PREDICTING SMALL-DIAMETER LOBLOLLY PINE ABOVEGROUND BIOMASS IN NATURALLY REGENERATED STANDS

Kristin M. McElligott, Don C. Bragg, and Jamie L. Schuler

Abstract—There is growing interest in managing southern pine forests for both carbon sequestration and bioenergy. For instance, thinning otherwise unmerchantable trees in naturally regenerated pine-dominated forests should generate biomass without conflicting with more traditional forest products. However, we lack the tools to accurately quantify the biomass in these submerchantable size classes. To help remedy this, we destructively sampled 54 small-diameter loblolly pines (Pinus taeda L.) from stands on the Crossett Experimental Forest (CEF) in southeastern Arkansas. After harvesting, each tree was divided into stemwood, foliage and branch, and taproot components, then oven-dried and weighed. We then fit an exponential equation based on the National Biomass Estimator (NBE) to predict aboveground oven-dry biomass as a function of diameter at breast height (d.b.h.). The resulting model fit the sample data well (pseudo-R² = 0.996). Comparing the CEF local biomass model with the pine submodel of the NBE suggested that the NBE would consistently underestimate small-diameter loblolly pine biomass on the CEF. While this difference appeared small, its cumulative effect could be appreciable. For example, in a young loblolly pine stand averaging 5 cm d.b.h. and 5,000 stems ha⁻¹, the NBE would predict almost 9 percent less biomass than the new CEF biomass model—a difference of nearly 2 metric tons ha⁻¹. Such locally derived equations offer silviculturists opportunities to better assess the potential of naturally regenerated pine stands to produce fiber and thus may be worth the investment of time and resources to develop.

INTRODUCTION

To better understand the potential influence southern pine forests will have on emerging cellulosic biofuel, bioenergy, and carbon markets, it is imperative that we estimate the quantity of biomass stored in these forests as accurately as possible. Naturally regenerated pine-dominated forests present unique opportunities for these potential markets because they are often overstocked when young, and thinning otherwise unmerchantable material could generate some of the biomass needed to meet biofuel or bioenergy targets without conflicting with more traditional forest products (Koch and McKenzie 1976, Westbrook and others 2007). However, in many regions we lack the tools needed to quantify the biomass in these submerchantable size classes and are therefore unable to accurately estimate the fiber production, total biomass, or carbon in forests (Chaturvedi and Raghubanshi 2013, McGarrigle and others 2011).

Stand-level biomass is typically estimated from an allometric equation that predicts oven-dry biomass for individual stems based on diameter at breast height (d.b.h.) and then summed to yield biomass per unit land surface area (Whittaker and Woodwell 1968). Because of the growing need for landowners to quantify tree biomass, managers often apply equations from other regions, stand conditions, and species than those actually found on the site. Research has repeatedly shown that such application is less than ideal (Bragg 2011, Chave and others 2005, Crow and Schlaegel 1988, Melson and others 2011, Parresol 1999, Payadeh 1981, Ruark and others 1987, Zianis and others 2005) because model choice and implementation can dramatically impact estimates, and errors in biomass estimation can accumulate when used incorrectly [for instance, if applied to dissimilar species or extrapolated beyond the original diameter range for which the model was derived (Chave and others 2005, Fonseca and others 2012, Parresol 1999)].

Small-diameter trees constitute a significant proportion of naturally regenerated forests in southeastern Arkansas. While numerous models capable of predicting aboveground live-tree biomass for southern pines have been developed (Jenkins and others 2003, Newbold and others 2001, Van Lear and others 1986), few of these were actually derived using Arkansas forests and fewer still specifically included small stems. Therefore, to more accurately predict biomass for small-diameter loblolly pines, we developed a site- and species-specific biomass equation for the USDA Forest Service’s Crossett Experimental Forest (CEF). To evaluate the predictive ability of this locally fit

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model, we compared our predictions with the commonly used National Biomass Estimator (NBE; Jenkins and others 2003). Additionally, we also contrasted cumulative (per ha) biomass predictions using the local model and the NBE to determine the influence of model choice on stand-level biomass estimates.

MATERIALS AND METHODS

Study Site
This study was conducted on the CEF, which is located 11 km south of the city of Crossett in Ashley County, AR. Established in 1934 by the Forest Service, the CEF covers nearly 680 ha in southeastern Arkansas and is dominated by naturally regenerated forests of loblolly (Pinus taeda L.) and shortleaf (Pinus echinata Mill.) pine, with a minor hardwood component. The relatively flat, rolling terrain of the CEF varies between 36 and 48 m above sea level, with local differences rarely exceeding 3 m. The soils of the CEF are primarily silt loams with a loblolly pine site index of 25 to 30 m (50 year base age) (Gill and others 1979).

Sample Tree Selection and Measurement
Small-diameter (< 15 cm d.b.h.) loblolly pines were destructively sampled across the naturally regenerated pine-dominated forests of the CEF. Trees of this size were chosen to address logistical issues related to collecting and weighing above- and belowground biomass of large specimens. In addition, the smallest trees from this diameter range (those < 10 cm d.b.h.) are often not sampled when developing biomass equations (Snowdon and others 2000), yet may compose a significant fraction of many forests, including those on the CEF.

Model development entailed destructively sampling these pines. Smaller sample trees were pulled directly from the soil using a small tractor with a hydraulic boom extension lift. Bigger pine trees that could not be lifted from the ground were partially excavated using a backhoe attachment for the tractor, and then pulled. Once out of the ground, pines were separated into aboveground (foliage + branch and stemwood), and belowground (taproot) components. For this study, only the aboveground components were modeled. All components were dried in an air-forced oven at 90°C to a constant weight, and the stem, branch, and foliage components then summed to produce aboveground, oven-dry biomass.

Model Comparison
Aboveground live-tree oven-dry biomass ($B_D$, in kilograms) values were then fit to the CEF model (based on the NBE) using ordinary least squares regression:

$$B_D = b_0 + e^{b_1 + b_2 \ln(d.b.h.)}$$  

where $b_i$ are fitted coefficients. The slightly different NBE also predicts $B_D$:

$$B_D = e^{-2.5356 + 2.4349 \ln(d.b.h.)}$$

The NBE is a conservative and well-documented national model and is generally considered the standard biomass equation used nationwide by researchers and agencies to estimate tree- and stand-level forest biomass, including the official greenhouse gas inventories for the United States (EPA 2008).

RESULTS

Individual Tree Biomass
We sampled 54 loblolly pines from 0.9- to 15.0-cm d.b.h. (average of 4.6 cm; standard deviation of 3.6 cm). After processing and drying, the measured $B_D$ for these trees ranged from 0.23 to 60.87 kg, averaging 7.19 kg (standard deviation = 12.77 kg).

Local Model Fit
The following CEF biomass model:

$$B_D = 0.174544 + e^{-2.4571 + 2.41911 \ln(d.b.h.)}$$

fit the data well (pseudo-R$^2 = 0.996$). Not surprisingly, a local equation using a single species did a better job of fitting loblolly pine data from the CEF than the more general NBE (fig. 1). For the size range we considered, the NBE had few prominent departures but consistently underestimated $B_D$ across the sampled d.b.h. range. Because of the scale of figure 1, this propensity was not readily apparent. To better demonstrate the differences between the actual $B_D$ data and both sets of model predictions from the 0- to 15-cm d.b.h. range, we have enlarged that section of sampled data and model predictions for pines up to 5-cm d.b.h. (fig. 2).

The most noticeable difference appeared to be in the smallest of the trees (those < 3 cm d.b.h.), for which the NBE underestimated $B_D$ at a
Figure 1—Observed and predicted aboveground live-tree oven-dry biomass as a function of stem diameter for small (up to 15 cm d.b.h.) loblolly pine from the Crossett Experimental Forest.

Figure 2—Observed and predicted aboveground live-tree oven-dry biomass as a function of stem diameter for the smallest (0.9- to 5.0-cm d.b.h.) loblolly pines from the Crossett Experimental Forest sampled for this study.

proportionally higher rate with decreasing diameter (table 1). As an example, for a loblolly pine 5 cm in d.b.h., the CEF model forecast an individual stem biomass of 4.4 kg while the NBE predicted 4.0 kg, a relative difference of 9 percent. However, at the smallest size class measured (1.0 cm), the CEF model predicted an individual stem biomass of 0.26 kg and the NBE predicted 0.08 kg, or 70 percent less biomass.

Table 1—Predicted aboveground live oven-dry biomass ($B_0$) for 1.0-, 2.5-, 5.0-, and 15.0-cm d.b.h. loblolly pines

<table>
<thead>
<tr>
<th>D.b.h. (cm)</th>
<th>NBE</th>
<th>Local CEF</th>
<th>Relative difference$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.08</td>
<td>0.26</td>
<td>70</td>
</tr>
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<td>2.5</td>
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<td>0.96</td>
<td>23</td>
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<tr>
<td>5.0</td>
<td>3.99</td>
<td>4.38</td>
<td>9</td>
</tr>
<tr>
<td>10.0</td>
<td>21.56</td>
<td>22.67</td>
<td>5</td>
</tr>
<tr>
<td>15.0</td>
<td>57.87</td>
<td>60.15</td>
<td>4</td>
</tr>
</tbody>
</table>

$^a$Relative $B_0$ difference = [(NBE $B_0$ – local $B_0$) / local $B_0$] × 100.

DISCUSSION

Small-diameter trees can make up a large fraction of biomass in southern pine forests, making the accurate prediction of this component important. A significant initial step in improving the reliability of predictive models is understanding the role of model choice on the quantification of biomass. While this rapidly advancing field has witnessed considerable improvement over the years, many landowners have few other choices than to apply models developed for more general conditions, as is the case with perhaps the most commonly applied design, the NBE. In many instances, the use of generalized forms such as the NBE can be as effective as more site- and species-specific equations applied to individual trees in a stand (Snowdon and others 2000). However, there is also evidence that biomass models developed for other regions or silvicultural origins will yield notably different predictions from those of locally derived equations (Bragg 2011) because of considerable geographic variability in the growth and yield of most tree species (especially loblolly pine) as a function of genetics, site conditions, growth rate, and other factors (Jordan and others 2008, Mitchell and Wheeler 1959, Schultz 1997).

It is therefore quite possible that the use of a general national-scale allometric equation may underestimate the biomass of some species and overestimate the biomass of others, resulting in errors in calculating the biomass of the forest as
Table 2—Per ha differences in stand-level predicted pine-only aboveground biomass ($B_D$) and potential carbon dioxide equivalent ($CO_2e$) revenue, assuming the given stocking at the specified average tree d.b.h.

<table>
<thead>
<tr>
<th>D.b.h.</th>
<th>Stocking cm</th>
<th>Basal area $^2$</th>
<th>NBE</th>
<th>Local CEF</th>
<th>NBE</th>
<th>Local CEF</th>
<th>NBE</th>
<th>Local CEF</th>
<th>NBE</th>
<th>Local CEF</th>
<th>Difference</th>
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<tbody>
<tr>
<td>1.0</td>
<td>5,000</td>
<td>0.4</td>
<td>0.4</td>
<td>1.3</td>
<td>0.7</td>
<td>2.4</td>
<td>9.90</td>
<td>32.52</td>
<td>22.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>5,000</td>
<td>2.5</td>
<td>3.7</td>
<td>4.8</td>
<td>6.8</td>
<td>8.8</td>
<td>92.16</td>
<td>120.06</td>
<td>27.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>5,000</td>
<td>9.8</td>
<td>19.9</td>
<td>21.9</td>
<td>36.6</td>
<td>40.2</td>
<td>498.32</td>
<td>547.30</td>
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<td>10.0</td>
<td>3,000</td>
<td>23.6</td>
<td>64.7</td>
<td>68.0</td>
<td>118.7</td>
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<tr>
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<td>2,500</td>
<td>44.2</td>
<td>144.7</td>
<td>150.4</td>
<td>265.5</td>
<td>275.9</td>
<td>3,615.94</td>
<td>3,758.41</td>
<td>142.48</td>
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</table>

**a** $CO_2e = B_D \times 0.5 \times 3.67$

**b** Potential revenues assumes $13.62 per ton of $CO_2e$, as experienced in February 2013 California Air Resources Board allowance auction (California ARB 2013).

...a whole (Zhou and Hemstrom 2009). The underestimates of loblolly pine from the CEF predicted by the NBE almost certainly arose from how the pine submodel of the NBE was derived. The NBE pine equation is not specific to loblolly pine; rather, it was generated from “pseudodata” produced by 43 different equations using 14 different species of *Pinus* ranging from eastern white pine (*Pinus strobus* L., specific gravity = 0.34) to longleaf pine (*Pinus palustris* Mill., specific gravity = 0.54) (Jenkins and others 2003, 2004). Because of this generality, and the fact that southern pine species such as loblolly and shortleaf (specific gravities = 0.47) often have significantly denser wood than most other pines (Miles and Smith 2009), it is not surprising the NBE under-predict loblolly pine sampled on the CEF. These results demonstrate the importance of locally derived models, especially when biomass predictions are extrapolated to stands.

Even though the absolute differences between the CEF local biomass model (equation 3) and the NBE (equation 2) are not dramatic for individual loblolly pines in this sample range (table 1), subtle and consistent biases for individual trees can have a major cumulative impact when scaled up to stand- or regional-scale estimates. For example, in a very young loblolly pine forest averaging 5,000 stems ha$^{-1}$ and 1.0 cm in d.b.h., the CEF biomass model predicted biomass of over three times the amount forecast by the NBE (1.3 versus 0.4 tons ha$^{-1}$). In a thinned pine stand with 2,500 stems ha$^{-1}$ averaging 15.0 cm in d.b.h., the NBE predicted $B_D$ of 144.7 tons ha$^{-1}$ of biomass, while the CEF model yielded 150.4 tons, a difference of 5.7 tons (table 2).

Such a disparity may not be noticed if the biomass products are weight-scaled at a mill, but those purchased in terms of standing stocks may be affected greatly. Sequestered carbon, for instance, can be traded (sold) in the form of carbon dioxide equivalents ($CO_2e$) stored in trees based on modeled values. Converting the biomass predictions of both the NBE and local CEF models to $CO_2e$, and then assuming the February 2013 price ($13.62 per ton of $CO_2e$) of carbon allowances on the California Air Resources Board market (California ARB 2013) makes this point clearly. For the 15-cm d.b.h. scenario, this difference amounts to $142.48 ha^{-1}$ difference between the model outcomes (table 2). A consistent disparity simply from using a different model, with no change to tree size or stocking, has considerable economic and silvicultural implications. Whether in terms of more traditional forest products (chips, pulpwood, or even hog fuel) or the new currency of sequestered carbon, failure to capture the actual value of the biomass on a given parcel is detrimental to the landowner and may also misrepresent the carbon stored by a particular treatment, especially when a large number of small-diameter stems are involved.

**CONCLUSIONS**

Expanding markets for biomass in energy production improves the silvicultural opportunities for balancing sawtimber and woody biomass by providing much-needed small-diameter and low-grade markets (Koning and Skog 1987). Southern forests provide an abundance of underutilized wood, such as logging residues and small-diameter timber. Using this material for bioenergy markets could alleviate the competition with traditional timber...
commodities while providing multiple forest management options for increased growth, improved forest health, and supplemental income (Munsell and Germain 2007). However, accurate biomass estimations from stem to stand scale and across a range of size classes are needed to better realize these opportunities in emerging woody bioenergy markets and carbon accounting procedures being implemented by various commercial enterprises and regulatory agencies (for example, California ARB 2009). The determination of biomass quantities in the face of carbon-driven forest management may also impact forest policy (Galik and others 2013).

While general models like the NBE make the simulation process easier and yield reasonable biomass estimates for many species with little to no existing biomass information, it can obscure significant differences resulting in potentially major consequences for forest managers and landowners. The availability of locally derived equations, such as our model for small-diameter loblolly pine on the CEF, offers silviculturists a means to better assess the potential of naturally regenerated pine stands to produce fiber, and thus may be worth the investment of time and resources to develop.

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LITERATURE CITED


