakes region. To date, we have compiled original data from over 150 studies with over 15,000 trees.

There are models or legacy data for 166 of the 346 tree species in the Forest Inventory and Analysis database (FIADB). Preliminary estimates suggest that the top 20 species by volume comprise nearly 85 percent of the biomass in the FIADB and 47 percent of the trees destructively sampled in the literature. Though 95 percent of the trees are less than 13 inches diameter at breast height (d.b.h) (Fig. 1), 95 percent of the hardwood and conifer biomass in FIADB is contained in trees less than 26 inches and 43 inches d.b.h., respectively.

Of the 262 studies, we could not discern whether 175 studies (25,372 trees) sampled with restrictions. We determined that 42 studies (4,291 trees) imposed sampling restrictions while 45 studies (10,820 trees) were random in their selection methods. Generally, the restrictions were evidenced in methodologies that avoided trees that were open-grown, heavily defoliated, broken at the top, low-forked, diseased, or otherwise distorted.

Maps for four example species indicate a general divergence between the observed and sampled centroids (Fig. 2). The Allegheny Plateau was an observed center of species biomass. Only eight trees were sampled for red maple (*Acer rubrum* L.) in this area (Wood 1971) and none of the trees were over 11.8 inches d.b.h.

With regard to biomass components, we identified 24,412 trees that have been destructively sampled for above stump (≥ 0 inches) biomass across the United States (Table 1). Most of these trees (19,862) measured stem biomass, while 16,559 and 12,961 provided estimates of wood and bark, respectively. Branch and foliage biomass were estimated for 19,431 and 21,510 trees, respectively. A smaller number of trees contain estimates for total aboveground biomass (AGB)

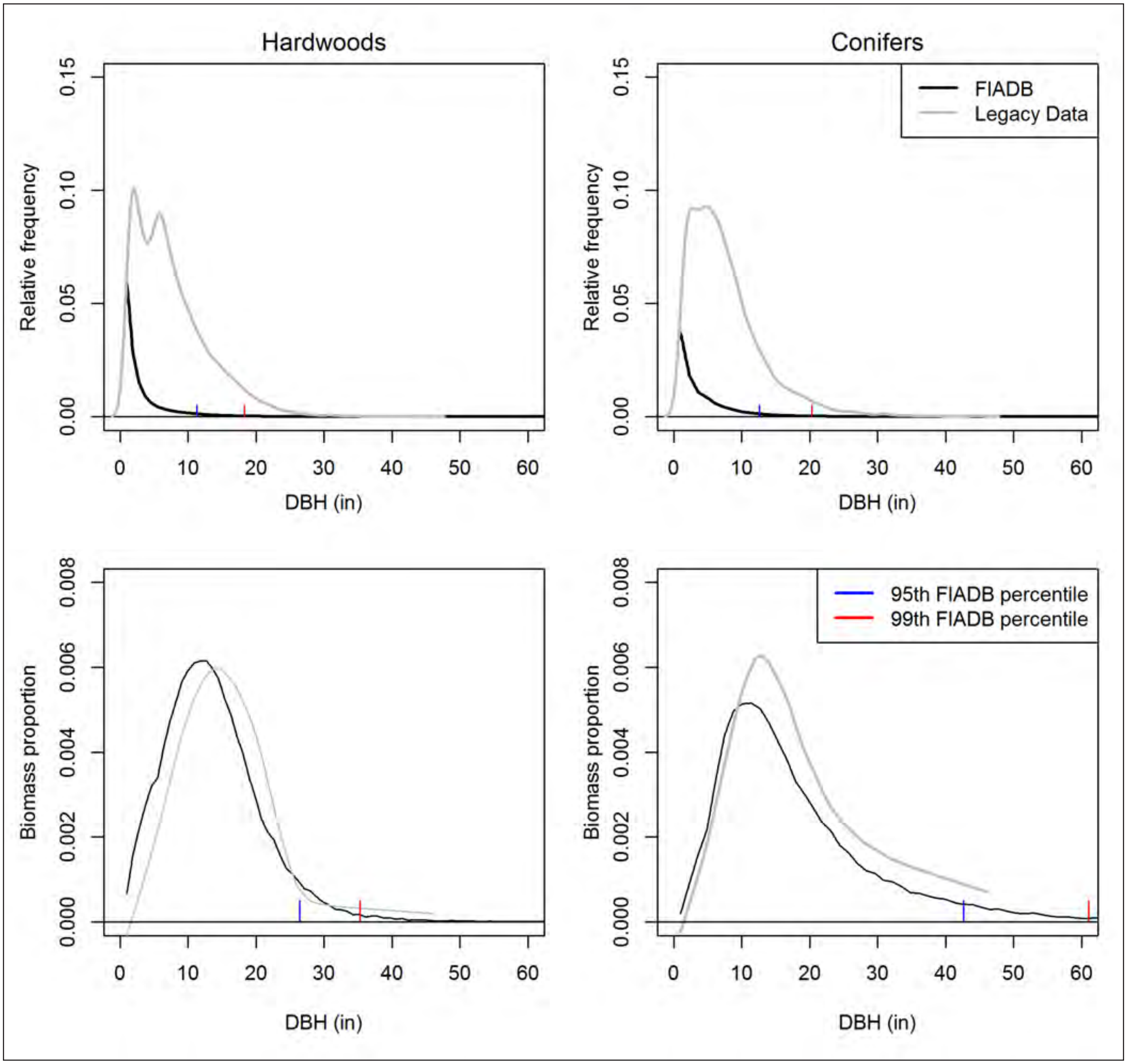

Figure 1—Comparison between the frequency of trees by diameter in the Forest Inventory and Analysis (FIA) database and legacy databases (top panels) for hardwoods and conifers. Bottom panels show the proportion of biomass by diameter in the FIA database.

leaving the stump component poorly represented. Although root biomass contain 17 percent of the whole tree (FIADB), it is largely under-sampled as only 3,834 trees had root biomass measurements.

Table 2 shows the FIADB proportion by species, region, and diameter class compared to the number of legacy trees sampled for aboveground wood and bark biomass. This summary is an estimation of biomass using the trees measured in the FIADB without accounting for the density of plots. Representation is good for the top 20 percent of biomass, but there is an obvious gap in large Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees. Certain hardwoods, such as sugar maple (*Acer saccharum* Marsh.) and northern red oak (*Querus rubra* L.) in the North Central region, and 10-20 inch d.b.h. red maple, and northern red oak in the Northeast, are relatively undersampled. SCVs indicate good representation for major species in the SE.

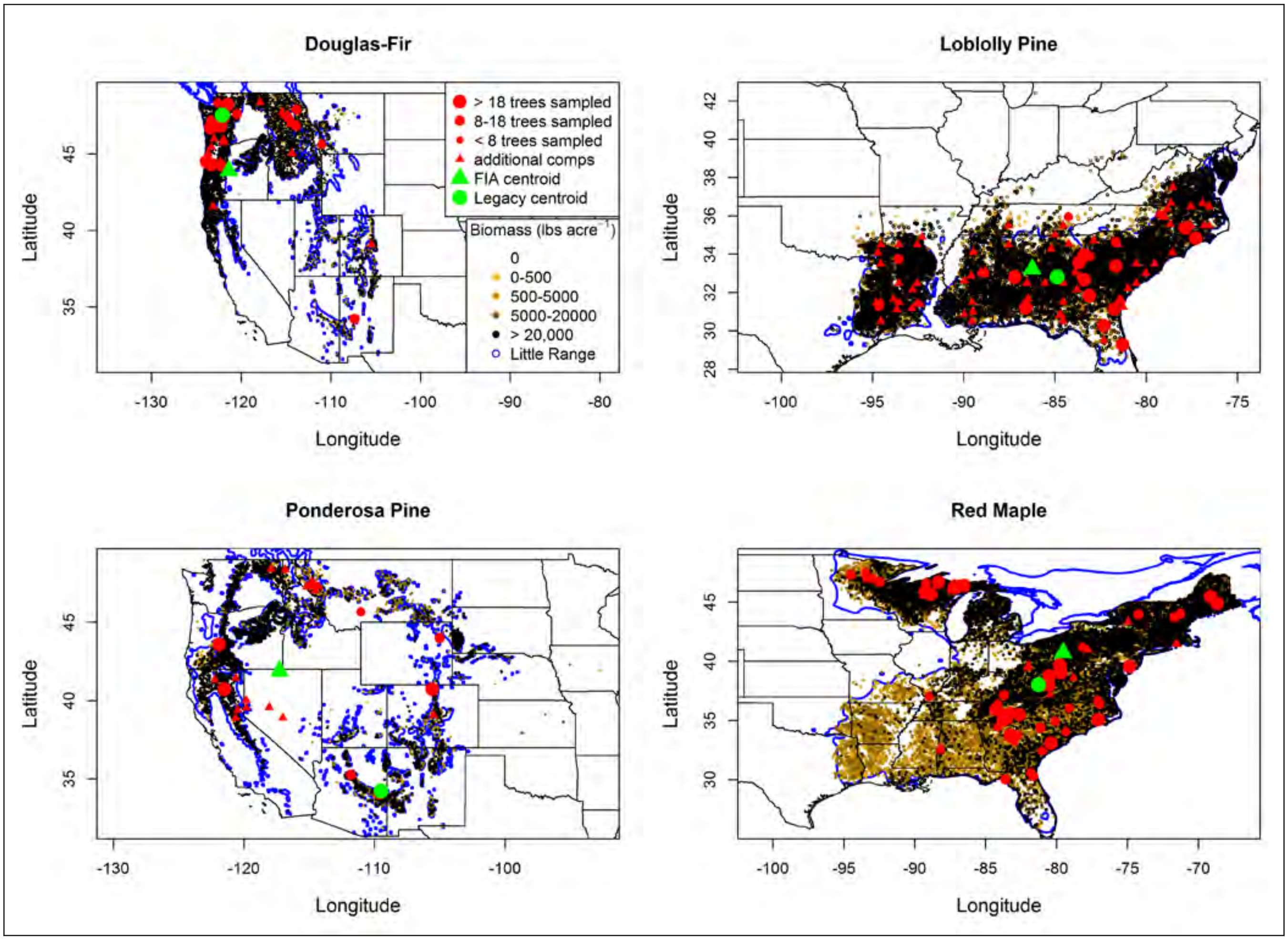

Figure 2—Known biomass study locations and maximum sample size sampled for the four most prevalent species by volume across the United States plotted over biomass per acre as estimated from the FIA database. Centroids are calculated only for studies with actual data.

DISCUSSION

Three primary sampling gaps were observed in this assessment: 1) larger diameter classes (>25 inches d.b.h.); 2) root biomass; and 3) spatial gaps. Examining the top four species by volume in the United States, we observed gaps in the southern Cascades in Douglas-fir. Sampling here would pull the legacy biomass centroid towards the FIA biomass centroid. Red maple studies were largely absent in the Allegheny Plateau and northern Michigan, while ponderosa pine observations were largely absent in eastern Oregon.

We present SCV to assess whether sampling intensity is sufficient. The largest gaps had a high percentage of biomass in the FIADB and low number of trees sampled. Consequently, the lower the SCV value the bigger the gap. Since funding poses a serious limitation for this type of research, we might set an SCV goal of 1 and assess how many trees, by grouping, need sampled. Where the SCV exceeds the SCV goal we would have a sufficient sample under this scenario. Otherwise we would prioritize trees with the lowest SCV (e.g., large Douglas-fir trees in the PNW, red oak in the NORCEN, and eastern white pine *(Pinus strobus* L.) in the NE).

Nearly half of the studies likely imposed some sort of sampling restriction. While the CRM method applies a cull volume deduction to the stem, most generalized biomass models do not obviously account for this and may overestimate for poorly formed unhealthy trees. We recommend that future studies examine how variation in tree form and health influences biomass and carbon content estimation.

FIA is currently sampling trees across the United States to fill in current species-, spatial-, and size-related gaps. Emphasis is on sampling large trees and recent work has been conducted in Pennsylvania, Oregon, and Michigan. The costs associated with destructively sampling trees can be incredibly high. As such, university partners are seeking additional collaborators to share resources and knowledge to achieve common goals.

LITERATURE CITED

Clark, A. I.; 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, Southern Research Station. 76 p.

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.

O'Connell, B. M.; LaPoint, E.B.; Turner, J.A.; Ridley, T.; Pugh, S.A.; Wilson, A.M.; Waddell, K.L.; Conkling, B.L. 2014. The forest inventory and analysis database: Database description and user guide version 6.0 for Phase 2. Washington, DC: U.S. Department of Agriculture, Forest Service. 632 p.

Pastor, J.; Aber, J.D.; Melillo, J.M. 1984. Biomass prediction using generalized allometric regressions for some northeast tree species. Forest Ecology and Management. 7:265–274.

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.

Schmitt, M. D. C.; Grigal, D.F. 1981. Generalized biomass estimation equations for Betula papyrifera Marsh. Canadian Journal of Forest Research. 11: 837–840.

Wang, Y. 2014. National biomass estimator library. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 18 p.

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

Young, H. E.; Ribe, J.H.; Wainwright, K. 1980. Weight tables for tree and shrub species in Maine. Misc. Rpt. 230. Orono, ME: University of Maine, Live Sciences and Agriculture Experiment Station. 84 p.